IN THE UNITED STATES DISTRICT COURT
FOR THE EASTERN DISTRICT OF NORTH CAROLINA
SOUTHERN DIVISION
No. 7:23-CV-897

IN RE:	)	**NOTICE OF CONTINUATION OF FILING**
	)	**ADDITIONAL EXHIBITS REGARDING**
CAMP LEJEUNE WATER LITIGATION	)	**UNITED STATES' MOTION TO EXCLUDE**
	)	**PLAINTIFFS' PHASE I EXPERT**
This Document Relates To:	)	**TESTIMONY IN SUPPORT OF USING**
ALL CASES	)	**ATSDR'S WATER MODELS TO**
	)	**DETERMINE EXPOSURE LEVELS FOR**
	)	**INDVIDUAL PLAINTIFFS**

The United States files this Notice of Continuation of Filing Additional Exhibits in support of its Motion to Exclude Plaintiffs' Phase I Expert Testimony in Support of Using ATSDR's Water Models to Determinate Exposure Levels for Individual Plaintiffs and Memorandum in Support.

[Signature page to follow.]

Dated: April 29, 2025

Respectfully submitted,

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CERTIFICATE OF SERVICE

I hereby certify that on April 29, 2025, I electronically filed the foregoing using the Court's Electronic Case Filing system, which will send notice to all counsel of record.

/s/ Haroon Anwar
HAROON ANWAR

Exhibit Index

Exhibit	Description
1	Mary P. Anderson & William W. Woessner, *Applied Groundwater Modeling: Simulation of Flow and Advective Transport* (2d ed. 2015)
2	Feb. 13, 2025, Deposition Transcript of R. Jeffrey Davis
3	Jan. 16, 2013, Letter from ATSDR to Veterans Affairs
4	Aug. 3, 2015, Veteran Affairs Press Release
5	Expert Report of Morris Maslia
6	Rebuttal Report of Morris Maslia
7	March 28, 2005, ATSDR Expert Panel Transcript (Day 1)
8	March 29, 2005, ATSDR Expert Panel Transcript (Day 2)
9	April 29, 2009, ATSDR Expert Panel Transcript (Day 1)
10	April 30, 2009, ATSDR Expert Panel Transcript (Day 2)
11	Expert Report of Mustafa Aral
12	Feb. 25, 2025, Deposition Transcript of Leonard F. Konikow
13	Feb. 14. 2025, Deposition Transcript of Norman L. Jones
14	Mar. 13, 2025, Deposition Transcript of Morris Maslia
15	Rebuttal Report of Leonard F. Konikow
16	Expert Report of R. Jeffrey Davis and Norman L. Jones
17	Rebuttal Report of R. Jeffrey Davis and Norman L. Jones
18	*The Handbook of Groundwater Engineering*, Chapter 20 on Groundwater Modeling by Leonard F. Konikow & Thomas E. Reilly
19	ATSDR "Chapter A: Summary of Findings" Report for Tarawa Terrace Model
20	Frank Bove, Morris Maslia et al., *Evaluation of exposure to contaminated drinking water and specific birth defects and childhood cancers at Marine Corps Base Camp Lejeune, North Carolina: a case–control study* 12 Env't Health 104 (2013)
21	Jun. 19, 2008, Navy Letter to ATSDR
22	June 30, 2010, Deposition Transcript of Morris Maslia
23	March 10, 2009, ATSDR Response to Navy Letter
24	ATSDR Disclaimer for Tarawa Terrace Water Modeling
25	ATSDR "Chapter A: Summary of Findings" Report for Hadnot Point/Holcomb Boulevard Modeling
26	U.S. Government Accountability Office Report on Camp Lejeune (May 2007)
27	2009 ATSDR Expert Panel Summary Report
28	ATSDR Chapter A– Supplement. 6 Report for Hadnot Point/Holcomb Boulevard Model
29	2009 National Research Council Report on Camp Lejeune
30	2011 T. Prabhakar Clement Issue Paper
31	2012 ATSDR Response to T. Prabhakar Clement Issue Paper
32	Feb. 6, 2025 Deposition Transcript of Mustafa Aral
33	Feb. 21, 2007, ATSDR/Robert Faye Comments to Leonard L. Konikow
34	ATSDR Chapter H Report for Tarawa Terrace Model
35	Sept. 26, 2024, Deposition Transcript of Morris Maslia
36	Jan. 12, 2007, Email from Morris Maslia
37	Jan. 13, 2007, Email from Robert Faye

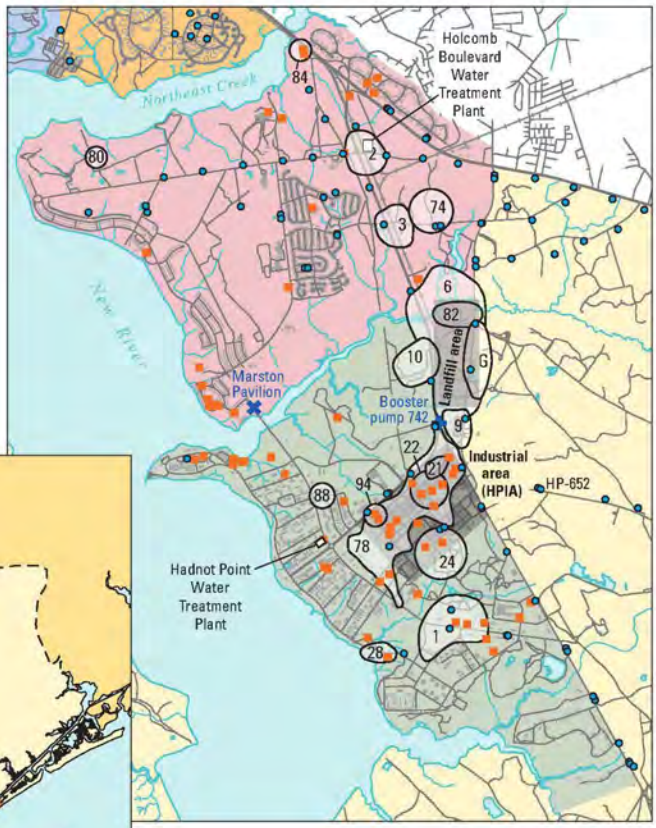
Exhibit	Description
38	Sept. 26, 2011 Email from Barbara Anderson

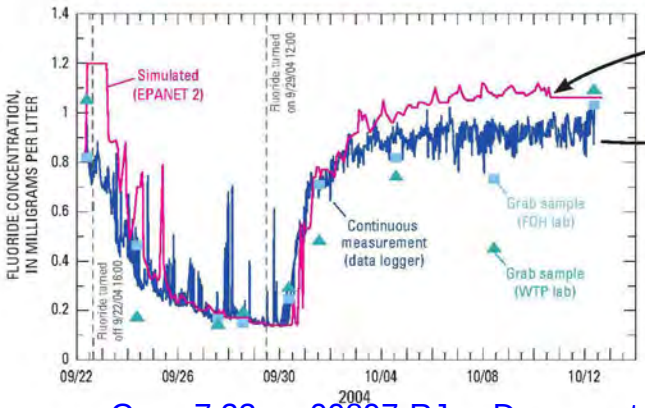
EXHIBIT 28

CONTAINS INFORMATION SUBJECT TO PROTECTIVE ORDER: DO NOT DISCLOSE TO UNAUTHORIZED PERSONS.

Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina

Chapter A–Supplement 6
Characterization and Simulation of Fate and Transport of Selected Volatile Organic Compounds in the Vicinities of the Hadnot Point Industrial Area and Landfill





ATSDR
AGENCY FOR TOXIC SUBSTANCES AND DISEASE REGISTRY

Atlanta, Georgia – March 2013

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Front cover: Historical reconstruction process using data, information sources, and water-modeling techniques to estimate historical contaminant concentrations.

Maps: U.S. Marine Corps Base Camp Lejeune, North Carolina; Holcomb Boulevard and Hadnot Point areas showing extent of sampling at Installation Restoration Program sites (white numbered areas), above-ground and underground storage tank sites (orange squares), and water-supply wells (blue circles).

Photograph (upper): Hadnot Point water treatment plant (Building 20).

Photograph (lower): Well house building for water-supply well HP-652.

Graph: Measured fluoride data and simulation results for Paradise Point elevated storage tank (S-2323) for tracer test of the Holcomb Boulevard water-distribution system, September 22–October 12, 2004; simulation results obtained using EPANET 2 water-distribution system model assuming last-in first-out plug flow (LIFO) storage tank mixing model. [WTP lab, water treatment plant water-quality laboratory; FOH lab, Federal Occupational Health Laboratory]

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Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina

Chapter A–Supplement 6
Characterization and Simulation of Fate and Transport of Selected Volatile Organic Compounds in the Vicinities of the Hadnot Point Industrial Area and Landfill

By L. Elliott Jones, René J. Suárez-Soto, Barbara A. Anderson, and Morris L. Maslia

Agency for Toxic Substances and Disease Registry
U.S. Department of Health and Human Services
Atlanta, Georgia

March 2013

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Appendix Figures Graphs showing—

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Tables

Appendix Table

Conversion factors and definitions of common terms and abbreviations used throughout the Chapter A report series are listed in the front of the Chapter A report.

Use of trade names and commercial sources is for identification only and does not imply endorsement by the Agency for Toxic Substances and Disease Registry, the U.S. Department of Health and Human Services, or the U.S. Geological Survey.

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Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina

Chapter A–Supplement 6

Characterization and Simulation of Fate and Transport of Selected Volatile Organic Compounds in the Vicinities of the Hadnot Point Industrial Area and Landfill

By L. Elliott Jones,[1] René J. Suárez-Soto,[2] Barbara A. Anderson,[2] and Morris L. Maslia[2]

Introduction

This supplement of Chapter A (Supplement 6) describes the reconstruction (i.e., simulation) of historical concentrations of tetrachloroethylene (PCE), trichloroethylene (TCE), and benzene[3] in production wells supplying water to the Hadnot Point water treatment plant (HPWTP) at U.S. Marine Corps Base (USMCB) Camp Lejeune, North Carolina (Figure S6.1). A fate and transport model (i.e., MT3DMS [Zheng and Wang 1999]) was used to simulate contaminant migration from source locations through the groundwater system and to estimate monthly mean contaminant concentrations in water withdrawn from water-supply wells in the vicinity of the Hadnot Point Industrial Area (HPIA) and the Hadnot Point landfill (HPLF) area.[4] The reconstructed contaminant concentrations were subsequently input into a flow-weighted, materials mass balance (mixing) model (Masters 1998) to estimate monthly mean concentrations of the contaminants in finished water[5] at the HPWTP (Maslia et al. 2013). The calibrated fate and transport models described herein were based on and used groundwater velocities derived from groundwater-flow models that are described in Suárez-Soto et al. (2013). Information and data pertinent to historical operations of water-supply wells are described in Sautner et al. (2013) and Telci et al. (2013).

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[1] U.S. Geological Survey, Georgia Water Science Center, Norcross, Georgia.

[2] Agency for Toxic Substances and Disease Registry, Atlanta, Georgia.

[3] Chapter A–Supplement 6 (this supplement) focuses solely on analyses and simulation of benzene dissolved in groundwater. For analyses and simulation of benzene characterized as a light nonaqueous phase liquid (LNAPL), refer to Jang et al. (2013).

[4] The Hadnot Point Industrial Area (HPIA) is a formally designated name and acronym used in many Camp Lejeune references (e.g., Baker Environmental, Inc. [1994], CH2M HILL [2006]), and the ATSDR Hadnot Point–Holcomb Boulevard Chapter reports and Chapter A supplements follow this naming convention. The acronym HPLF is used in the ATSDR Hadnot Point–Holcomb Boulevard report series for brevity and convenience to identify the Hadnot Point landfill.

[5] For this study, finished water is defined as groundwater that has undergone treatment at a water treatment plant and was subsequently delivered to a family housing unit or other facility. Throughout this report and the Hadnot Point–Holcomb Boulevard report series, the term finished water is used in place of terms such as finished drinking water, drinking water, treated water, or tap water.

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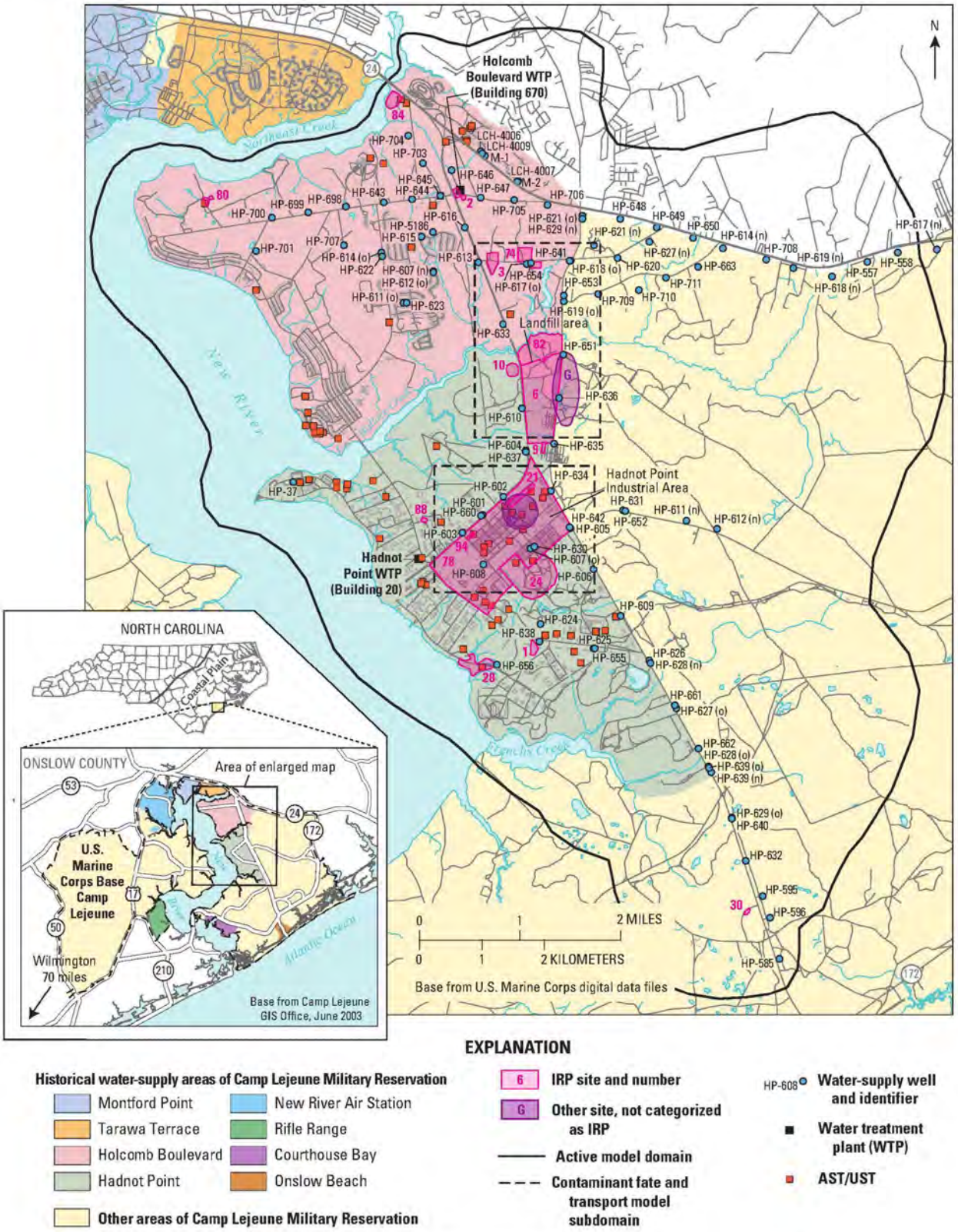

Figure S6.1. Groundwater-flow model domain, contaminant fate and transport model subdomains, Installation Restoration Program (IRP) and above-ground and underground storage tank (AST/UST) sites, and water-supply wells, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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Background

USMCB Camp Lejeune is located in the Coastal Plain of North Carolina, in Onslow County, south of the City of Jacksonville and about 70 miles northeast of the City of Wilmington, North Carolina (Figure S6.1). The area of investigations is inclusive of the HPWTP and Holcomb Boulevard water treatment plant (HBWTP) service areas, hereafter called the study area or the Hadnot Point–Holcomb Boulevard (HPHB) study area. In general, the study area is bordered on the north by Northeast Creek and North Carolina Highway 24 (SR24), to the west by New River, to the south by Frenchs Creek, and generally to the east by the drainage divides of the upstream tributaries of Wallace Creek and Frenchs Creek. Total study area is approximately 50 square miles (mi^2).

Eight water-distribution systems have supplied or currently (2013) are supplying finished water to family housing and other facilities at USMCB Camp Lejeune, North Carolina. The three water-distribution systems of interest to this study—Tarawa Terrace (TT), Hadnot Point (HP), and Holcomb Boulevard (HB)—historically supplied finished water to a majority of family housing at USMCB Camp Lejeune. Two of the three water-distribution systems were contaminated with volatile organic compounds (VOCs). Groundwater supplied to the Tarawa Terrace water treatment plant (TTWTP), and subsequently to TT housing areas and other facilities, was contaminated with PCE and related degradation products such as TCE and vinyl chloride (VC). Similarly, groundwater supplied to the HPWTP was contaminated with TCE, as well as PCE and refined petroleum products such as benzene, toluene, ethylbenzene, and xylenes (BTEX). Groundwater supplied to the HBWTP was mostly uncontaminated (Faye et al. 2010, Tables C11–C12), except for the intermittent transfers of contaminated Hadnot Point finished water to the Holcomb Boulevard water-distribution system during 1972–1985 (Maslia et al. 2013).

The HPWTP was constructed probably during 1941 and 1942, along with much of the original infrastructure of USMCB Camp Lejeune. Construction of the HBWTP was completed during the summer of 1972 (Scott A. Brewer, USMCB Camp Lejeune, written communication, September 29, 2005).[6] For the period of interest to this study (1942–2008), 96 water-supply wells have historically or are currently (2013) providing groundwater to the HPWTP and HBWTP (Sautner et al. 2013; Telci et al. 2013). The operational chronology of water-supply wells during the period of interest to the study (1942–2008) is shown in Figure A5[7] (Maslia et al. 2013) and is discussed in detail in Sautner et al. (2013).

Conceptual Models

Conceptual models for groundwater flow and contaminant migration are used as the bases to develop, apply, and calibrate complex numerical models that simulate groundwater flow and contaminant fate and transport within the HPHB study area. For groundwater flow, the conceptual model is described in detail in Faye et al. (2013); a related numerical model is described in detail in Suárez-Soto et al. (2013) and is briefly summarized below. Following that summary, a detailed description of the conceptual model of contaminant migration, which includes a discussion of contaminant sources and histories is presented.

Groundwater Flow

Conceptualization, development and calibration of a three-dimensional groundwater-flow model, used as the basis for the fate and transport model is described by Suárez-Soto et al. (2013). Briefly, the groundwater-flow model simulates the flow of groundwater from its source as recharge from precipitation, into the uppermost aquifer—the Brewster Boulevard upper aquifer—through the underlying aquifers—including the Tarawa Terrace and the Upper and Middle Castle Hayne aquifers (Table S6.1)—to discharge locations at water-supply or remediation wells, New River, or various tributaries of New River. The model area is bounded to the north, east, and south by topographic divides at the headwaters of the drainage areas of the north flowing tributaries of Northeast Creek, Wallace Creek, and Frenchs Creek, and to the west by New River (Figure S6.1).

Contaminant Migration

Contaminant migration is limited to PCE, TCE, and benzene within the HPIA and the HPLF area (Figure S6.1). Conceptually, it is assumed that hydraulic-head gradients are the only mechanism for fluid flow and that Darcy's law is valid, chemical reactions do not affect fluid or aquifer properties, and a contaminant dissolves in groundwater such that there are no density effects.

Using site and building history, contaminant data, and remediation efforts described in Faye et al. (2010, 2012), contaminant sources that potentially affected water-supply wells were identified and are listed in Table S6.2. Sources with sufficient supporting documentation were included in the conceptual and numerical models and are described hereafter.

[6] Based on information contained in the written communication from USMCB Camp Lejeune, the start of continuous operations at the HBWTP is estimated to be about June 1972.

[7] References to figures, tables, or appendixes in the Chapter A report (e.g., Figure A1) are found in Maslia et al. (2013).

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Table S6.1. Correlation between geologic and hydrogeologic units and model layers, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[—, not applicable]

[1]Geologic units			[1]Hydrogeologic units	[1]Thickness	[2]Model layer number
System	Series	Formation	Aquifer and confining unit	Range, in feet	
Quaternary	Holocene Pleistocene	Undifferentiated	Brewster Boulevard upper aquifer	4 to 42	1
Tertiary	Pliocene	Absent	Absent	Absent	
	Miocene	Pungo River Formation, undifferentiated	Brewster Boulevard upper confining unit	1 to 22	
			Brewster Boulevard lower aquifer	4 to 48	
		Belgrade Formation, undifferentiated	Brewster Boulevard lower confining unit	2 to 30	2
			Tarawa Terrace aquifer (upper part)	8 to 86	3
	Oligocene	River Bend Formation, undifferentiated	Tarawa Terrace aquifer (middle and lower parts)		
			Upper Castle Hayne confining unit (previously designated the Tarawa Terrace confining unit in Faye [2007])	4 to 40	4
	Late Eocene	Unnamed	Upper Castle Hayne aquifer–River Bend unit	16 to 70	5
		Castle Hayne Formation	Local confining unit	8 to 23	
			Upper Castle Hayne aquifer–Lower unit	10 to 48	
	Middle Eocene		Middle Castle Hayne confining unit	12 to 27	6
			Middle Castle Hayne aquifer	62 to 122	7
			Lower Castle Hayne confining unit	18 to 38	Base of model
			Lower Castle Hayne aquifer	64 to 86	
	Paleocene	Beaufort Formation, undifferentiated	Beaufort confining unit (generally occurs at top of Beaufort Formation)	—	

[1] From Faye (2012)

[2] From Suárez-Soto et al. (2013)

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Table S6.2. Inventory of potential contaminant-source areas in the vicinity of historically contaminated water-supply wells, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[AST/UST, above-ground storage tank/underground storage tank; IRP, Installation Restoration Program; PCE, tetrachloroethylene; TCE, trichloroethylene; HPFF, Hadnot Point fuel farm; Bldg, Building; J, laboratory qualifier indicating concentration was estimated]

[1]Historically contaminated water-supply wells	Sample dates	Contaminants detected	Number of detections/ number of analyses	Statistics for detected concentrations, in micrograms per liter					Potential source locations	
				Minimum	25th percentile	50th percentile	75th percentile	Maximum	[2]AST/UST sites	[3]IRP sites (source areas)
Hadnot Point Industrial Area (HPIA)										
HP-602	7/1984–1/1991	Benzene PCE TCE	6/8 3/8 7/8	17 1.5 0.7J	67.5 2.4 20.1	175 3.2 300	342.5 13.6 440	720 24 1,600	HPFF, Bldg 1115, Bldg 1101	Site 78 (Bldg 901/902 area), Site 21
HP-603	12/1994–9/1995	TCE	3/7	1.0J	2.0	3.0	3.8	4.6J	Bldg 1613, Bldg 61, Bldg 1502, Bldg 1601, Bldg 1607	Site 78 (Bldg 1601), Site 94
HP-608	12/1984–11/1986	Benzene TCE	3/4 4/4	1.6 9.0	2.7 12	3.7 39.5	3.9 77	4 110	Bldg 1601, Bldg 1502, Bldg 1607, Bldg S1856	Site 78 (Bldg 1601), Site 24
HP-634	12/1984–1/1991	PCE TCE	1/5 1/5	10 1,300	10 1,300	10 1,300	10 1,300	10 1,300	Bldg 738, Bldg 900, Bldg 903	Site 78 (Bldg 901/902 area), Site 21
HP-660	12/1984–1/1991	PCE TCE	2/5 4/5	4.4 1.0J	4.6 19.8	4.7 118	4.9 215	5.0 230	Bldg 1115, Bldg 1401, Bldg 1502, Bldg 1601, Bldg 1613	Site 78 (Bldg 1601), Site 94
Hadnot Point landfill area (HPLF)										
HP-651	1/1985–1/1991	PCE TCE	5/5 5/5	45 13	53 32	307 3,200	386 17,600	400 18,900	Unknown	Site 6, Site 82
HP-653	1/1985–1/1991	TCE	2/3	2.6	3.3	4.1	4.8	5.5	Unknown	Unknown
HP-610	2/1985–10/1992	TCE	1/2	37	37	37	37	37	Unknown	Site 6
HP-645 area										
HP-645	11/1986–2/1987	Benzene	2/3	20	87.5	155	222.5	290	Bldg 645, Bldg 40	Site 2
Other areas										
HP-637	12/1984–8/1992	TCE	1/5	0.9J	0.9J	0.9J	0.9J	0.9J	Unknown	Site 6, Site 9, Site 78
HP-652	1/1985–12/2001	TCE	1/5	9.0	9.0	9.0	9.0	9.0	Unknown	Unknown
HP-706	9/1995–1/1998	Benzene	2/2	0.6	2.0	3.4	4.7	6.1	Unknown	Unknown

[1]See Figure A8 (Maslia et al. 2013) for locations

[2]Sites managed under the AST/UST program at Camp Lejeune. At these sites, an environmental release has occurred and subsequent investigations and/or remediation activities are conducted under the auspices of the Resource Conservation and Recovery Act (RCRA) and within the North Carolina Department of Environment and Natural Resources underground storage tank regulatory framework; refer to Faye et al. (2012) for additional details on selected AST/UST sites at Camp Lejeune

[3]Sites managed under the IRP at Camp Lejeune. At these sites, an environmental release has occurred and subsequent investigations and/or remediation activities are conducted within the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) regulatory framework. Within Site 78, specific local source areas are listed parenthetically; refer to Faye et al. (2010) for additional details on IRP sites at Camp Lejeune

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Hadnot Point Industrial Area (HPIA) Contaminant Sources

HPIA contaminant source areas include (1) TCE and benzene releases around Building 1601, (2) TCE releases around Buildings 901, 902, and 903, (3) benzene releases in the Hadnot Point fuel farm (HPFF) area, (4) benzene releases in Building 1613, (5) TCE releases around Building 1115, and (6) TCE releases around Building 1401 (Figure S6.2). With the exception of benzene releases in the HPFF area and Building 1613, all sources mentioned above are included in the numerical models described in this supplement. Benzene releases as light nonaqueous phase liquid (LNAPL) from sources in the HPFF and Building 1613 areas and the simulation of the fate and transport of benzene as an LNAPL are described in Jang et al. (2013).

Building 1601 was constructed during the 1940s and was originally used as a garage for motor vehicles and a vehicle maintenance facility (Faye et al. 2010). Disposal of waste oil and other chemicals in a 1,600-gallon[8] (gal) underground storage tank (UST 1601) was probably the source for detections of TCE—and possibly benzene—in well HP-608 (Figure S6.2).

The steel tank (UST 1601) was installed in 1942 according to Geraghty and Miller (1990) and removed during remediation activities performed during June 29, 1993 (Peele's Pump and Tank Company 1993). Two additional tanks and fuel dispenser islands located southeast from Building 1601 could have also contributed to the contamination of benzene detected in HP-608. These tanks were connected to the HPFF by a 4-inch diameter underground pipeline that ran along East Street (Catlin Engineers & Scientists 1996, OHM Remediation Services Corporation 2001).The content from these tanks probably leaked through joints, valves, or other weak points and entered the subsurface. Over time, the contaminants migrated through the subsurface and entered the groundwater system. The predevelopment groundwater-flow direction was south and southwest of Building 1601 toward well HP-608; therefore, a plume probably formed in a southwest direction. Water-supply well HP-608 started pumping around 1942 and probably did not change the direction of the plume substantially but did increase the horizontal migration of contaminants toward the water-supply well (HP-608).

TCE releases around Buildings 901, 902, and 903 probably occurred from the leaking of two USTs and the degreasing activities around this area (Figure S6.2). A 440-gal UST located east of Building 901 could have possibly contributed to the contamination of TCE in the area (Environmental Science and Engineering, Inc. 1988). Similarly, a UST of unknown capacity located between Buildings 902 and 903 could have contributed to the TCE contamination in the area. The installation dates of these tanks are unknown; however, the buildings surrounding this area were constructed around 1948, and presumably the tanks were installed at the same time. The highest concentration of TCE around this area (13,000 micrograms per liter [µg/L]) corresponds to an unpaved area southeast of Building 901 where contaminants could have entered the subsurface due to degreasing activities near Building 901. The contaminants probably entered the groundwater system near the sources identified previously and migrated west and northwest in the direction of groundwater flow. About 1963, with the onset of pumping in well HP-634, the groundwater flow in this area was affected, causing the TCE plume to migrate somewhat backward toward the water-supply well (HP-634). Sources around Buildings 901–903 were probably removed during remediation efforts that began about January 1995 (Sovereign Consulting Inc. 2007).

TCE releases around Buildings 1115 and 1401 have been documented to a lesser degree. The presence of chlorinated alkenes around Building 1115 is documented by Faye et al. (2012, Table D5), and the concentrations varied from below detection limits to maximum values of 160 µg/L for TCE, 11 µg/L for PCE, 110 µg/L for total DCE, and 6 µg/L for VC. The chlorinated alkenes found around Building 1115 are presumably the result of natural attenuation of TCE.

[8]UST 1601 tank capacity is reported as 1,600 gallons in Richard Catlin & Associates (1996) and as 1,500 gallons in Geraghty and Miller (1990). The capacity reported by Richard Catlin & Associates (1996) is used in this report.

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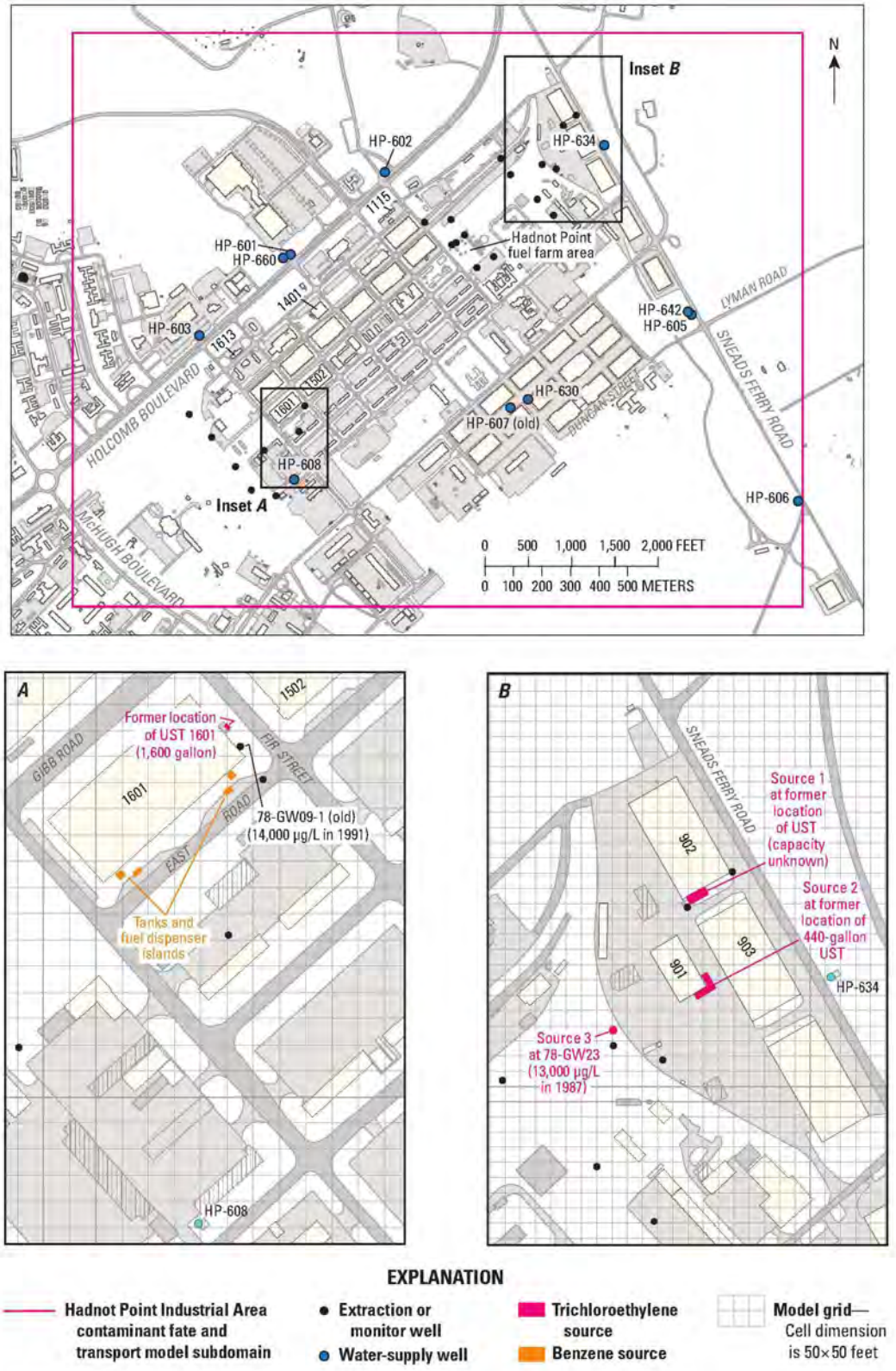

Figure S6.2. Contaminant fate and transport model source areas, selected water-supply wells, model features, water-supply wells, and source locations and enlarged maps for *(A)* Building 1601 area and *(B)* Building 901 area for the Hadnot Point Industrial Area model, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. [See Table S6.5 for contaminant source location; µg/L, micrograms per liter]

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Hadnot Point Landfill (HPLF) Area Contaminant Sources

In the HPLF area, disposal of TCE and PCE at storage lot 203 and possibly at Installation Restoration Program (IRP) Site 82 probably first occurred during the early operation of the landfill in the 1940s (Figure S6.3). It is not known whether the materials were disposed directly to the ground surface or leaked from disposal drums or other containers. The PCE and TCE concentrations in soil and groundwater samples were used as evidence for the location of the sources.

Elevated concentrations of TCE (up to 180,000 µg/L) and PCE (up to 6,500 µg/L) were detected in a deep monitoring well (06-GW01D) that was constructed in the Upper Castle Hayne aquifer during October 1992 (Figure S6.3). At the location of monitoring well 06-GW01D, near the eastern end of the boundary between storage lot 203 and IRP Site 82, the contaminants migrated from the ground surface downward through a sequence of hydrogeologic units (the Brewster Boulevard aquifer system, the Brewster Boulevard lower confining unit, the Tarawa Terrace aquifer, and the Tarawa Terrace confining unit) before reaching the Upper Castle Hayne aquifer (Table S6.1). The Upper Castle Hayne aquifer is more permeable than the overlying units, and TCE and PCE were dissolved into the groundwater of the aquifer and were transported in a north-northwesterly direction by groundwater flowing toward Wallace Creek. Because there are few monitoring wells constructed in the hydrogeologic units below the Upper Castle Hayne aquifer, and none downgradient of monitoring well 06-GW01D, it is unknown if a pool of DNAPL formed at the base of the Upper Castle Hayne aquifer or if the DNAPL continued a downward migration to underlying units.

Eventually, a plume of TCE- and PCE-contaminated groundwater in the Upper Castle Hayne aquifer extended from the source location(s) north-northwestward to Wallace Creek, which is a local groundwater drain. Near the source locations, the vertical groundwater gradient is downward. The vertical gradient is reversed near Wallace Creek, however, and groundwater flows upward from the Castle Hayne aquifer through the overlying hydrologic units and discharges to Wallace Creek. Near Wallace Creek, the TCE- and PCE-contaminated groundwater follows the groundwater flow upward and into the creek.

Water-supply well HP-651, located east of the northeastern corner of storage lot 203 (Figure S6.3), was put in service in July 1972 and pumped water from the Upper Castle Hayne aquifer. The long-term average pumping rate from water-supply well HP-651 was about 130 gallons per minute (gpm) for the next 12 years and 7 months, until the well was taken out of service during January 1985.[9] The radius of influence of water-supply well HP-651 extended to the presumed TCE and PCE source location near monitoring well 06-GW01D within a few months after July 1972. During the time HP-651 operated, the groundwater-flow direction in the Upper Castle Hayne aquifer changed from north-northwestward to eastward toward water-supply well HP-651, and part of the TCE- and PCE-contaminated groundwater also began to flow toward water-supply well HP-651. After well HP-651 was taken out of service, the original north-northwestward groundwater-flow direction was restored, and the TCE- and PCE-contaminated groundwater that had been drawn toward water-supply well HP-651 began to migrate toward Wallace Creek.

[9] For water-supply well capacities, histories, and monthly pumping rates, refer to Sautner et al. (2013) and Telci et al. (2013).

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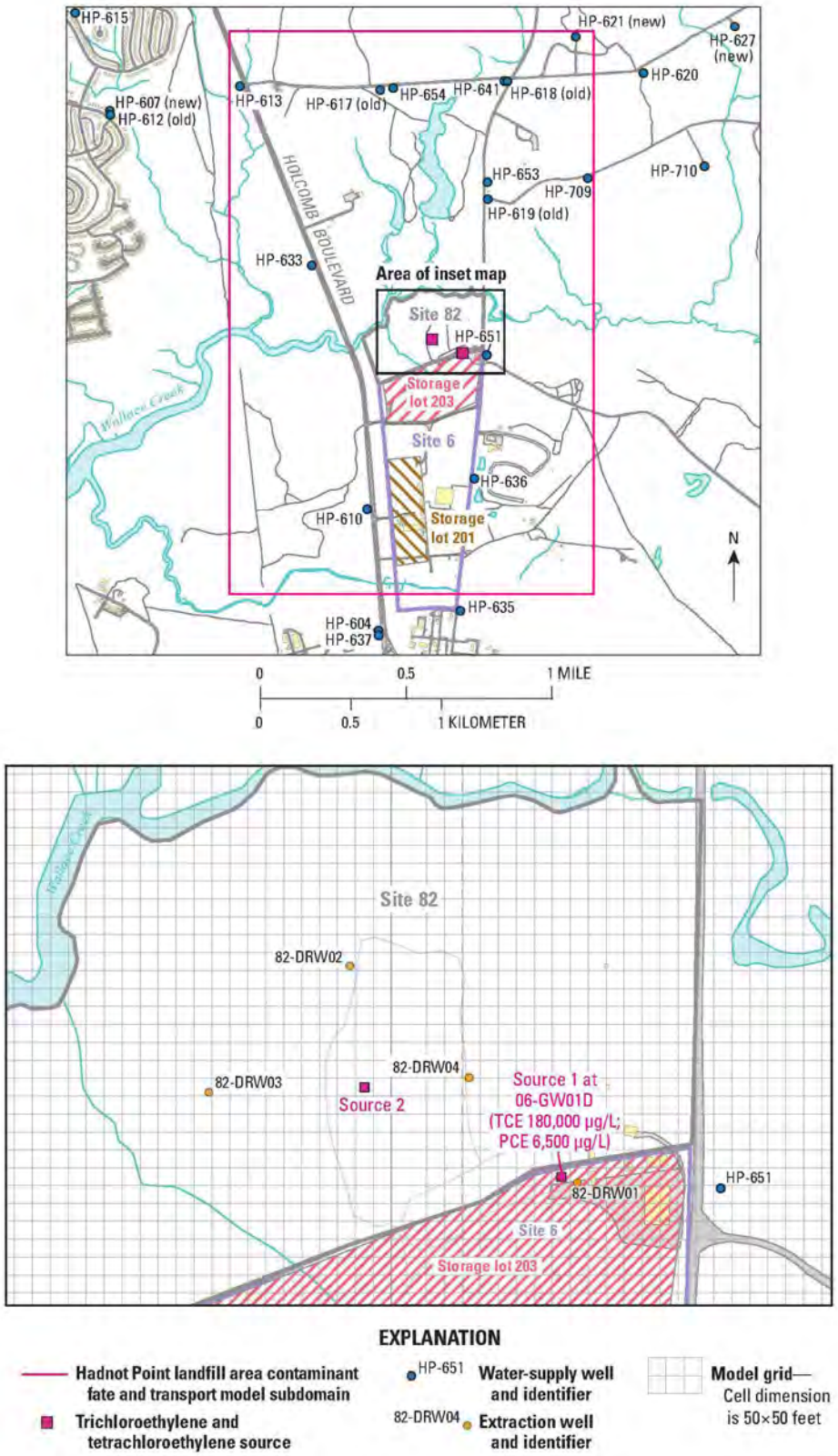

Figure S6.3. Contaminant fate and transport model source locations, selected water-supply wells, model features, water-supply wells, and source locations and enlarged map for Installation Restoration Program Site 82 area for the Hadnot Point landfill model, Hadnot Point–Holcomb Boulevard Study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. [See Table S6.5 for contaminant source location; µg/L, micrograms per liter]

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Mathematics of Contaminant Fate and Transport

The partial differential equation describing the fate and transport of contaminants dissolved in a three-dimensional groundwater system, under a local equilibrium assumption,[10] can be written as follows (Zheng and Wang 1999):

$$Rn_E \frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left(n_E \boldsymbol{D}_{ij} \frac{\partial C}{\partial x_j} \right) - \frac{\partial}{\partial x_i}\left(n_E V_i C\right) + q_s C_s - q'_s C - \lambda_1 n_E C - \lambda_2 \rho_b \bar{C} \quad , \tag{S6.1}$$

where[11]:

R is retardation factor, dimensionless;[12]
n_E is effective porosity, dimensionless;
C is dissolved concentration $[ML^{-3}]$;
t is time $[T]$;
$x_{i,j}$ is distance along the respective Cartesian coordinate axis $[L]$;
$\boldsymbol{D}_{ij}$ is the hydrodynamic dispersion tensor $[L^2T^{-1}]$;
V_i is groundwater or linear pore velocity, $[LT^{-1}]$, which is related to the specific discharge (q_i) or Darcy velocity vector through the relation, $V_i = \boldsymbol{q}_i / n_E$;
q_s is volumetric flow rate per unit volume of aquifer representing fluid sources (positive) and sinks (negative) $[T^{-1}]$;
C_s is concentration of the source or sink flux $[ML^{-3}]$;
q'_s $\partial n_E / \partial t$ is the rate of change in transient groundwater storage $[T^{-1}]$;
λ_1 is the first-order reaction rate for the dissolved phase $[T^{-1}]$;
λ_2 is the first-order reaction rate for the sorbed (solid) phase—λ_2 is zero for this study $[T^{-1}]$;
ρ_b is bulk density of the subsurface medium $[ML^{-3}]$; and
$\bar{C}$ is concentration of contaminant sorbed in the subsurface solids $[MM^{-1}]$.

Boundary Conditions

Equation S6.1 is subject to the following three types of boundary conditions:

- **Type 1:** Specified concentration boundary (Dirichlet condition), in which the concentration is specified along a boundary. A specified concentration boundary in a transport model is a source that provides contaminant mass to the model domain or is a sink that removes mass from the model domain. Contaminant sources for PCE, TCE, and benzene in the HPIA or HPLF models were simulated using a Type 1 boundary and are further described in subsequent sections.
- **Type 2:** A specified concentration gradient (Neumann condition) normal to the boundary. A special case of a Neumann or Type 2 boundary condition is a no-dispersive mass flux boundary condition, in which case, the value of the boundary condition is set to zero.
- **Type 3:** A combination of a Type 1 and Type 2 boundary condition (Cauchy condition), in which the concentration value and the concentration gradient are specified. The Type 3 or Cauchy boundary condition represents the total flux (dispersive and advective) normal to the boundary. If it can be assumed that the advective flux dominates the dispersive flux, then the Type 3 boundary condition can be handled by using the source/sink term in Equation S6.1.

[10] Local equilibrium is assumed for various sorption processes to indicate that sorption is sufficiently rapid compared to the transport time scale.

[11] In the notation throughout this report, M = mass units, L = length units, and T = time units.

[12] Refer to section on Sorption for a detailed definition of retardation factor.

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Initial Conditions

The mathematical equation of contaminant fate and transport (Equation S6.1) describes the transient changes of contaminant concentration in groundwater. To obtain a solution to Equation S6.1, initial conditions must be specified that require the specification of the value of the contaminant concentration throughout the model domain. The initial condition for the model is a concentration of zero for all contaminants (e.g., PCE, TCE, and benzene) at simulation time equal to zero (i.e., January 1942).

Review of Assumptions

A number of assumptions have been made in developing the mathematical equation for contaminant fate and transport described by Equation S6.1. The main assumptions are listed below and follow those described by Konikow et al. (1996).

1. Darcy's law is valid in the solution domain, and hydraulic-head gradients are the only mechanism for fluid flow.
2. Aquifer hydraulic conductivity is independent of time (constant). If an aquifer is anisotropic, it is assumed that the principal axes of the hydraulic conductivity tensor are aligned with the modeling grid coordinate system, so that the cross-terms of the hydraulic conductivity tensor are eliminated.
3. Gradients of fluid density, viscosity, and temperature do not affect the velocity distribution.
4. Chemical reactions do not affect fluid or aquifer properties.
5. Dispersivity coefficients are constant with time, and the aquifer is isotropic with respect to longitudinal dispersivity.
6. The contaminant's solubility is such that it dissolves in groundwater and does not affect groundwater density.

The implication of assumption 6, above, is that contaminants such as TCE and PCE, which are denser than water, are characterized as DNAPLs, and benzene, which is less dense than water, is characterized as an LNAPL and cannot be simulated using Equation S6.1. With respect to TCE and PCE, available field data (Faye et al. 2012) indicate that observed groundwater concentrations are less than respective saturation limits; therefore, these contaminants were dissolved in groundwater, and Equation S6.1 is applicable. With respect to benzene in the fuel farm area, field data indicate substantial "floating" product (Faye et al. 2012); therefore, a mathematical equation describing benzene by different fluid phases and densities (relative to groundwater) was applied. This specific situation, dissolution of benzene from an LNAPL and migration in groundwater, is described in Jang et al. (2013). For conditions in the vicinity of Building 1601, where field data indicated benzene concentration in a dissolved phase (Faye et al. 2012), Equation S6.1 is appropriate and was used to simulate the migration of benzene in groundwater.

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Three-Dimensional Contaminant Fate and Transport Model

The finite-difference, groundwater-flow model of the HPHB study area of USMCB Camp Lejeune, described in Suárez-Soto et al. (2013), was used as the basis for simulating contaminant transport in the HPIA and the HPLF area. Contaminant fate and transport simulations were conducted by using two variably spaced grid models that were refined in the HPIA and HPLF area to comply with numerical discretization requirements for simulating contaminant migration using 50-foot (ft)×50-ft finite-difference cells. Groundwater flow was simulated by using the numerical code MODFLOW-2005 (Harbaugh 2005), originally developed by McDonald and Harbaugh (1984). MT3DMS[13] (Modular 3-Dimensional Transport, Multi-Species) version 5.3, developed by Zheng and Wang (1999), was the numerical code used to simulate contaminant fate and transport for the variably spaced grid models representing the HPIA and HPLF area.[14]

The HPIA model has the same boundaries as the variably spaced grid model that is described in Suárez-Soto et al. (2013). The HPIA model domain consists of 288 rows, 298 columns, and 7 layers; the active model area is about 50 mi^2 and has 453,654 active cells. The more finely discretized (50×50-ft grid) area of the model domain is bounded by the Holcomb Boulevard–Sneads Ferry Road intersection in the north, McHugh Boulevard in the west, the McHugh Boulevard–Duncan Street intersection in the south, and Lyman Road in the east (Figure S6.2). The 50×50-ft area of the model is 8,400 ft (1.59 miles [mi]) from west to east, is 6,600 ft (1.25 mi) from north to south, and consists of 132 rows and 168 columns.

The HPLF model also has the same boundaries as the variably spaced grid model that is described in Suárez-Soto et al. (2013). The HPLF model domain consists of 348 rows, 268 columns, and 7 layers; the active model area is about 50 mi^2 and has 532,287 active cells. The more finely discretized (50×50-ft grid) area of the HPLF model domain is in a less developed area of USMCB Camp Lejeune than the HPIA model and is bisected west to east roughly through the middle by Wallace Creek (Figure S6.3). The 50×50-ft-grid area of the HPLF model is 6,600 ft (1.25 mi) from west to east and extends almost a mile south of Wallace Creek to Bearhead Creek and almost a mile north of Wallace Creek. The area of the grid is 10,200 ft (1.93 mi) from north to south and consists of 204 rows and 132 columns.

Vertical discretization for both models consists of seven layers. Model layers 1, 3, 5, and 7 represent water-bearing units, and model layers 2, 4, and 6 explicitly represent confining units. Several hydrogeologic units were combined in layers 1 and 5. Model layers and corresponding hydrogeologic units are listed in Table S6.1. Details and information pertaining to the hydrogeologic framework used to derive groundwater-flow and contaminant fate and transport model layers are described by Faye (2012).

Monthly water-supply-well pumping model arrays are based on time-series output from the analysis of well operations discussed in Sautner et al. (2013) and Telci et al. (2013). The only exception is that in addition to pumping from water-supply wells, the HPLF model also included pumping from six shallow and four deep extraction (remediation) wells that began operation at IRP Site 82 during October 1996. Some monthly and some quarterly pumping rates for extraction wells were tabulated by Engineering and Environment, Inc. and Michael Baker Jr., Inc. (2004). During months of missing record, quarterly rates were distributed evenly for each of the 3 months in the quarter.

Initial conditions of hydraulic head corresponded to simulated predevelopment (steady-state) hydraulic heads obtained from the calibrated model described in Suárez-Soto et al. (2013). For contaminant concentrations, the initial conditions were set to a concentration of zero for all contaminants (e.g., PCE, TCE, and benzene) at simulation time equal to zero (i.e., January 1942).

Time discretization for the HPIA and HPLF models consists of 798 monthly stress periods (January 1942–June 2008) and 1 time step per stress period.[15] Horizontal hydraulic conductivity, horizontal anisotropy, vertical anisotropy, specific yield, specific storage, and recharge are identical to the 300×300-ft regional model described in Suárez-Soto et al. (2013). Therefore the 50×50-ft-grid area of the model has blocks of 36 cells (6×6) with properties that identically correspond to one 300×300-ft cell of the regional model.

In the HPIA and HPLF models, pumping from water-supply wells is the same as for the HPHB study area model described in Suárez-Soto et al. (2013). Water-supply wells that are within the 50×50-ft grid of the HPIA and HPLF models were assigned to the appropriate cell according to their location (using North Carolina State Plane coordinates), although that location may not coincide with the closest cell to the center of the corresponding 300×300-ft grid cell to which it was assigned in the HPHB model. The refinement of well locations within the more finely discretized areas of the HPIA and HPLF models results in some slight differences in the simulated locations of pumping stresses.

[13] MT3DMS—three-dimensional mass transport, multispecies model developed on behalf of the U.S. Army Engineer Research and Development Center. MT3DMS-5.3 (Zheng and Wang 1999) is the specific version of MT3DMS code used for the HPHB study area analyses; references to MT3DMS in text, figures, tables, and appendixes refer to MT3DMS-5.3.

[14] Henceforth, the contaminant fate and transport model applied to the Hadnot Point Industrial Area will be referred to as the HPIA model; the contaminant fate and transport model applied to the Hadnot Point landfill area will be referred to as the HPLF model.

[15] Refer to Suárez-Soto et al. (2013, Appendix S4.6) for a sequential list of stress periods and corresponding month and year.

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Solute sources of TCE, PCE, and benzene were placed at locations within model layers based on information of contaminant releases and spills and measured contaminant concentrations in water-supply, monitor, and extraction wells (Faye et al. 2012). Locations of the aforementioned modeled contaminant sources are shown in Figures S6.2 and S6.3 and are listed in Table S6.2. Transport model parameter values for contaminant-source concentrations, retardation factors, and biochemical degradation rates were adjusted by using manual trial-and-error means to achieve reasonable matches between historical measured concentrations and simulated values at selected water-supply, monitor, and extraction wells. Calibrated parameter values are within reasonable and acceptable parameter-value limits found in the literature and also applied to the TT study area (Faye 2008). Specific comparisons between measured and simulated concentrations are described in the Historical Reconstruction Results section.

Hydrodynamic Dispersion

To compute values of hydrodynamic dispersion coefficients, MT3DMS requires the cell-by-cell assignment of the effective molecular diffusion coefficient (D^*) for the simulated chemical in groundwater, longitudinal dispersivity (α_L), and the ratios of transverse horizontal and vertical dispersivity (α_T and α_V, respectively) to α_L. All of these dispersion parameters for the HPIA and HPLF models are the calibrated values derived by Faye (2008) for migration of PCE within the TT study area. Longitudinal dispersivity was assigned a value of 25 ft to all cells in all layers (Table S6.3). Ratios of α_T/α_L and α_V/α_L of 0.1 and 0.01, respectively, were assigned to all cells in all layers. D^* was assigned a value of 1.0×10^{-3} square feet per day (ft^2/d) throughout the model. These parameter values were not modified during model calibration.

Table S6.3. Calibrated model parameter values used to simulate contaminant fate and transport, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[—, not applicable; ft, foot; ft^3, cubic foot; d, day; g, gram; mg, milligram; L/kg, liter per kilogram; PCE, tetrachloroethylene; TCE, trichloroethylene; HPIA, Hadnot Point Industrial Area; HPLF, Hadnot Point landfill]

[1]Model parameter	[2]Model layer number						
	1	2	3	4	5	6	7
[3]Contaminant fate and transport models, January 1942–June 2008—Subdomain area (50-ft×50-ft cells)							
Distribution coefficient, K_d (ft^3/mg):							
PCE	1.1×10^{-8}	1.1×10^{-8}	1.1×10^{-8}	1.1×10^{-8}	1.1×10^{-8}	1.1×10^{-8}	1.1×10^{-8}
TCE	5.3×10^{-9}	5.3×10^{-9}	5.3×10^{-9}	5.3×10^{-9}	5.3×10^{-9}	5.3×10^{-9}	5.3×10^{-9}
Benzene	4.0×10^{-9}	4.0×10^{-9}	4.0×10^{-9}	4.0×10^{-9}	4.0×10^{-9}	4.0×10^{-9}	4.0×10^{-9}
Bulk density, ρ_b (g/ft^3)	46,700	46,700	46,700	46,700	46,700	46,700	46,700
Effective porosity, n_E	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Biodegradation, λ (d^{-1}):							
HPIA (TCE)	2.0×10^{-3}	2.0×10^{-3}	2.0×10^{-3}	2.0×10^{-3}	2.0×10^{-3}	2.0×10^{-3}	2.0×10^{-3}
HPIA (benzene)	1.0×10^{-4}	1.0×10^{-4}	1.0×10^{-4}	1.0×10^{-4}	1.0×10^{-4}	1.0×10^{-4}	1.0×10^{-4}
HPLF (PCE and TCE)	1.4×10^{-4}	1.4×10^{-4}	1.4×10^{-4}	1.4×10^{-4}	1.4×10^{-4}	1.4×10^{-4}	1.4×10^{-4}
Effective molecular diffusion coefficient, D^*(ft^2/d)	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}
Dispersivity (ft):							
Longitudinal, α_L	25	25	25	25	25	25	25
Transverse, α_T	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Vertical, α_V	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Source concentration, C (mg/L):							
HPIA (TCE)	640	640	640	0	0	0	0
HPIA (benzene—dissolved)	1.7	—	—	—	—	—	—
HPLF (PCE)	42–105	33–83	27–66	18–46	6–16	0	0
HPLF (TCE)	256–384	256–384	256–384	256–384	256–384	256–384	256–384

[1] Symbolic notation used to describe model parameters obtained from Harbaugh (2005), Zheng and Wang (1999)

[2] See Table S6.1 for correlation between geologic and hydrogeologic units and model layers for the HPHB study area; refer to Faye (2012) and Suárez-Soto et al. (2013) for details: aquifers are designated as model layers 1, 3, 5, and 7; confining units are designated as model layers 2, 4, and 6

[3] See Figures S6.1–S6.3 for groundwater-flow model domain and contaminant fate and transport model subdomains

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Sorption

Sorption in the HPHB study area is assumed to be similar to sorption in the TT study area of USMCB Camp Lejeune described in Faye (2008). Sorption processes (i.e., adsorption and absorption) for the HPIA and HPLF models were represented in MT3DMS by using a linear isotherm sorption model. The input data required to simulate sorption include porosity, distribution coefficient, and soil bulk density. Constant values were assigned to the aforementioned model parameters throughout the model owing to the lack of site-specific field data. MT3DMS uses values assigned to porosity, distribution coefficient, and soil bulk density to compute a retardation factor. The retardation factor is related to the linear equilibrium isotherm by the following formula (Freeze and Cherry 1979; Zheng and Wang 1999):

$$R = V_w / V_c = 1 + K_d \rho_b / n_E, \qquad \text{(S6.2)}$$

where

R is retardation factor, dimensionless;
K_d is distribution coefficient $[L^3M^{-1}]$;
ρ_b is bulk density of the porous media $[ML^{-3}]$;
n_E is effective porosity of the porous media, dimensionless;
V_w is linear groundwater velocity $[LT^{-1}]$; and
V_c is solute velocity $[LT^{-1}]$.

The distribution coefficient, K_d, is a chemical- and soil-specific parameter used to quantify how a chemical partitions between an aqueous phase and a soil or sediment phase. Typically, K_d values are calculated based on laboratory-scale experimental data that quantify partitioning behavior for a chemical in simple systems (e.g., octanol water) and field data or estimates for the amount of organic material present in the soil or aquifer material of interest (USEPA 1996). Model-specific K_d values for benzene (0.11 liter per kilogram [L/kg]), TCE (0.15 L/kg), and PCE (0.30 L/kg) were derived by using partitioning data for each chemical (Mackay et al. 2006; USEPA 1996), an assumed value of 0.002 for the site-specific organic carbon fraction of aquifer material, and refinement during the model calibration process. Final model-specific K_d values are well within the range of values calculated from multiple sources of partitioning data (Table S6.4). When using consistent model units of feet and milligrams,[16] the input K_d values for benzene, TCE, and PCE are 4.0×10^{-9}, 5.30×10^{-9}, and 1.06×10^{-8} cubic feet per milligram (ft^3/mg), respectively (Table S6.3).

The value of bulk density, ρ_b, is based on default parameter values published by the USEPA (1996) for soil specific gravity—1.65 grams per cubic centimeter (g/cm^3) or 4.67×10^6 milligrams per cubic foot (mg/ft^3) in consistent model units. Effective porosity, n_E, was assumed to be 20 percent (0.2) for all model layers (Faye 2008). Both parameters—ρ_b and n_E—were not adjusted during model calibration. Applying the aforementioned parameter values to Equation S6.2, the resulting dimensionless retardation factors (R) for benzene, TCE, and PCE, are 1.9, 2.2, and 3.5, respectively.

[16] All model parameter values must be supplied to MT3DMS in model consistent units. For the HPHB study area models, MT3DMS units are as follows: Length units are in feet (ft), Time units are in days (d), and Mass units are in milligrams (mg).

Table S6.4. Chemical-specific distribution coefficients and retardation factors calculated from multiple sources of partition coefficient data, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[USEPA, U.S. Environmental Protection Agency; TCE, trichloroethylene; PCE, tetrachloroethylene; g/cm^3, gram per cubic centimeter]

Contaminant	Distribution coefficient, K_d, in liters per kilogram (L/kg)			Retardation factor[1]
	Minimum	Maximum	Basis for calculation	
Benzene	0.028	0.946	Range of K_d values calculated by using fraction organic carbon (f_{OC}) value of 0.002 and 63 different soil organic carbon/water partition coefficient (K_{OC}) and octanol/water partition coefficient (K_{OW}) values compiled in Mackay et al. (2006) and USEPA (1996)	1.2–8.8
TCE	0.03	0.99	Range of K_d values calculated by using fraction organic carbon (f_{OC}) value of 0.002 and 64 different soil organic carbon/water partition coefficient (K_{OC}) and octanol/water partition coefficient (K_{OW}) values compiled in Mackay et al. (2006) and USEPA (1996)	1.2–9.2
PCE	0.03	21.43	Range of K_d values calculated by using fraction organic carbon (f_{OC}) value of 0.002 and 53 different soil organic carbon/water partition coefficient (K_{OC}) and octanol/water partition coefficient (K_{OW}) values compiled in Mackay et al. (2006) and USEPA (1996)	1.2–177.8

[1] Retardation factor calculated using Equation S6.2; porosity equals 0.2, and bulk density equals 1.65 g/cm^3

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Biochemical Reactions

Contaminants of interest to this study (i.e., PCE, TCE, and benzene) were probably degraded due to microbial activity as indicated by the presence of degradation by-products (e.g., *cis*-1,2-dichloroethylene [1,2-cDCE], *trans*-1,2-dichloroethylene [1,2-tDCE], and VC) (Faye et al. 2010, 2012). Biodegradation of PCE and TCE probably occurred through reductive dechlorination, and benzene was probably degraded under anaerobic conditions. Biodegradation pathways and biochemical reactions are complex and further explained by Lawrence (2007). In general, the presence of certain elements, such as an electron acceptor, an electron donor, a carbon source, nitrogen, macronutrients, and micronutrients, are required for bacteria to grow and to achieve biodegradation (Madigan et al. 2003). Biodegradation rates are further controlled by temperature, pH, and other environmental factors. Biological reaction kinetics are poorly understood in uncontrolled systems (e.g., groundwater-flow systems), and typically they have been modeled using simple models such as first-order or Michaelis-Menten kinetics (Yu and Semprini 2004). For the HPHB study area, biodegradation of dissolved contaminants was simulated using a first-order degradation rate, which is expressed by the relation

$$C = C_0 e^{-\lambda_1 t}, \qquad \text{(S6.3)}$$

where

C is contaminant concentration [ML^{-3}];

C_0 is initial contaminant concentration [ML^{-3}];

e is base of Naperian or natural logarithms, dimensionless;

λ_1 is the biochemical degradation rate constant for the dissolved phase, [T^{-1}]; and

t is elapsed time, [T].

Degradation rates are calculated by using multiple approaches, including laboratory methods, field experiments, and modeling analyses. It is important to understand that degradation kinetics vary spatially and temporally and represent an estimate under very specific conditions; therefore, degradation rates represent conditions of a dynamic process. For example, laboratory methods, such as a microcosm test (USGS 2013), are able to separate the effects of degradation from other processes such as dispersion. However, microcosm tests are closed systems in which chemical properties can change substantially over time and may not represent conditions present in an open system (e.g., aquifer). Field experiments may adequately represent aquifer conditions; however, field experiments seldom measure degradation rates, and attenuation rates are usually calculated instead. Attenuation rates are typically a combination of multiple processes such as degradation, sorption, and dispersion. In practice, it is typical to compute attenuation rates if possible because they can provide some insight about degradation.

Attenuation rates were computed for multiple chlorinated solvents using site-specific field data and are described in detail in Appendix S6.1. Attenuation rates for PCE range from about 1.5×10^{-4} to 9.8×10^{-4} per day (d^{-1}), which in terms of half-life correspond to about 4,500 to 700 d, respectively. TCE attenuation rates range from about 3.6×10^{-4} to 1.5×10^{-3} d^{-1}, which in terms of half-life correspond to about 1,900 to 460 d, respectively. CH2M HILL (2010) reported low levels of total organic carbon, which could impede degradation.

Aronson and Howard (1997) reported mean first-order degradation rates for TCE and PCE for multiple sites across the United States. The mean rates reported for TCE and PCE are 2.5×10^{-3} d^{-1} and 2.9×10^{-3} d^{-1}, respectively. Benzene rates reported by Cozzarelli et al. (2010), USEPA (1999), Wiedemeier (1995), and Wilson et al. (1994) were reviewed and further described by Jang et al. (2013), and a value of 1×10^{-4} d^{-1} was selected. Because degradation rates vary widely, the values were adjusted during the calibration process. Mean values for TCE and PCE, previously described, were initially used in contaminant fate and transport simulations and were adjusted to history-match (reconstruct) the concentrations at certain water-supply and monitor wells (Figures S6.4 and S6.6). For example, a low reaction rate was required for the contaminants to migrate to the locations of and at the concentrations detected in the six downgradient extraction wells in the Brewster Boulevard aquifer (shallow wells 82-SRW01–82-SRW06, model layer 1) and the four downgradient extraction wells in the Upper Castle Hayne aquifer (deep wells 82-SWR01–82-SWR04, model layer 5). The final calibrated degradation rate values at the HPIA are 2.0×10^{-3} d^{-1} for TCE and 1.0×10^{-4} d^{-1} for benzene. At the HPLF, the final calibrated values are 1.4×10^{-4} d^{-1} for TCE and PCE (Table S6.3).

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Source Concentrations

Sources in the HPIA and HPLF models were simulated using a specified concentration (Type 1) boundary condition. Source locations and durations were estimated by using the information previously described in the Conceptual Models section of this report and in Faye et al. (2010, 2012). Source location, concentration, and duration are summarized in Table S6.5. The sources were placed in the nearest cell to the physical feature representing the source. For example, the nearest cell to the center of the leaking storage tank was used in Building 1601 to represent a TCE source. In the landfill area, the cell containing the monitor well with the highest concentrations was used to represent a TCE and PCE source. Source duration varied for each of the locations. Historical records delineating the start date of fuel spills or releases from the UST systems were not available. Consequently, a rationale for the source start date was formulated based on the installation date of UST systems and empirical data on the cause and timing of fuel leaks and releases from UST systems. In 1987, the USEPA published a report indicating that fuel delivery piping and spills/overfills accounted for more fuel releases (in terms of number of releases, not volume of release) than the associated storage tanks themselves (USEPA 1987). In fact, fuel piping and fittings were implicated in 80–85 percent of all releases from UST systems (USEPA 1987). In a separate study containing an analysis of 1,244 leak incident reports across the United States, the USEPA reported mean and median age for UST system piping leaks as 11 and 9 years, respectively (USEPA 1986). Therefore, for this analysis, the median age of 9 years was used.

The maximum concentration used in the model did not exceed the respective solubility limit for the corresponding contaminant—1,280 milligrams per liter (mg/L) for TCE, 210 mg/L for PCE, and 17 mg/L for benzene in a fuel mixture (Lawrence 2007; USEPA 2011). Sources in the HPIA area are TCE and benzene; sources in HPLF area are PCE and TCE. Contaminant fate and transport for source chemicals in the HPIA (TCE and benzene) and the HPLF area (PCE and TCE) were modeled concurrently using the MT3DMS model code.[17]

[17] MT3DMS identifies species by numbers. In the HPIA model input files, TCE and benzene are species 1 and 2, respectively. In the HPLF model input files, TCE and PCE are species 1 and 2, respectively.

Table S6.5. Calibrated contaminant fate and transport model parameter values used to describe contaminant sources in the Hadnot Point Industrial Area (HPIA) and Hadnot Point landfill (HPLF) area, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Source area[1]	Cell location (row, column, layer)[2]	Concentration, in milligrams per liter	Source duration
Trichloroethylene (TCE)			
Building 1601	165, 116, 1–3	640	January 1951–June 1993
Building 900 area			
Source 1	102, 178, 1–3	640	January 1957–December 1994
Source 2	108, 179, 1–3		
Source 3	113, 173, 1–3		
Building 1401	122, 138, 1–3	640	January 1951–June 1993
Building 1115	145, 121, 1–3	640	January 1951–June 1993
Landfill area			
Source 1	159, 156, 1–7	256–384	January 1948–June 2008
Source 2	154, 145, 1–7		
Tetrachloroethylene (PCE)			
Landfill area			
Source 1	159, 156, 1–5	16–105	January 1948–June 2008
Source 2	154, 145, 1–5	6–42	
Benzene			
Building 1601			
Source 1	168, 117, 1	1.7	January 1951–June 1993
Source 2	171, 113, 1		

[1] Refer to Figures S6.2 and S6.3 for maps showing location

[2] Cell location corresponds to their respective models (i.e., HPIA or HPLF). Cell location with coordinates row 1, column 1 and layer 1 corresponds to the northwest corner and uppermost cell of the total model domain

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Four source areas of TCE were identified and included in the HPIA model.

1. A 1,600-gal waste-solvent storage tank between Buildings 1601 and 1502 (row 165, column 116, layers 1–3) (Figure S6.2).
2. Building 900 area (Figure S6.2):
   a. Source 1: An underground storage tank in the area between Buildings 902 and 903 (row 102, column 178, layers 1–3), which was used for engine degreasing.
   b. Source 2: A 440-gal underground storage tank east of Building 901 used to store TCE (row 108, column 179, layers 1–3), and
   c. Source 3: High concentrations of TCE southwest of Building 901 (row 113, column 173, layers 1–3) probably associated with degreasing activities in the area,
3. Building 1115 (row 122, column 138, layers 1–3).
4. Building 1401 (row 145, column 121, layers 1–3).

All TCE sources in the HPIA were assigned a concentration of 640 mg/L, which corresponds to 50 percent of the TCE solubility limit.[18]

Benzene was simulated in the HPIA model to account for the benzene source resulting from two storage tanks related to a fuel dispensing island on the south side of Building 1601 (Figure S6.2). The sources are located in two cells (row 168, column 117, layer 1, and row 171, column 113, layer 1). The specified concentration is 1.7 mg/L, which corresponds to 10 percent of the effective solubility limit.[19]

In the HPLF model, a single source of TCE was initially placed near monitor well 06-GW01D (row 159, column 156, layers 1–7) in all model layers where the maximum concentrations of TCE were detected, beginning in January 1948 (Figure S6.3). The dominant groundwater-flow path from that location to Wallace Creek caused the TCE migration to bypass the area of monitor well 06-GW27DW and extraction well 82-DRW03 to the northeast, where groundwater samples from the early 1990s through the early 2000s had concentrations of TCE as great as 22,000 µg/L. A second source of TCE roughly midway between extraction wells 82-DRW03 and 82-DRW04 (row 154, column 145, layers 1–7) was added during the calibration process to approximate the historical TCE concentrations detected in the two wells 06-GW27DW and 82-DRW03. The two TCE source locations in the HPLF model are shown in Figure S6.3.

Because the highest concentration of TCE was detected in well 06-GW01D, which is completed in model layer 5 (Upper Castle Hayne aquifer–River Bend and Lower units—Table S6.1), it was assumed that TCE migrated vertically from the source, presumed to be at or near ground surface, downward through confining layers into the Castle Hayne aquifer system quickly compared to the length of time that the contaminants have had to migrate laterally through the aquifer layers (from the late 1940s until first detected in groundwater samples in the mid-1980s). Thus, TCE was applied as a constant-concentration source of equal concentration in each model layer (1–7). Based on adjustments made during the calibration process, the concentration of TCE at the first HPLF source was 384 mg/L (30 percent of the solubility limit of TCE in water), and the concentration of TCE at the second HPLF source was 256 mg/L (20 percent of the solubility limit).

Adjustment in the PCE source concentration in layer 1 during the calibration process resulted in PCE concentrations of 105 mg/L at the first source (row 159, column 156) and 42 mg/L at the second source (row 154, column 145). The layer 1 PCE source concentrations correspond to 50 percent and 20 percent, respectively, of the solubility limit of PCE in water, which is 210 mg/L (Lawrence 2007). Initial simulations using constant PCE-concentration sources through all layers indicate that the simulated PCE concentration was either too high in layer 5 or too low in layer 1 to match measured PCE concentrations. To achieve closer agreement with observed PCE data, the PCE source concentration was reduced linearly in successive layers at increasing depths to layer 5, where the PCE concentration was 15 percent of the layer 1 concentration (Tables S6.2 and S6.3). An analytical model simulating vertical migration of PCE, the analytical contaminant transport analysis system or ACTS (Maslia and Aral 2004), was used to evaluate and estimate the decrease in PCE concentration in successive layers of greater depth for different values of half-life ($t_{1/2}$) of PCE and retardation factor (R).[20] Results of the analytical model provided estimates that were reasonable based on tested ranges of PCE $t_{1/2}$ and R. PCE source concentration was decreased about 85 percent between model layers 1 and 5 based on results from the analytical model.

[18] The water solubility of TCE is reported as 1,280 mg/L at 25 degrees Celsius (°C) (Lawrence 2007).

[19] Effective solubility means the solubility of a compound that will dissolve from a chemical mixture (e.g., gasoline). The effective solubility of a compound from a chemical mixture is less than its aqueous solubility (Mississippi Department of Environmental Quality 2007). Benzene solubility in water at 25 °C is 1,780 mg/L (ATSDR 2007). The source of benzene is fuel and its effective solubility is 17 mg/L (USEPA 2011).

[20] The half-life ($t_{1/2}$) is the elapsed time when half of the initial concentration remains and is related to the biochemical degradation rate (r) by Equation S6.3: $t_{1/2} = ln(2)/r$.

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Historical Reconstruction Results

This section presents and discusses details pertinent to simulation results of TCE, PCE, and benzene concentrations in groundwater and at selected water-supply wells determined through the historical reconstruction process. Readers interested in a detailed discussion of the historical reconstruction process should refer to Maslia et al. (2013).

Hadnot Point Industrial Area

The discussion and presentation of HPIA historical reconstruction (model) results presented herein focus on water-supply wells HP-601, HP-602, HP-608, and HP-634—the only wells with reconstructed (simulated) concentrations that exceeded 1 µg/L. Among the aforementioned water-supply wells, well HP-634 has the maximum reconstructed TCE concentration (659 µg/L), and well HP-608 has the maximum reconstructed benzene concentration (11 µg/L).

Figure S6.4 shows the reconstructed (simulated) TCE concentrations for selected water-supply wells in the HPIA (wells HP-601, HP-602, HP-634, and HP-660).[21,22] Monthly reconstructed TCE concentrations derived using the aforementioned analyses for selected water-supply wells are tabulated and listed in Appendix A3. These results should be interpreted as monthly mean concentrations of TCE (occurring on the last day of each month) dissolved in groundwater at the aforementioned water-supply wells (locations shown on Figure S6.2). The reconstructed concentrations at water-supply wells are flow-weighted concentration values for supply wells that are open to multiple water-bearing units. The flow ratios for each model layer are listed in Suárez-Soto et al. (2013, Table S4.7). As can be seen in the graphs of Figure S6.4, observation data in water-supply wells are limited. For example, well HP-634 only has one measured concentration data point that exceeds the detection limit for comparison to reconstructed TCE concentrations. For water-supply wells HP-602 and HP-608, measurements were taken on the same day or within a time span of 1 month or less (Table A4), whereas model results represent a mean concentration over an entire month. Not only does this make it difficult to calibrate a numerical model that at best only approximates the physics, chemistry, and biology of "real-world" conditions, but it calls into question which observation data and data values should be used for comparisons with simulated concentrations. Given the aforementioned limitations and constraints, the reconstructed (simulated) TCE concentrations reasonably agree with measured data and "real-world" conditions.

Areal distributions of reconstructed TCE concentrations for model layers 1, 3, and 5 for four periods—January 1951, January 1968, November 1984, and June 2008—are shown in Figure S6.5. Model layers 1, 3, and 5 represent major water-bearing units in the study area and are correlated with the Brewster Boulevard aquifer system, the Tarawa Terrace aquifer, and the Upper Castle Hayne aquifer, respectively (Table S6.1). The specific simulation dates noted above were selected to show typical historical reconstruction results because (1) January 1951 represents an early time period after the onset of pumping, (2) January 1968 represents the start of the epidemiological health study, (3) November 1984 represents the month prior to the shutdown of many of the contaminated water-supply wells, and (4) June 2008 represents the end of the historical reconstruction simulation and a time when all contaminated water-supply wells had been removed from service for more than 20 years. Viewed synoptically, the maps in Figure S6.5 illustrate a progression in the areal distribution of TCE by model layer at the HPIA from the early onset of pumping (January 1951) to substantial effect of TCE at water-supply wells (January 1968 and November 1984), to dilution and reduction in the TCE concentration at the end of the historical reconstruction simulation (June 2008) because of the cessation of pumping of historically contaminated HPIA water-supply wells. Larger scale maps showing additional HPIA details such as building identification are provided in Appendix A4.

Benzene sources around Building 1601 resulted in a maximum reconstructed concentration of 11 µg/L at water-supply well HP-608 during September 1979 (Appendix A3). The simulated concentration first exceeded the current maximum contaminant level (MCL)[23] for benzene (5 µg/L) during September 1967. A summary of historical reconstruction results for TCE and benzene in the HPIA is listed in Table A14.

[21] Water-supply well HP-660 replaced HP-601 and probably operated from July 1984 to November 1984—see Figure A5 and Sautner et al. 2013.

[22] Results for benzene concentrations in water-supply well HP-602 (Figure S6.4 and Appendix A3) were derived by simulating benzene as an LNAPL—details provided in Jang et al. (2013).

[23] Values of MCL referenced in HPHB study area reports and supplements refer to current values of MCLs—see Table A3.

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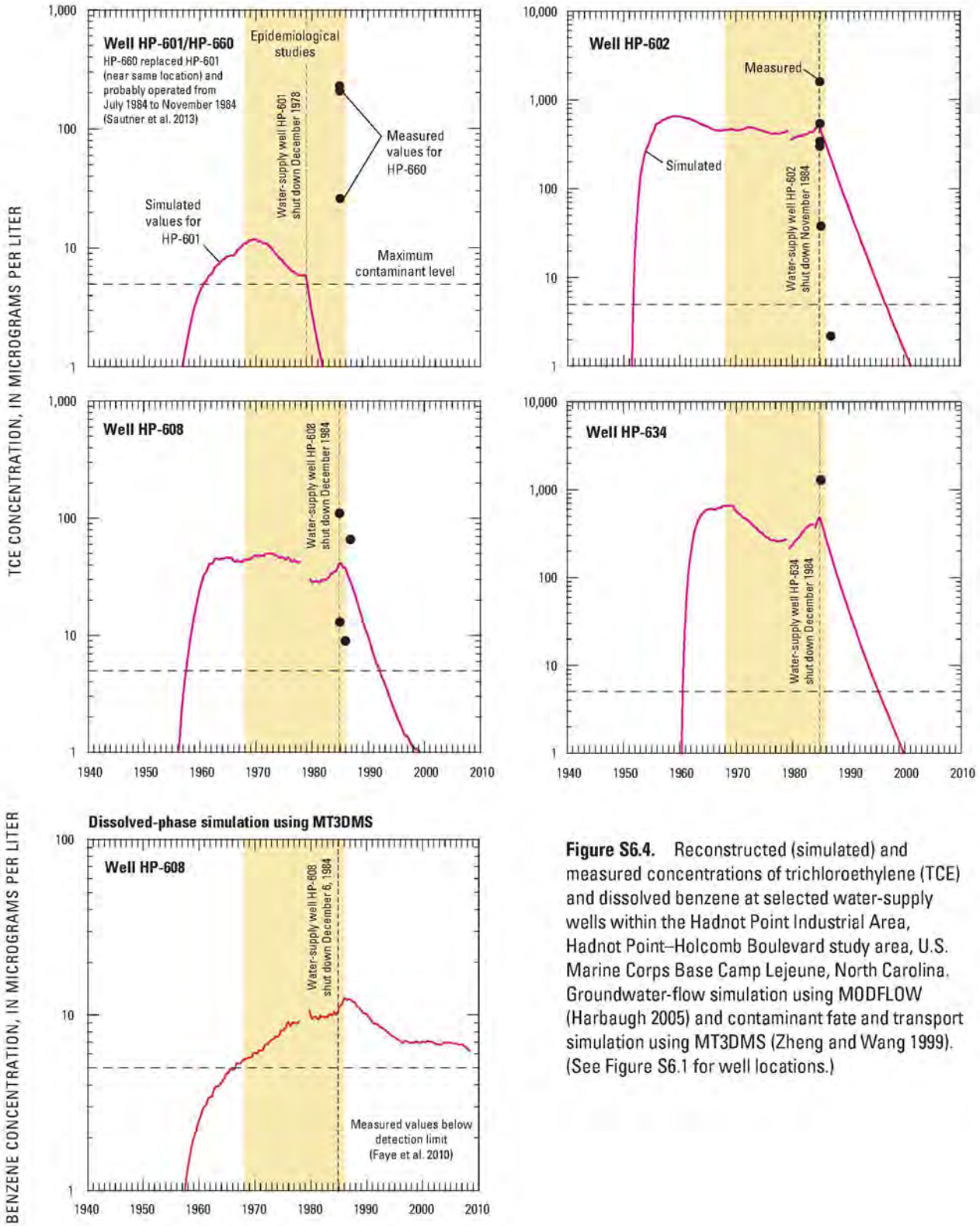

Figure S6.4. Reconstructed (simulated) and measured concentrations of trichloroethylene (TCE) and dissolved benzene at selected water-supply wells within the Hadnot Point Industrial Area, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. Groundwater-flow simulation using MODFLOW (Harbaugh 2005) and contaminant fate and transport simulation using MT3DMS (Zheng and Wang 1999). (See Figure S6.1 for well locations.)

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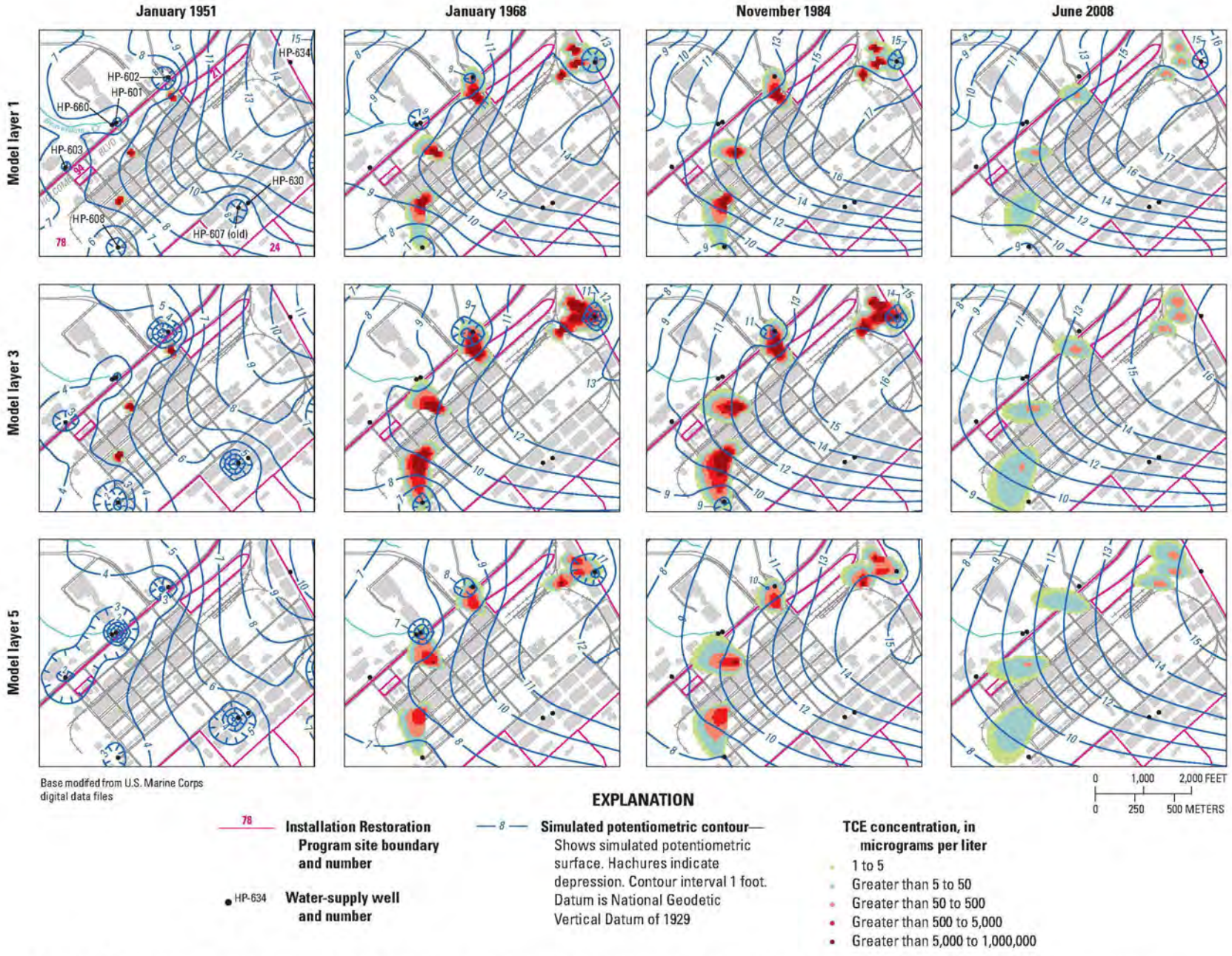

Figure S6.5. Reconstructed (simulated) water levels and distribution of trichloroethylene (TCE) within the Hadnot Point Industrial Area fate and transport model subdomain, model layers 1, 3, and 5, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1951, January 1968, November 1984, and June 2008. (See Figure A11 for location and building numbers; see Appendix A6 for more detailed maps and results.)

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Hadnot Point Landfill Area

For the HPLF model, the primary result is the reconstructed (simulated) monthly mean concentrations of PCE and TCE at water-supply well HP-651 (Figure S6.6), which was the only water-supply well in the HPLF area where water-quality samples indicated measured concentrations of PCE and TCE greater than the MCL (5 µg/L). The reconstructed concentration of PCE first exceeded the MCL during April 1973; the reconstructed concentration of TCE first exceeded the MCL during August 1972. The maximum reconstructed concentration of PCE was 353 µg/L during December 1982, and the maximum reconstructed concentration for TCE was 7,135 µg/L during December 1978.

After pumping ceased at water-supply well HP-651 during February 1985, the reconstructed concentrations of PCE and TCE at well HP-651 declined for the remainder of the simulation period, ending during June 2008. Reconstructed contaminant concentrations of both PCE and TCE at well HP-651 exceeded measured concentrations after pumping ceased. A plausible explanation for this observation is that the calibrated PCE and TCE source concentrations were constant in time and were not varied temporally. Most likely, contaminant-source concentrations diminished during the HP-651 post-production period. However, data were not available to justify introducing time-varying contaminant-source concentrations.

To evaluate the effect of the remediation extraction-well system that began operating during January 1996, the source concentration in the model most likely would have to be reduced to calibrate to measured concentration data at extraction and monitor wells subsequent to January 1996—this type of analysis is beyond the scope of this study. However, measured PCE and TCE concentration data obtained from extraction wells were used to assist with fate and transport model calibration for the HPLF area. Reconstructed and observed concentrations of PCE and TCE for four deep extraction wells, 82-DRW01–82-DRW04, are shown in Figure S6.6.

Reconstructed PCE and TCE concentration trends in extraction well 82-DRW01 show substantial variability (Figure S6.6). A plausible explanation for this variability is that extraction well 82-DRW01 is located near water-supply well HP-651 and is represented in the model by the cell directly adjacent to the first specified-concentration source cell for PCE and TCE. Because extraction well 82-DRW01 is located between the contaminant source and water-supply well HP-651, the reconstructed PCE and TCE concentrations increased sharply when well HP-651 began operating during July 1972. The reconstructed PCE and TCE concentrations began to decrease during February 1985 when production from water-supply well HP-651 ceased. A subsequent increase in PCE and TCE concentrations occurs when the extraction-well system began operating during January 1996, and another decrease in PCE and TCE concentrations occurs when production from extraction well 82-DRW01 ceased during January 2006. The close proximity of extraction well 82-DRW01 to the specified-concentration source model cell also is a likely reason for reconstructed PCE and TCE concentrations exceeded measured PCE and TCE concentrations.

PCE and TCE concentrations in the other three extraction wells (82-DRW02, 82-DRW03, and 82-DRW04) exhibit similar but less variable trends. The reconstructed concentrations in wells 82-DRW03 and 82-DRW04 begin to decrease slightly when water-supply well HP-651 began operating during July 1972 (Figure S6.6) due to the migration of contaminant plumes eastward toward well HP-651. Because extraction well 82-DRW02 is located beyond the radius of influence of water-supply well HP-651, the PCE and TCE concentrations continue to rise when water-supply well HP-651 began operating. The PCE and TCE concentrations in extraction wells 82-DRW03 and 82-DRW04 increase when the extraction-well system began operating during January 1996 because the contaminant plume migrates toward these extraction wells. However, concentrations in downgradient extraction well 82-DRW02 decrease due to the reversal of plume migration caused by the relatively high rate of extraction at well 82-DRW04.

Historical reconstruction results for PCE and TCE in the IRP Site 82 area are shown in areal plots (Figures S6.7–S6.14) of reconstructed contaminant concentrations at the following different times:

1. January 1958: 10 years after introduction of contaminant sources during January 1948 in the HPLF area model (Figure S6.7).
2. January 1968: 20 years after introduction of contaminant sources in the HPLF model (Figure S6.8).
3. June 1972: 24.5 years after introduction of contaminant sources in the HPLF model and just prior to the start of pumping at water-supply well HP-651 (Figure S6.9).
4. June 1978: 6 years after the start of pumping at water-supply well HP-651 (Figure S6.10).
5. November 1984: 12.5 years after the start of pumping at water-supply well HP-651 and 2 months prior to cessation of operations at the well (Figure S6.11).
6. December 1995: Nearly 11 years after pumping operations at water-supply well HP-651 ceased and prior to beginning of pumping at extraction wells (Figure S6.12).
7. December 2005: 10 years after the start of pumping at extraction wells, just prior to the end of pumping at extraction well 82-DRW01 (Figure S6.13).
8. June 2008: End of historical reconstruction simulation, 12.5 years after the start of pumping at extraction wells and 2.5 years after pumping at extraction well 82-DRW01 ceased (Figure S6.14).

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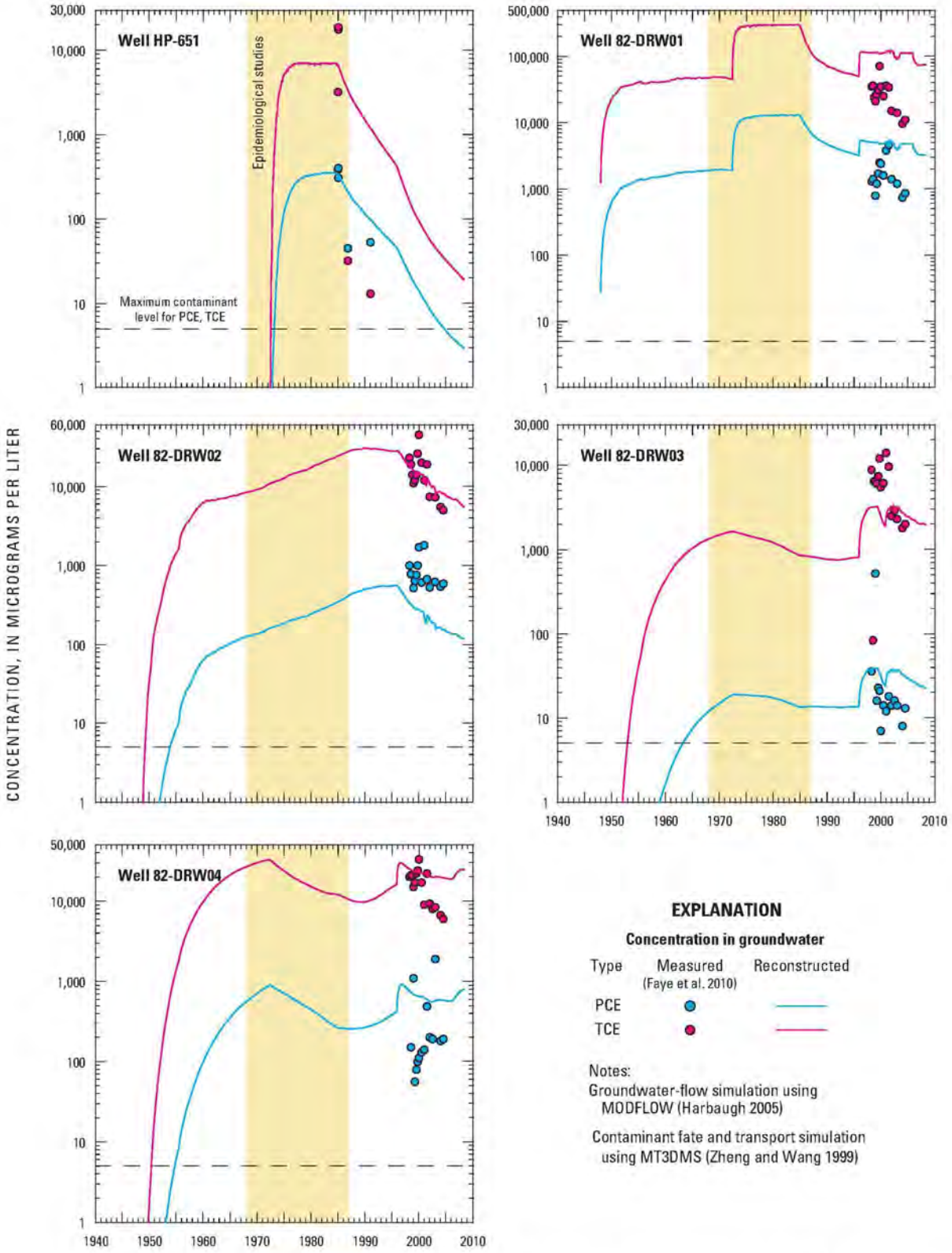

Figure S6.6. Reconstructed (simulated) and measured concentrations of trichloroethylene (TCE) and tetrachloroethylene (PCE) at water-supply well HP-651 and extraction wells 82-DRW01, 82-DRW02, 82-DRW03, and 82-DRW04, model layer 5, Hadnot Point landfill area, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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Historical reconstruction results for each of the aforementioned eight monthly times are presented for the PCE and TCE contaminant plumes in Figures S6.7–S6.14. Collectively these results show the spatial distribution of PCE and TCE over time. All results are for model layer 5, the Upper Castle Hayne aquifer, which supplied water to well HP-651 and deep extraction wells 82-DRW01–82-DRW04. The PCE and TCE plumes are similar in shape for each of the eight monthly simulation results presented. Note, however, that the TCE plume has substantially greater reconstructed concentrations than the PCE plume.

During January 1958, after 10 years of simulated contaminant migration to the northwest along the hydraulic gradient, the forward edge of the PCE plume has not reached Wallace Creek (Figure S6.7*A*). The TCE plume, characterized by higher concentrations that are a consequence of greater contaminant mass and resulting source concentrations, has reached Wallace Creek by January 1958 (Figure S6.7*B*). By January 1968, after 20 years of simulated contaminant migration, the westernmost edge of the PCE plume has reached Wallace Creek (Figure S6.8*A*), and the TCE plume reached Wallace Creek all along the forward margin (Figure S6.8*B*). By June 1972, the month before the beginning of pumping at well HP-651 and after 24.5 years of contaminant migration, the PCE and TCE plumes have migrated only marginally further than during January 1968 (Figure S6.9).

During June 1978, 6 years after the start of pumping at water-supply well HP-651, the upstream margins of the PCE and TCE plumes had migrated eastward from near the location of the first source (at monitor well 06-GW01D) and were captured by pumping at well HP-651 (Figure S6.10). A deep cone of depression developed in the potentiometric surface of the Upper Castle Hayne aquifer due to a relatively high pumping rate at well HP-651—about 23,000 cubic feet per day (ft^3/d). The direction of groundwater flow near well 06-GW01D shifted from northwestward toward Wallace Creek to eastward toward well HP-651. The same basic plume shape persisted from June 1978 through November 1984, which was about 2 months before the end of pumping at water-supply well HP-651. However, during November 1984, due to a higher monthly pumping rate (about 37,000 ft^3/d), the cone of depression in the potentiometric surface was deeper than during June 1978 (Figures S6.11 and S6.10, respectively), probably causing contaminants to migrate at a faster rate.

During December 1995, about 11 years after the end of pumping at water-supply well HP-651, the hydraulic gradient and groundwater-flow direction reverted to a north-northwesterly direction. The PCE and TCE plumes slowly migrated away from well HP-651 toward Wallace Creek (Figure S6.12).

During December 2005, the effect of pumping from the four deep extraction wells 82-DRW01–82-DRW04 was apparent in the water-level contours characterized by the deep cone of depression at extraction well 82-DRW04 and shallower cones of depression at the other three extraction wells (Figure S6.13). Since January 1995 and during the operation of the extraction-well system, the average pumping rate at well 82-DRW04 was about 28,400 ft^3/d, compared with the average pumping rates at extraction wells 82-DRW01–82-DRW03 of 5,900 ft^3/d, 4,800 ft^3/d, and 7,100 ft^3/d, respectively. Pumping at extraction well 82-DRW01 ended during January 2006; by June 2008, the shallow cone of depression associated with extraction well 82-DRW01 had recovered (Figure S6.14). Both the PCE and TCE plumes had a smaller areal extent during December 2005 (Figure S6.13) and June 2008 (Figure S6.14) as a result of the operation of the extraction-well system.

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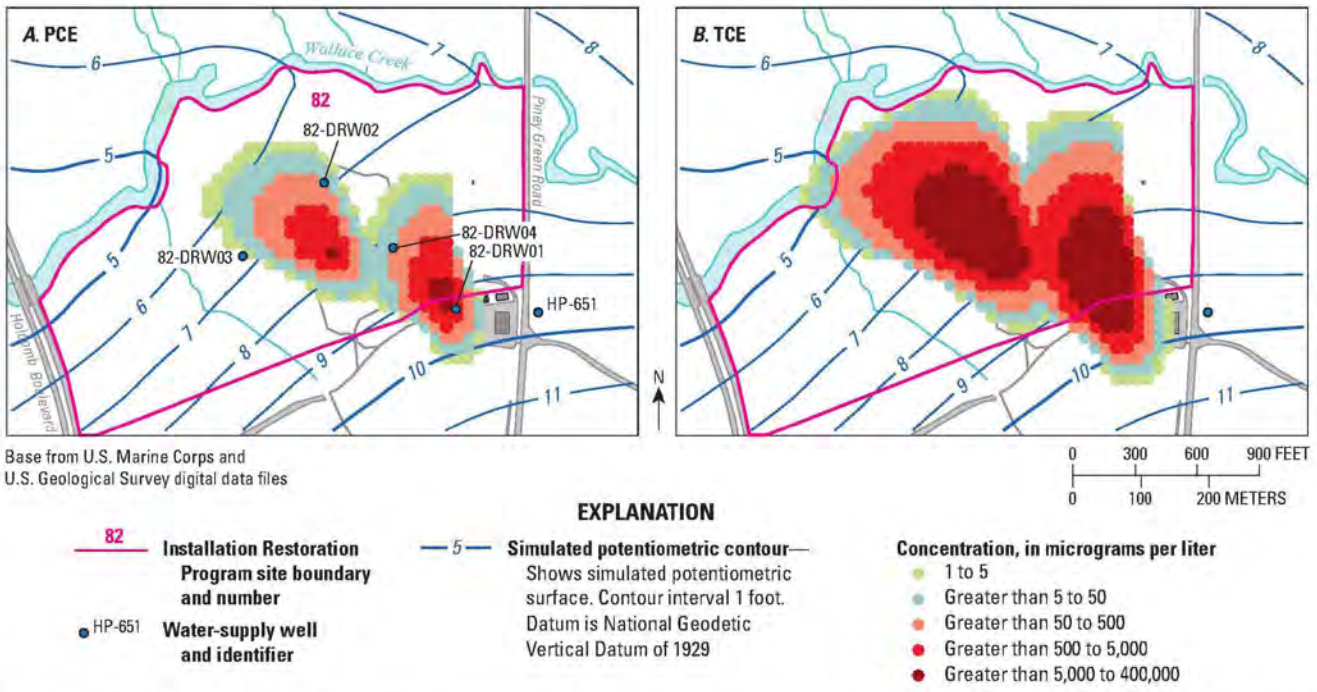

Figure S6.7. Reconstructed (simulated) water levels and distribution of *(A)* tetrachloroethylene (PCE) and *(B)* trichloroethylene (TCE) within the Hadnot Point landfill area fate and transport model subdomain, model layer 5, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1958.

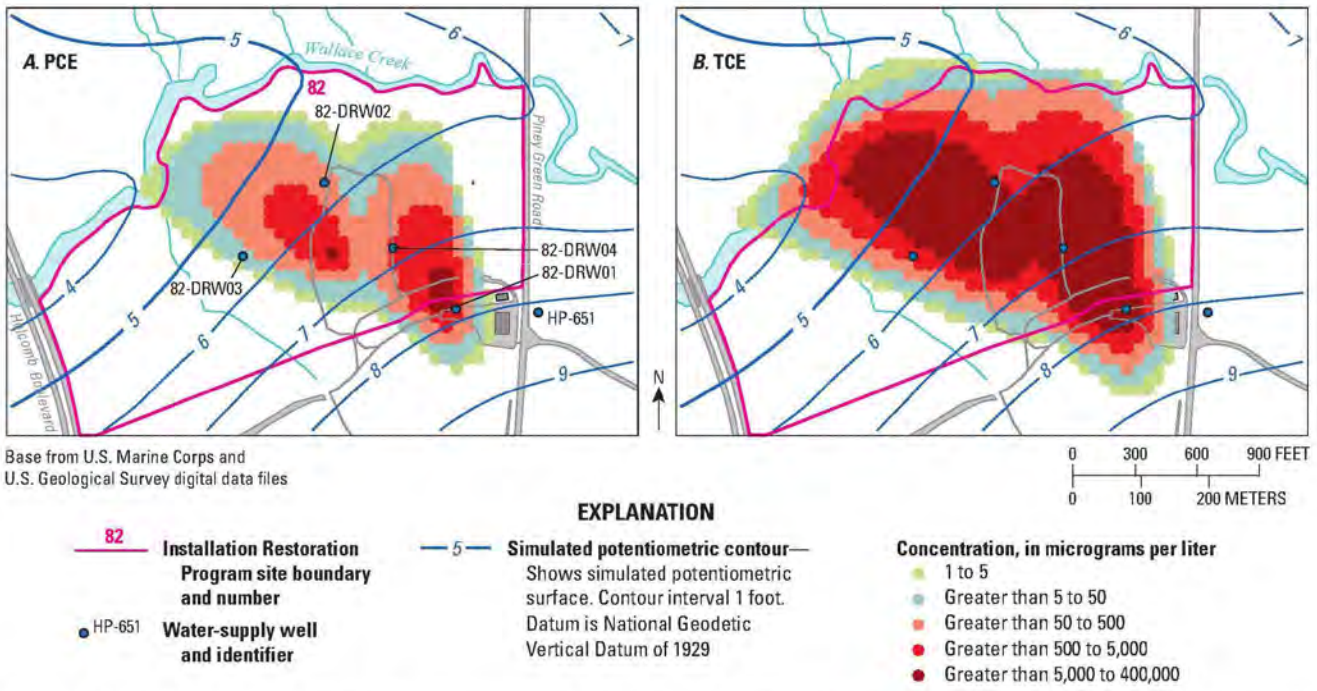

Figure S6.8. Reconstructed (simulated) water levels and distribution of *(A)* tetrachloroethylene (PCE) and *(B)* trichloroethylene (TCE) within the Hadnot Point landfill area fate and transport model subdomain, model layer 5, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1968.

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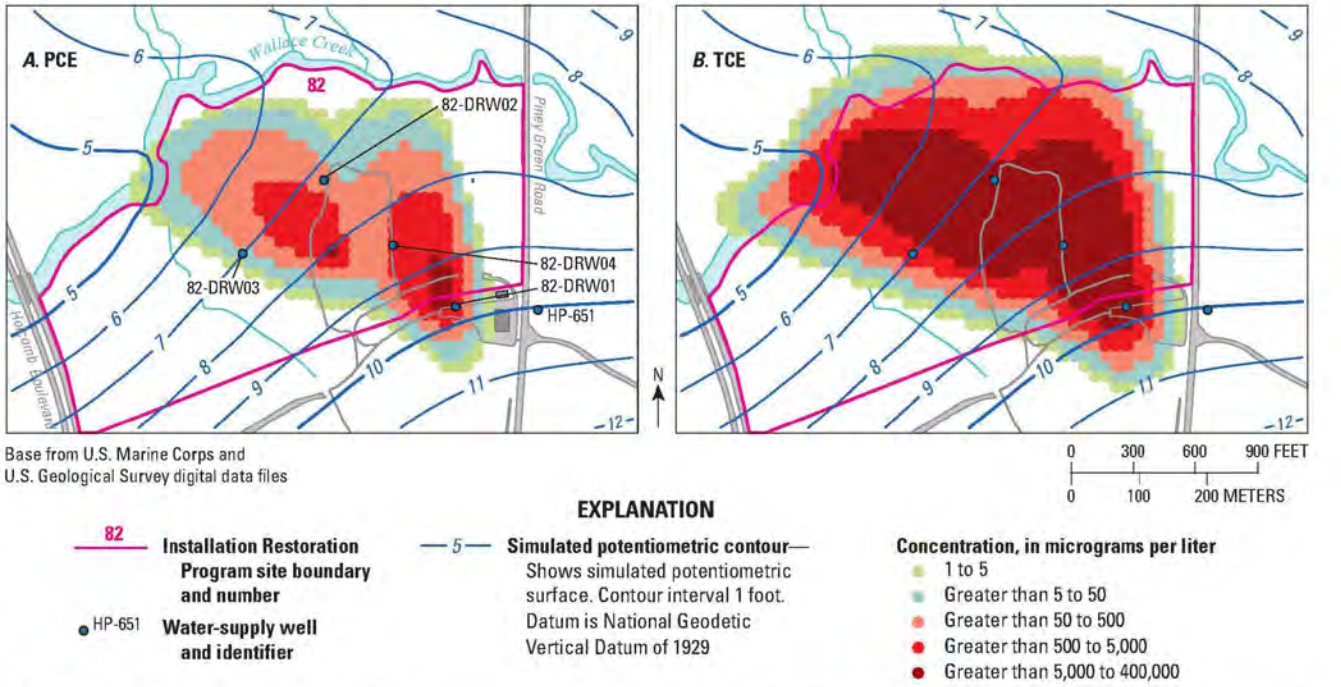

Figure S6.9. Reconstructed (simulated) water levels and distribution of *(A)* tetrachloroethylene (PCE) and *(B)* trichloroethylene (TCE) within the Hadnot Point landfill area fate and transport model subdomain, model layer 5, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, June 1972.

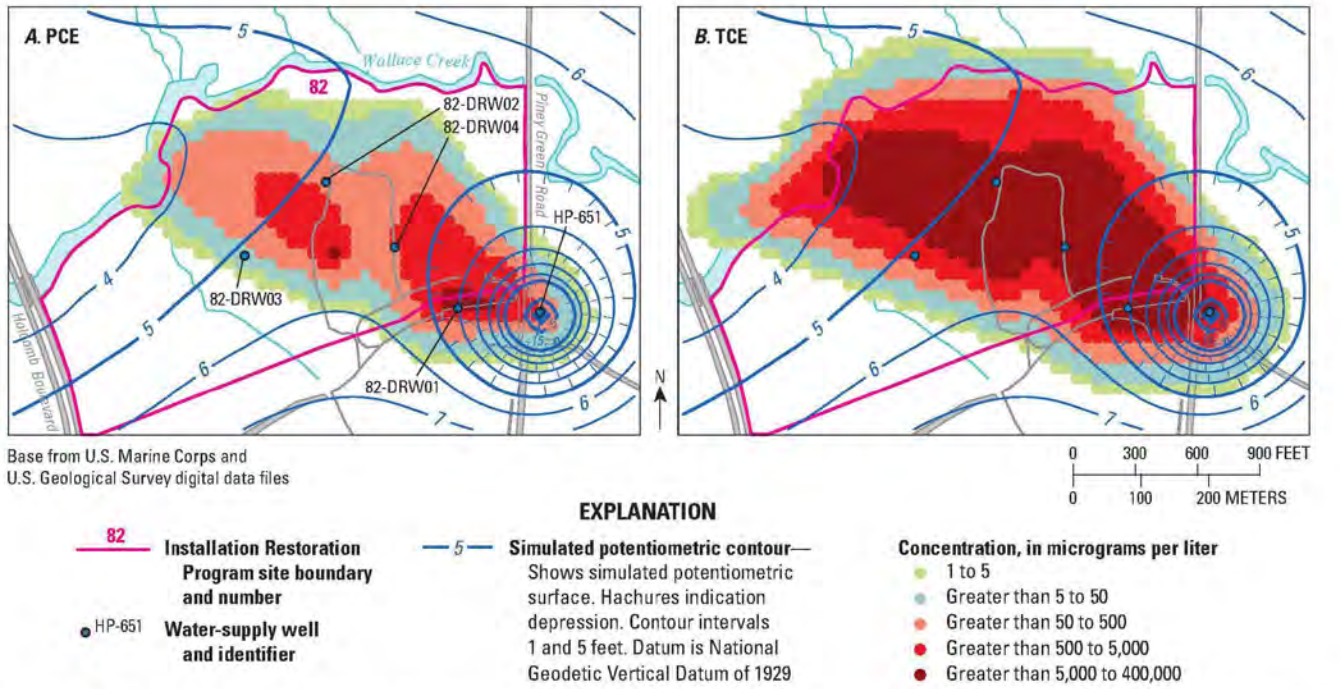

Figure S6.10. Reconstructed (simulated) water levels and distribution of *(A)* tetrachloroethylene (PCE) and *(B)* trichloroethylene (TCE) within the Hadnot Point landfill area fate and transport model subdomain, model layer 5, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, June 1978.

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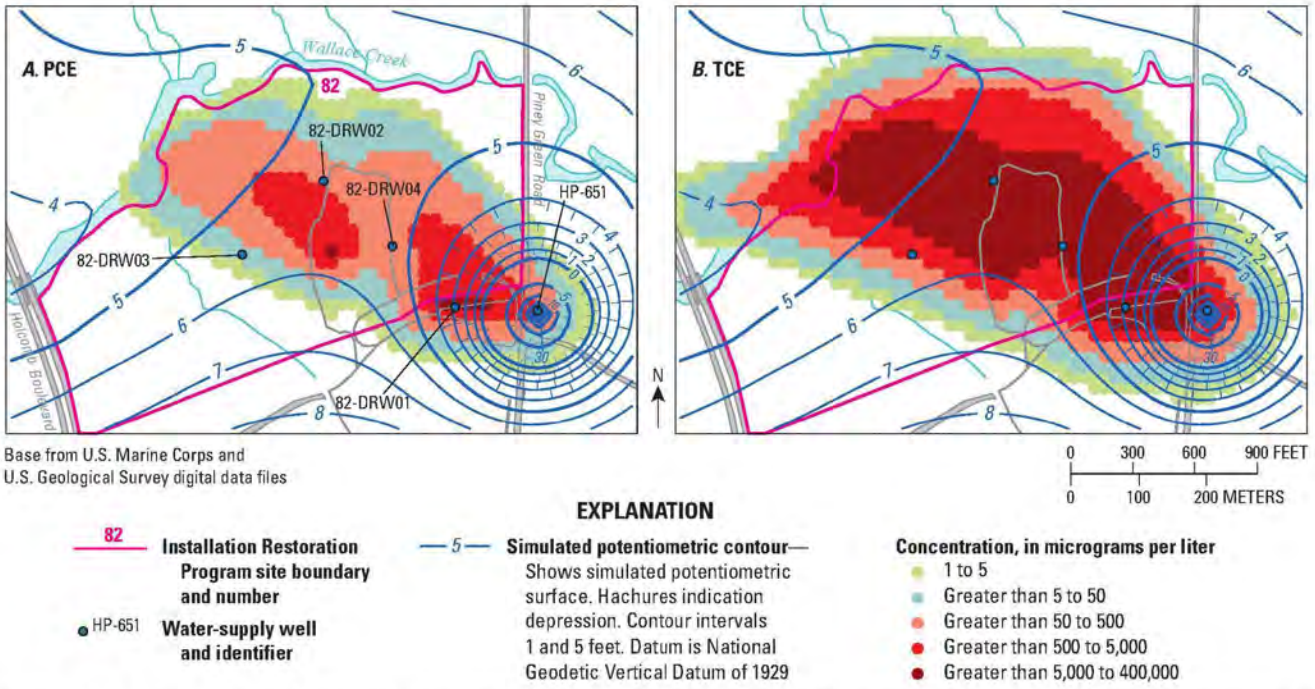

Figure S6.11. Reconstructed (simulated) water levels and distribution of *(A)* tetrachloroethylene (PCE) and *(B)* trichloroethylene (TCE) within the Hadnot Point landfill area fate and transport model subdomain, model layer 5, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, November 1984.

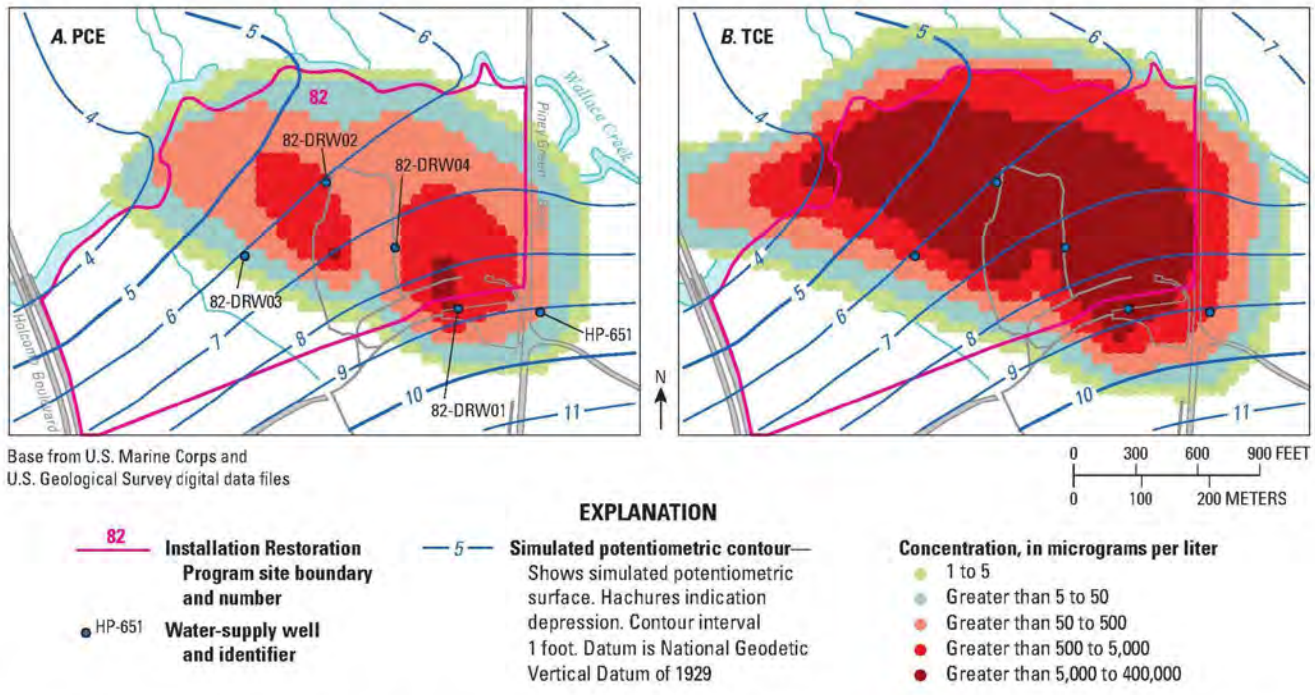

Figure S6.12. Reconstructed (simulated) water levels and distribution of *(A)* tetrachloroethylene (PCE) and *(B)* trichloroethylene (TCE) within the Hadnot Point landfill area fate and transport model subdomain, model layer 5, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, December 1995.

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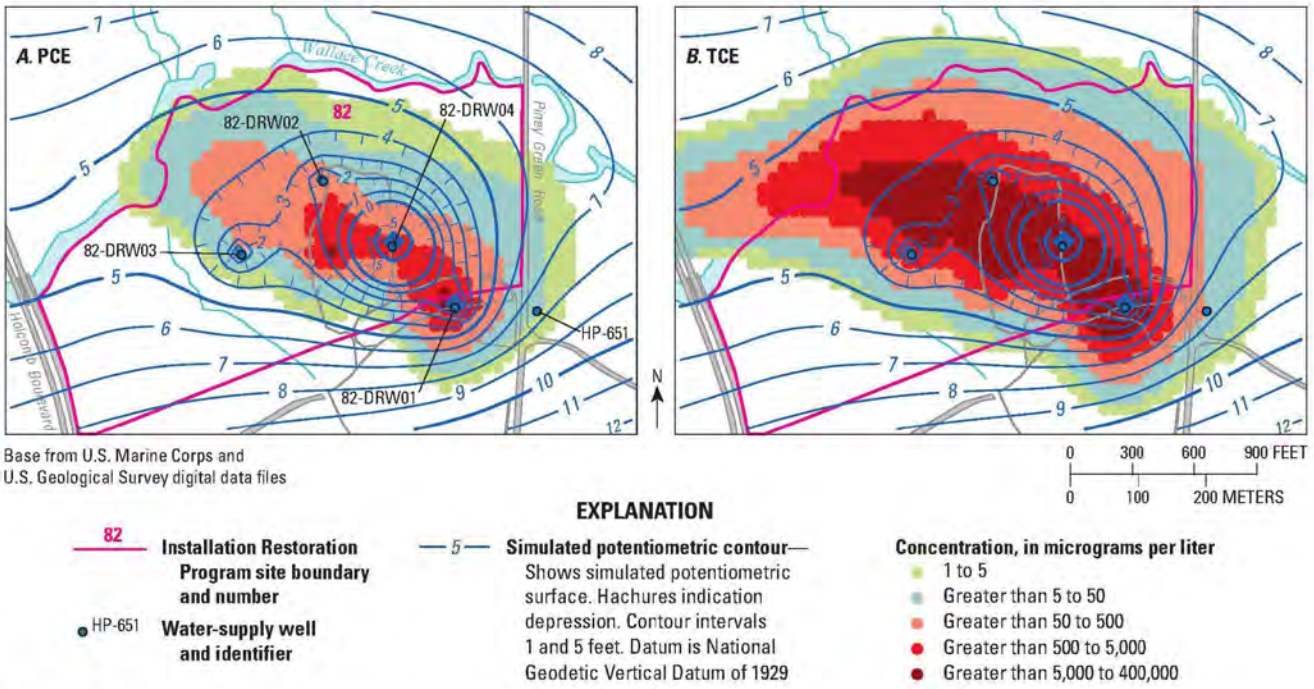

Figure S6.13. Reconstructed (simulated) water levels and distribution of *(A)* tetrachloroethylene (PCE) and *(B)* trichloroethylene (TCE) within the Hadnot Point landfill area fate and transport model subdomain, model layer 5, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, December 2005.

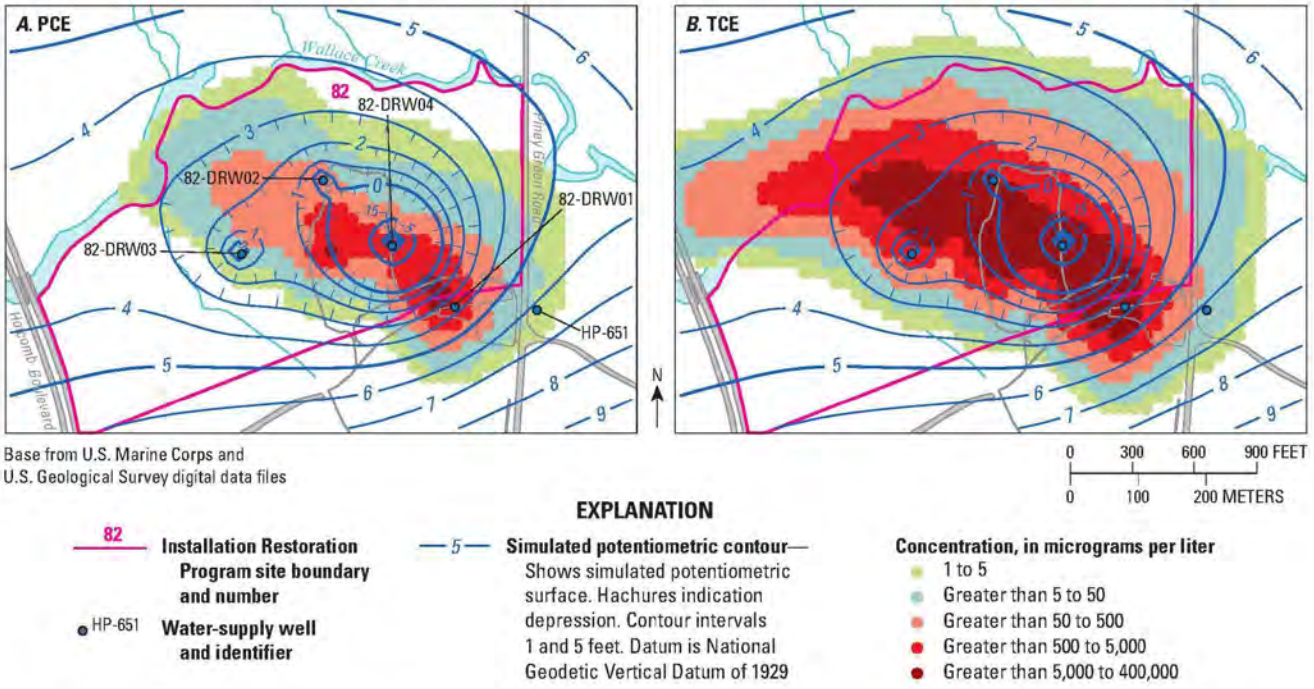

Figure S6.14. Reconstructed (simulated) water levels and distribution of *(A)* tetrachloroethylene (PCE) and *(B)* trichloroethylene (TCE) within the Hadnot Point landfill area fate and transport model subdomain, model layer 5, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, June 2008.

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Historical Reconstruction Results

For the HPLF model, historical reconstruction results from model layer 5—corresponding to the Upper Castle Hayne aquifer system (Table S6.1)—have been presented and discussed in detail. This is because water-supply well HP-651—the only contaminated water-supply well in the area—is open solely to the Upper Castle Hayne aquifer system. Areal distributions of reconstructed PCE and TCE concentrations for model layers 1, 3, and 5 for four periods—January 1968, June 1978, November 1984, and June 2008—are shown in Figures S6.15 and S6.16, respectively. Model layers 1, 3, and 5 represent major water-bearing units in the study area and are correlated with the Brewster Boulevard aquifer system, the Tarawa Terrace aquifer, and the Upper Castle Hayne aquifer, respectively (Table S6.1). The sizes and shapes of the PCE and TCE plumes are similar for each of the three model layers; the contaminant plumes originated at each of the two specified concentration nodes and migrated in a northwesterly direction toward Wallace Creek. After pumping started at water-supply well HP-651 during July 1972, the PCE and TCE plumes in model layer 5 migrated toward well HP-651 by June 1978 (Figures S6.9 and S6.10, respectively). By contrast, in model layers 1 and 3, PCE and TCE plumes migrated more slowly toward well HP-651. The prominent differences among the layers in the configuration of reconstructed water levels are due to variations in the input pumping rates for the model layers and the presence of the simulated groundwater drain representing Wallace Creek in model layer 1. Steep cones of depression are present in model layer 5 at well HP-651 during June 1978 and November 1984 (Figures S6.10 and S6.11, respectively) and at extraction well 82-DRW04 during June 2008 (Figure S6.14). However, the cones of depression are progressively shallower and less prominent in model layers 3 and 1 for these monthly results, indicating that contaminant migration in layer 5 is faster than in layers 1 and 3 because of higher velocities in model layer 5 induced by the operation of water-supply well HP-651. In model layer 1, Wallace Creek is apparent as a groundwater drain as indicated by water-level contours pointing sharply upstream.

To illustrate the relative effect of pumping water-supply well HP-651 and the subsequent operation of the extraction system, a section line (A–A') was constructed from a point upgradient (southeast) of water-supply well HP-651, to well HP-651, to three of the four extraction wells (82-DRW01, 82-DRW04, and 82-DRW02), then continuing northwestward across Wallace Creek, to a point beyond Wallace Creek (Figure S6.17). The model cells coincident with section line A–A' are shown in Figure S6.17*A*, and the water levels for the previously discussed eight monthly historical reconstruction results are shown in Figure S6.17*B*. For results for 4 months—January 1958, January 1968, June 1972, and December 1995—there was no pumping from any of the wells along the section. Thus, water levels reflect the unstressed gradient from the southeast end of section line A–A' to Wallace Creek. The small differences in water levels for the unstressed monthly results are due to differences in simulated recharge.

During June 1978, more than 25 ft of drawdown (water-level decline from unstressed periods) are apparent at water-supply well HP-651 as a consequence of pumping the well at a rate of about 120 gpm. The higher rate of pumping at well HP-651 during November 1984 (about 190 gpm) produces a drawdown of almost 40 ft. By December 2005, the cones of depression due to pumping at three extraction wells are apparent. Extraction well 82-DRW04, which had the highest average pumping rate of all of the extraction wells (about 150 gpm), causes a drawdown of more than 20 ft, whereas the other two extraction wells, 82-DRW02 and 82-DRW01 (average pumping rates of about 25 gpm and 30 gpm, respectively), cause a drawdown of less than 5 ft. By June 2008, pumping at extraction well 82-DRW01 has ended, and the water level has recovered.

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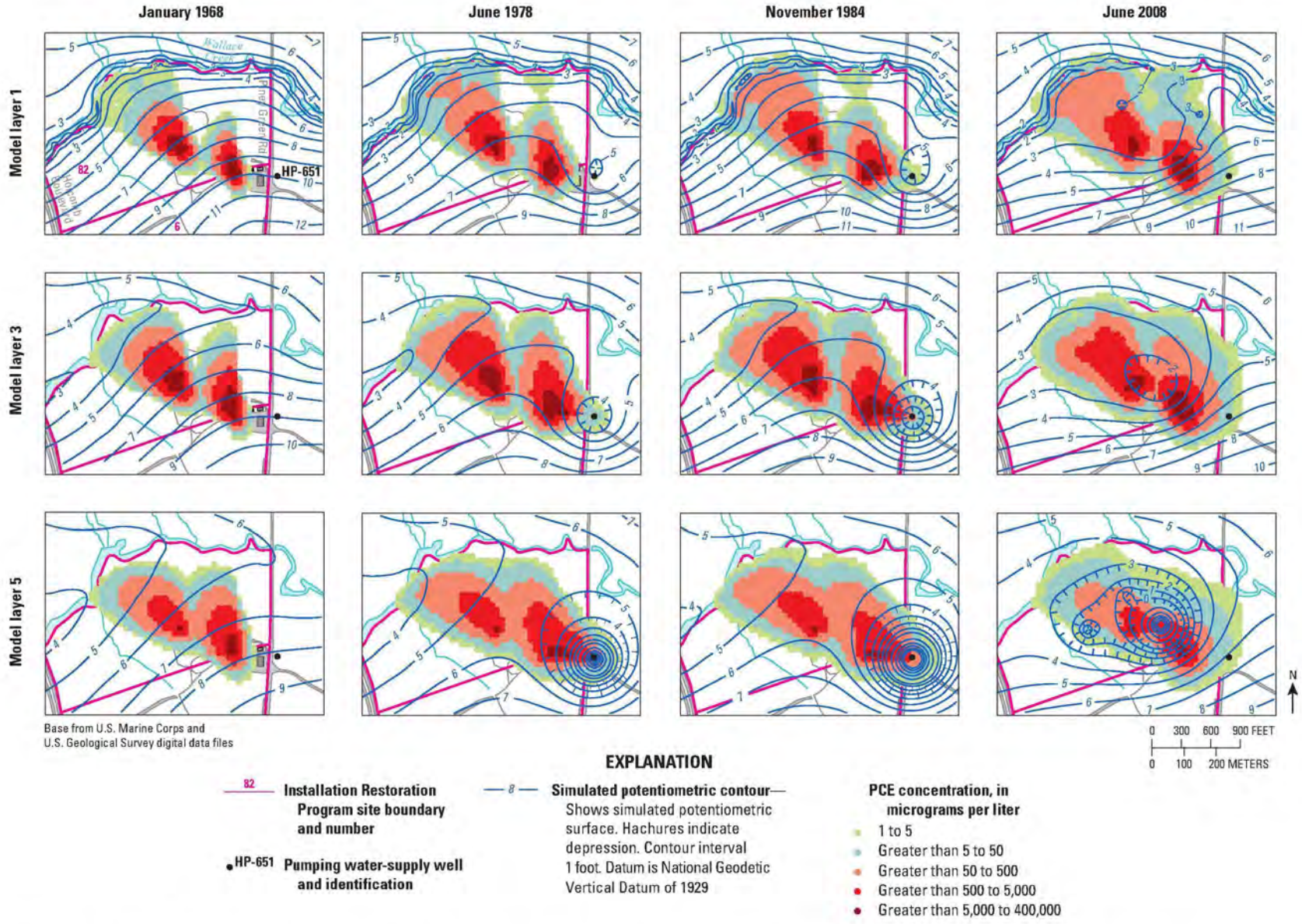

Figure S6.15. Reconstructed (simulated) water levels and distribution of tetrachloroethylene (PCE) within the Hadnot Point landfill area fate and transport model subdomain, model layers 1, 3, and 5, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1968, June 1978, November 1984, and June 2008. (See Figure A14 for location; see Appendix A6 for more detailed maps and results.)

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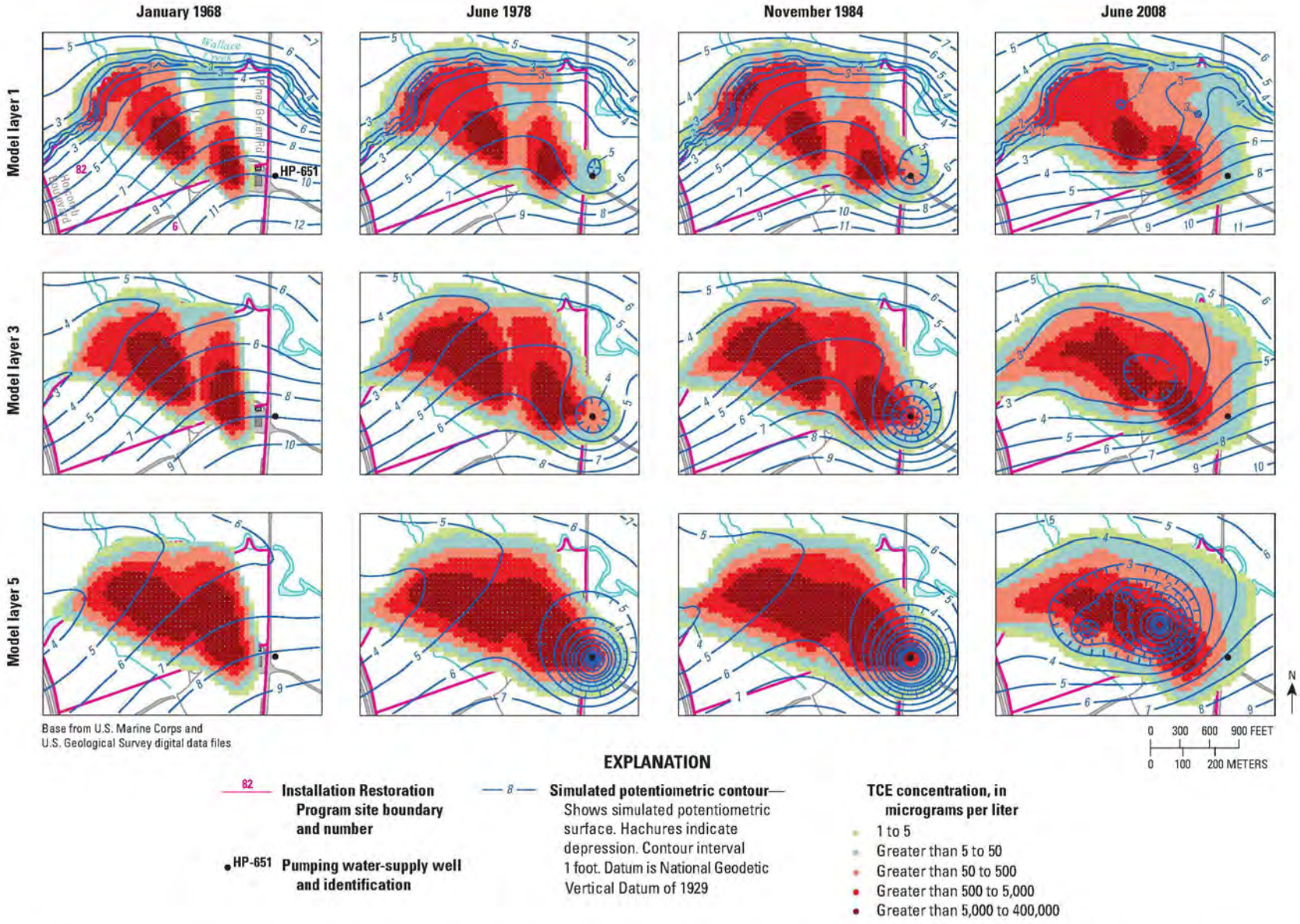

Figure S6.16. Reconstructed (simulated) water levels and distribution of trichloroethylene (TCE) within the Hadnot Point landfill area fate and transport model subdomain, model layers 1, 3, and 5, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1968, June 1978, November 1984, and June 2008. (See Figure A13 for location; see Appendix A4 for more detailed maps and results.)

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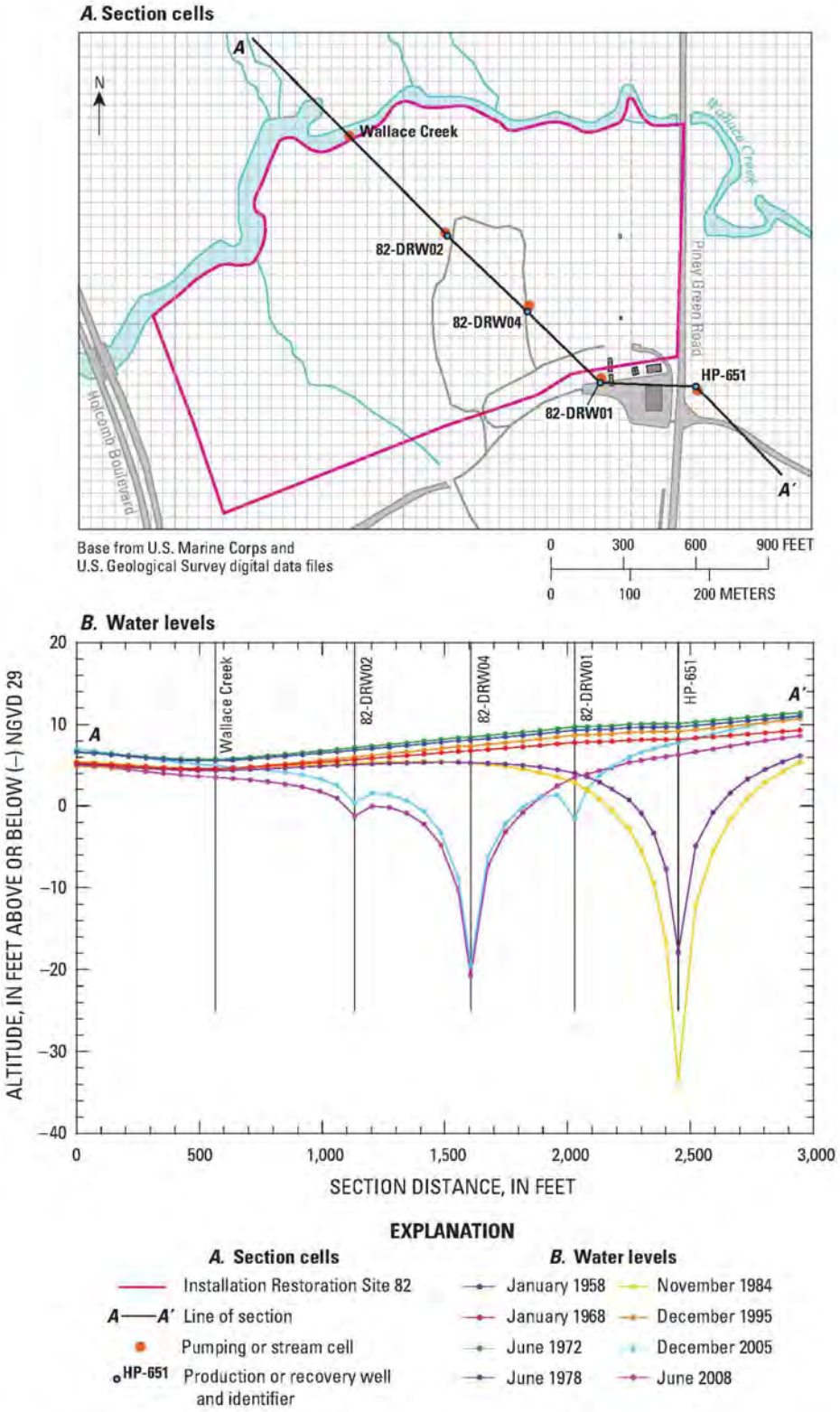

Figure S6.17. *(A)* Line of section *A–A′* and *(B)* simulated water levels within the Hadnot Point landfill area fate and transport model subdomain, model layer 5, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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Sensitivity Analyses

Sensitivity analyses were conducted by using ranges of values of selected parameters associated with the MODFLOW model input (flow parameters) and the MT3DMS model input (fate and transport parameters). Simply stated, sensitivity analysis is a method for evaluating the effect of variation of model input parameter values (e.g., recharge, dispersivity), within physically realistic ranges of values, on resulting model output parameter values (e.g., potentiometric levels, contaminant concentrations). The results from all sensitivity analyses were used to define a range of finished-water concentrations at the HPWTP. Details of the sensitivity analyses conducted on groundwater-flow model parameter values that were used to evaluate parameter variation effects on groundwater levels are described in Suárez-Soto et al. (2013).

Flow Parameters

Flow parameters that were selected for the sensitivity analysis included the hydraulic conductivity, K_h, of each model layer, hydraulic conductivity of all layers, and recharge. Each parameter was decreased and increased by one order of magnitude from its calibrated value (Figure S6.18) in three steps in successive steady-state simulations by using parameter multipliers of 0.1, 0.2, 0.5, 2.0, 5.0, and 10.0.[24] The resulting root-mean-square (RMS) of water-level residuals defines a sensitivity curve or line for each of the aforementioned parameters of variation (Figure S6.18). For each parameter, minimum and maximum values of the multiplier (shown in the lower and upper tails of the sensitivity curve, respectively) that have an RMS residual of 5 ft were determined through additional simulations and interpolation. If a tail of a sensitivity curve did not exceed an RMS residual of 5 ft when varying

[24] A multiplier of 1.0 indicates a calibrated parameter value.

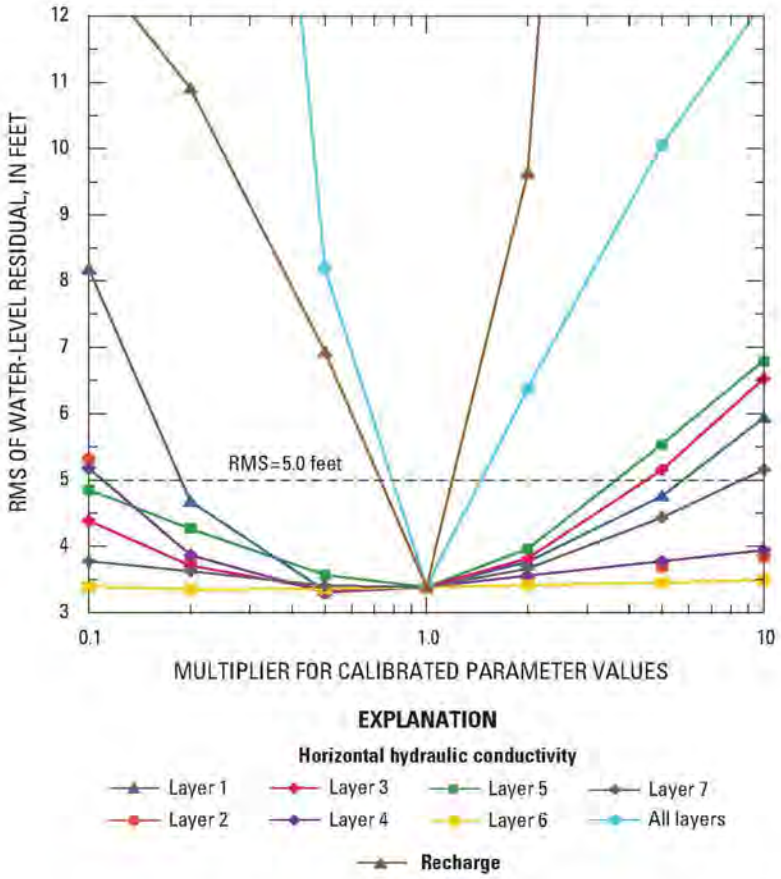

Figure S6.18. Sensitivity of steady-state (predevelopment) simulation results to changes in groundwater-flow model parameter values based on change in root-mean-square (RMS) of water-level residuals, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina (from Suárez-Soto et al. 2013).

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a parameter value by plus or minus one order of magnitude (multiplier less than 0.1 or greater than 10), the parameter being varied was interpreted and rated as insensitive. Otherwise, the multipliers resulting in RMS residuals of 5 ft were rated as low in sensitivity (multiplier of 0.1–0.2 or 5–10), moderate in sensitivity (multiplier of 0.2–0.5 or 2–5), or high in sensitivity (multiplier of 0.5–1 or 1–2) (Table S6.6). The values of the flow parameters corresponding to the minimum and maximum parameter multipliers determined in this manner are identified in this report as the *calibration-constrained* values of the flow parameter.

Interpretation of sensitivity analyses results shown in Figure S6.18 indicates that the steady-state (predevelopment) groundwater-flow potentiometric levels are most sensitive to changes in the hydraulic conductivity of all layers and to recharge; the least sensitive groundwater-flow model parameters are the hydraulic conductivities of layers 6 and 7. The rated sensitivities for hydraulic conductivities of the other model layers are a mixture of sensitivities ranging from insensitive, to low sensitivity, to moderate sensitivity (Table S6.6).

By using the calibration-constrained values of the aforementioned flow parameters, contaminant fate-and-transport simulations were conducted to determine the ranges of simulated PCE and TCE concentrations at historically contaminated water-supply wells that result from varying each of the flow parameters. PCE and TCE concentrations at water-supply well HP-651 (in the HPLF subdomain) that were simulated by using the calibrated and the calibration-constrained values of each flow parameter are shown in Appendix S6.2 (Figures S6.2.1– S6.2.4). TCE concentrations at water-supply well HP-634 (in the HPIA subdomain) that were simulated by using the calibrated and the calibration-constrained values of each flow parameter also are shown in Appendix S6.2 (Figures S6.2.5–S6.2.6).

Pumping rates of water-supply wells were varied by using an analysis similar to that described by Maslia et al. (2009). Resulting monthly pumping rate variation factors (or multipliers) derived by using the analysis described in Maslia et al. (2009) are listed in Table S6.7. Calibrated monthly pumping rates were multiplied by variation factors listed in Table S6.7. The corresponding PCE and TCE concentrations at well HP-651 and TCE concentrations at well HP-634 were simulated by using the calibrated and extreme values of water-supply well pumping (Appendix S6.2, Figures S6.2.3, S6.2.5, and S6.2.7).

Table S6.6. Minimum and maximum model flow-parameter multipliers and rated sensitivity of steady-state (predevelopment) simulation results to changes in flow parameters based on change in root-mean-square of water-level residuals, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[K_h, Hydraulic conductivity; <0.1, multiplier less than 0.1; >10.0, multiplier greater than 10.0]

Model parameter	Minimum	Maximum
K_h layer 1	0.18	5.87
K_h layer 2	0.11	>10.00
K_h layer 3	<0.10	4.59
K_h layer 4	0.11	>10.00
K_h layer 5	<0.10	3.74
K_h layer 6	<0.10	>10.00
K_h layer 7	<0.10	8.66
K_h all layers	0.66	1.51
Recharge	0.70	1.43

EXPLANATION

Sensitivity rating	Minimum	Maximum
Insensitive	<0.10	>10
Low	0.10 to 0.20	5 to 10
Moderate	0.20 to 0.50	2 to 5
High	0.50 to 1	1 to 2

Table S6.7. Minimum and maximum water-supply well pumping multipliers for Hadnot Point and Holcomb Boulevard water treatment plant service areas, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Month	Hadnot Point		Holcomb Boulevard	
	Minimum	Maximum	Minimum	Maximum
January	0.909	1.210	0.785	1.136
February	0.920	1.209	0.847	1.167
March	0.940	1.070	0.822	1.074
April	0.899	1.033	0.874	1.182
May	0.901	1.046	0.916	1.127
June	0.927	1.105	0.984	1.326
July	0.948	1.093	0.970	1.170
August	0.935	1.125	0.970	1.323
September	0.921	1.061	0.878	1.285
October	0.859	1.026	0.823	1.249
November	0.882	1.042	0.795	1.044
December	0.909	1.070	0.753	1.002

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Fate and Transport Parameters

Transport parameters for a contaminant fate and transport model applied to the TT study area are described in Maslia et al. (2007) and were the subject of an uncertainty analysis using pseudo-random number generation and Monte Carlo simulation. These transport parameters included distribution coefficient (K_d), bulk density (ρ), effective porosity (n_E), reaction rate (r), contaminant concentration (C), and longitudinal dispersivity (α_L). Because field data describing contaminant fate and transport parameters is lacking for the HPHB study area and the TT study area is adjacent to the HPHB study area, the probability density functions described by Maslia et al. (2009) were used to generate a range of transport parameters values for the analyses reported herein. The mean values listed in Table S6.8 correspond to the calibrated parameter values for the HPIA and HPLF models. The standard deviation listed in Table S6.8 are based on the standard deviations presented by Maslia et al. (2009). See Table S6.8 for details. The ranges of values—minimum and maximum—were used as input for the fate-and-transport models developed for the HPIA and HPLF models. Minimum and maximum values of the transport model parameters (Table S6.8) were derived by using the 2.5 and 97.5 percentiles (the mean ±1.96 times the standard deviation). However, α_L was assumed by Maslia et al. (2009) to be log-normally distributed. To obtain the 2.5 and 97.5 percentiles for α_L, the results of Maslia et al. (2009) were used to adjust the standard deviation of α_L, which was then transformed by the natural logarithm. Then, the 2.5 and 97.5 percentiles of $\ln(\alpha_L)$ were calculated and transformed back to an arithmetic scale.

PCE and TCE concentrations at water-supply well HP-651 and TCE concentrations at water-supply well HP-634 were simulated by using calibrated and 2.5 and 97.5 percentiles of each transport model parameter (Appendix S6.2). Except for longitudinal dispersivity, as discussed below, model results were generally most sensitive to variations in partition coefficient, porosity, and concentration. For the period of operation for well HP-651, contaminant concentrations were higher for minimum values of partition coefficient and porosity and maximum values of concentration.

It should be noted that the graphs showing PCE and TCE concentrations at water-supply well HP-651 using the 97.5 percentile of dispersivity increase the concentrations of PCE and TCE significantly more than changes in the other parameter values (Figures S6.2.7 and S6.2.8). The excessive increase in concentrations is related to increased contaminant mass entering the fate and transport subdomain area at the constant-concentration source cells. The higher value of α_L causes solute mass to move away from cells adjacent to the source cells more rapidly, increasing the local concentration gradient, which causes more contaminant mass to enter the system. In subsequent simulations, the constant-concentration sources for TCE were transformed into equivalent mass-loading rates based on an analysis of the average mass of TCE entering the system. The model was much less sensitive to increases in α_L when using the equivalent mass-loading boundary condition (Figure S6.19).

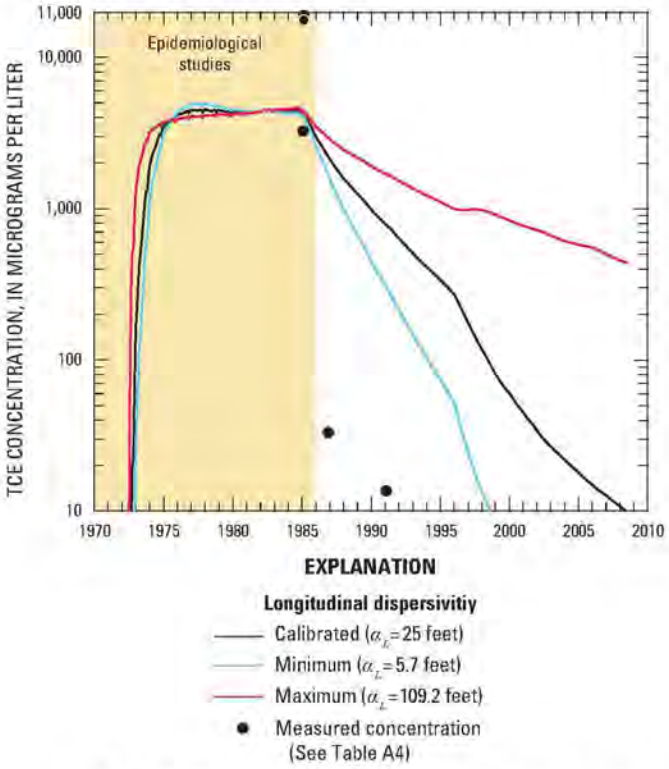

Figure S6.19. Trichloroethylene (TCE) concentrations at water-supply well HP-651 for calibrated value and minimum and maximum values of longitudinal dispersivitiy (α_L) for an equivalent mass-loading rate, Hadnot Point landfill area fate and transport model, layer 5, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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Table S6.8. Minimum and maximum transport model parameter values obtained by using normal statistics, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[TCE, trichloroethylene; PCE, tetrachloroethylene; HPLF, Hadnot Point landfill; HPIA, Hadnot Point Industrial Area; ft³/g, cubic feet per gram; g/ft³, grams per cubic foot; [–], dimensionless; d⁻¹, per day; mg/L, milligrams per liter; ft, feet]

[1]Model input parameter	Unit	Normal statistics		2.5–97.5 percentile range	
		[2]Mean, $\bar{X}$	[3]Standard deviation, σ	Minimum ($\bar{X}$–1.96 σ)	Maximum ($\bar{X}$+1.96 σ)
Distribution coefficient, K_d					
TCE	ft³/g	5.3×10^{-6}	1.3×10^{-6}	2.7×10^{-6}	7.9×10^{-6}
PCE	ft³/g	1.1×10^{-5}	2.7×10^{-6}	5.4×10^{-6}	1.6×10^{-5}
Bulk density, ρ_B	g/ft³	47,000	610	46,000	48,000
Effective porosity, n_E	[–]	0.20	4.5×10^{-2}	0.11	0.29
Reaction rate, r	d⁻¹				
PCE and TCE (HPLF)	d⁻¹	1.4×10^{-4}	3.4×10^{-5}	7.4×10^{-5}	2.1×10^{-4}
TCE (HPIA)	d⁻¹	2.0×10^{-3}	4.8×10^{-4}	1.1×10^{-3}	2.9×10^{-3}
Benzene (HPIA)	d⁻¹	1.0×10^{-4}	2.4×10^{-5}	5.3×10^{-5}	1.5×10^{-4}
Contaminant concentration, C					
Hadnot Point Industrial Area					
TCE	mg/L	640	52	540	740
Benzene	mg/L	1.7	0.14	1.4	2.0
Landfill					
TCE					
Source 1, layers 1–7	mg/L	380	31	320	450
Source 2, layers 1–7	mg/L	260	21	220	300
PCE					
Source 1					
Layer 1	mg/L	110	8.5	88	120
Layer 2	mg/L	83	6.8	70	96
Layer 3	mg/L	66	5.4	56	77
Layer 4	mg/L	46	3.7	39	53
Layer 5	mg/L	16	1.3	13	19
Source 2					
Layer 1	mg/L	42	3.4	35	49
Layer 2	mg/L	33	2.7	28	38
Layer 3	mg/L	27	2.2	23	31
Layer 4	mg/L	18	1.5	15	21
Layer 5	mg/L	6.0	0.49	5.0	7.0
[4]Longitudinal dispersivity, α_L	ft	3.2	0.75	5.7	109

[1] All parameters are assumed to be normally distributed except longitudinal dispersivity which is assumed to be lognormally distributed

[2] Mean values correspond to the calibrated values for the HPIA and HPLF models

[3] Standard deviation were obtained based on the standard deviations described by Maslia et al. (2009). For parameter calibrated values used in the HPIA and HPLF models that differed from the corresponding parameter values used in the TT study area model, the standard deviation was adjusted using the following formula:

$$\sigma_{HPHB} = \frac{\bar{X}_{HPHB}}{\bar{X}_{TT}} \sigma_{TT}$$

where

σ_{HPHB} is the standard deviation statistic used in the current study

$\bar{X}_{HPHB}$ is the mean statistic used in the current study. This value corresponds to the calibrated parameter value for the HPIA and HPLF models

$\bar{X}_{TT}$ is the mean statistic used in the Tarawa Terrace study described by Maslia et al (2009)

σ_{TT} is the standard deviation statistic used in the Tarawa Terrace study described by Maslia et al (2009)

[4] Longitudinal dispersivity is assumed to be log normally distributed. Mean and standard deviation values shown are log-transformed using the natural log before they were used to calculate the 2.5 and 97.5 percentile

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Cell-Size Sensitivity Analysis

Contaminant fate and transport simulations can exhibit numerical instabilities related to spatial discretization (finite difference grid cell size), which in turn can affect simulated concentrations and computed contaminant mass. The Peclet number (P_e) provides a criterion for controlling numerical oscillations due to spatial discretization when its value is less than or equal to 2 (Daus and Frind 1985; Zheng and Bennett 2002). The Peclet number is physically interpreted as the ratio of advective (V) to dispersive (D) transport terms and is defined as

$$P_e = \frac{V\Delta l}{D}, \tag{S6.4}$$

where

P_e is Peclet number, dimensionless;
V is simulated groundwater-flow velocity $[LT^{-1}]$;
Δl is a characteristic length $[L]$; and
D is dispersion coefficient $[L^2T^{-1}]$.[25]

In a one-dimensional, uniform flow field, Equation S6.4 reduces to

$$P_e = \frac{\Delta l}{\alpha_L}, \tag{S6.5}$$

where α_L is the aquifer dispersivity, $[L]$. By substituting into Equation S6.5 the finite difference cell dimension assigned to the HPIA and HPLF fate and transport model subdomains of 50 ft and the calibrated α_L value of 25 ft (Table S6.3), a P_e value of 2 is obtained, thereby satisfying the aforementioned criterion for controlling oscillations due to spatial discretization. Because of aquifer heterogeneity and water-supply well operations, the flow field in the HPHB study area is not uniform and is three-dimensional. Therefore, a more robust analysis for evaluating P_e (Equation S6.4) is presented.

In a three-dimensional groundwater-flow system, the dispersion coefficient (D) in Equation S6.4 is represented by a dispersion tensor and contains nine terms (Zheng and Bennett 2002):

$$\boldsymbol{D} = \begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{zx} & D_{zy} & D_{zz} \end{bmatrix}, \tag{S6.6}$$

where $\boldsymbol{D}$ is the dispersion tensor. The dispersion tensor components (e.g., D_{xx}, D_{xy}) are defined in terms of groundwater velocity ($\boldsymbol{V}$) and its directional components (V_x, V_y, and V_z), horizontal, transverse, and vertical dispersivity (α_L, α_T, and α_V; e.g., Table S6.3), and the effective molecular diffusion coefficient (D^*, Table S6.3). If the axes of the computational grid are aligned with the principal directions of groundwater velocity or the cross-terms of $\boldsymbol{D}$ are assumed to be negligible (and approaching zero), then Equation S6.6 reduces to a diagonal matrix containing only the diagonal terms of $\boldsymbol{D}$ such that (Zheng and Bennett 2002)

$$\boldsymbol{D} = \begin{bmatrix} D_{xx} & 0 & 0 \\ 0 & D_{yy} & 0 \\ 0 & 0 & D_{zz} \end{bmatrix}, \tag{S6.7}$$

where:

$$D_{xx} = \alpha_L \frac{V_x^2}{|\boldsymbol{V}|} + \alpha_T \frac{V_y^2}{|\boldsymbol{V}|} + \alpha_V \frac{V_z^2}{|\boldsymbol{V}|} + D^*, \tag{S6.8a}$$

$$D_{yy} = \alpha_L \frac{V_y^2}{|\boldsymbol{V}|} + \alpha_T \frac{V_x^2}{|\boldsymbol{V}|} + \alpha_V \frac{V_z^2}{|\boldsymbol{V}|} + D^*, \tag{S6.8b}$$

$$D_{zz} = \alpha_L \frac{V_z^2}{|\boldsymbol{V}|} + \alpha_T \frac{V_x^2}{|\boldsymbol{V}|} + \alpha_V \frac{V_y^2}{|\boldsymbol{V}|} + D^*, \text{ and} \tag{S6.8c}$$

$$|\boldsymbol{V}| = \sqrt{\left(V_x^2 + V_y^2 + V_z^2\right)}. \tag{S6.8d}$$

Equation S6.4 can now be solved using the diagonal term of the dispersivity tensor (Equation S6.7) to define a Peclet number corresponding to each directional axis, as follows:

$$P_{ex} = \frac{V_x \Delta x}{D_{xx}}, \tag{S6.9a}$$

$$P_{ey} = \frac{V_y \Delta y}{D_{yy}}, \text{ and} \tag{S6.9b}$$

$$P_{ez} = \frac{V_z \Delta z}{D_{zz}}. \tag{S6.9c}$$

In Equations S6.9a–c, Δx, Δy, and Δz correspond to the finite-difference cell dimensions along rows, columns, and model layers, respectively, for the HPIA and HPLF contaminant fate and transport model subdomain areas.

[25] L represents length units; T represents time units; L^0 indicates a dimensionless variable.

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To compute the Peclet numbers defined in Equations S6.9a–c, the directional values of velocity and the diagonal terms of the dispersion tensor were extracted from the MT3DMS contaminant fate and transport model code for specific finite-difference cells and simulation months of interest to the ATSDR epidemiological studies. For the HPIA, the cell nearest water-supply well HP-608 (Figure S6.2) was used to compute Equation S6.9 terms for conditions during January 1968 (start of health studies) and November 1984 (month prior to cessation of pumping of water-supply well HP-608). For the HPLF area, the cell nearest water-supply well HP-651 (Figure S6.3) was used to compute Equation S6.9 terms for conditions during June 1972 (start of operations of the well) and November 1984. Peclet number calculations for the calibrated HPIA and HPLF contaminant fate and transport subdomain model locations are listed in Table S6.9 along with values for components of velocity and the dispersion tensor.

For water-supply well HP-608 (HPIA subdomain model), results indicate that the computed Peclet numbers are below or somewhat higher than 2, the criterion indicated by Daus and Frind (1985) for controlling numerical oscillations. However, because the Peclet numbers were computed for a cell directly affected by water-supply well HP-608, cells further distant from the well would have substantially lower velocities, thereby meeting the Peclet criterion. For water-supply well HP-651 (HPLF subdomain model), results indicate that the computed Peclet numbers are greater than 6 for the horizontal Peclet number component (P_{ex}) and less than 1 for the transverse and vertical Peclet number components (P_{ey} and P_{ez}, respectively). These results indicate that the flow field near water-supply well HP-651 is an advective-dominated flow field, principally because well HP-651 was the only major water-supply well in the area and it was withdrawing groundwater solely from one zone—model layer 5. If the finite difference grid is refined whereby cell dimensions are reduced to 25 ft per side or 12.5 ft per side in the areal discretization (Δx and Δy), the resulting Peclet numbers in the vicinity of the aforementioned water-supply wells would approximately be reduced by corresponding factors of 2 and 4, respectively.

To further assess the propensity for numerical oscillations because of inappropriate spatial discretization (resulting in Peclet numbers greater than 2 in the vicinity of water-supply well HP-651), descriptions of model simulations conducted by using the aforementioned refined cell dimensions (25 ft and 12.5 ft per side) for the HPLF contaminant fate and transport subdomain model are presented below.

Table S6.9. Results of Peclet number calculations for the Hadnot Point Industrial Area (HPIA) and Hadnot Point landfill (HPLF) area contaminant fate and transport subdomain models, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Simulation month and year (Stress period)	Cell dimensions (ft)			Velocity (ft/d)			Dispersion (ft²/d)			Peclet number (Equation A8)		
	Δx	Δy	Δz	V_x	V_y	V_z	D_{xx}	D_{yy}	D_{zz}	P_{ex}	P_{ey}	P_{ez}
Hadnot Point Industrial Area, water-supply well HP-608[1]												
Jan. 1968 (313)	50.0	50.0	33.6	12.9	0.7	–0.7	223	37.5	0.7	2.9	0.1	3.5
Nov. 1984 (515)	50.0	50.0	33.6	5.1	–0.1	–0.04	133	20.4	0.4	1.9	0.3	2.9
Hadnot Point landfill (HPLF) area, water-supply well HP-651[2]												
June 1972 (367)	50.0	50.0	57.2	–16.5	–0.05	0.0	126	47.6	1.1	6.6	0.1	0.0
Nov. 1984 (515)	50.0	50.0	57.2	–23.0	–0.3	0.02	176	64.5	1.6	6.6	0.2	0.8

[1]See Figure A13 for well location; HPIA subdomain model cell location: row 184, column 114, layer 3

[2]See Figure A14 for well location; HPLF subdomain model cell location: row160, column 166, layer 5

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Sensitivity Analyses

Contaminant fate and transport simulations were conducted by using reduced finite-difference grid cell sizes of 25 ft and 12.5 ft per side. This grid refinement would effectively yield a reduction in the Peclet number by a factor of 2 to 4. Results of the contaminant fate and transport simulations for the HPLF subdomain area for TCE concentrations in water-supply well HP-651 are shown in Figure S6.20. The three concentration plots in the graph represent simulated TCE concentrations in well HP-651 that result from using finite-difference grid cell sizes of 50, 25, and 12.5 ft per side; the 50-ft cell size represents the calibrated model. These results indicate approximately the same results from the onset of pumping during July 1972 to cessation of pumping during February 1985, a period of interest to the ATSDR health studies. Additionally, simulated concentrations at water-supply well HP-651 are similar when using the three different cell sizes (50 ft, 25 ft, and 12.5 ft per side) and range from about 7,100 µg/L to 9,200 µg/L (Figure S6.20). By comparison, measured data range in value from 3,200 µg/L to 18,900 µg/L for the period January 16–February 4, 1985 (Table A4). Thus, sensitivity analysis results for variations in finite-difference cell sizes demonstrate that concentrations simulated by the HPHB study area contaminant fate and transport models were most likely unaffected by numerical oscillations caused by inappropriate (too large) spatial (cell size) discretization.

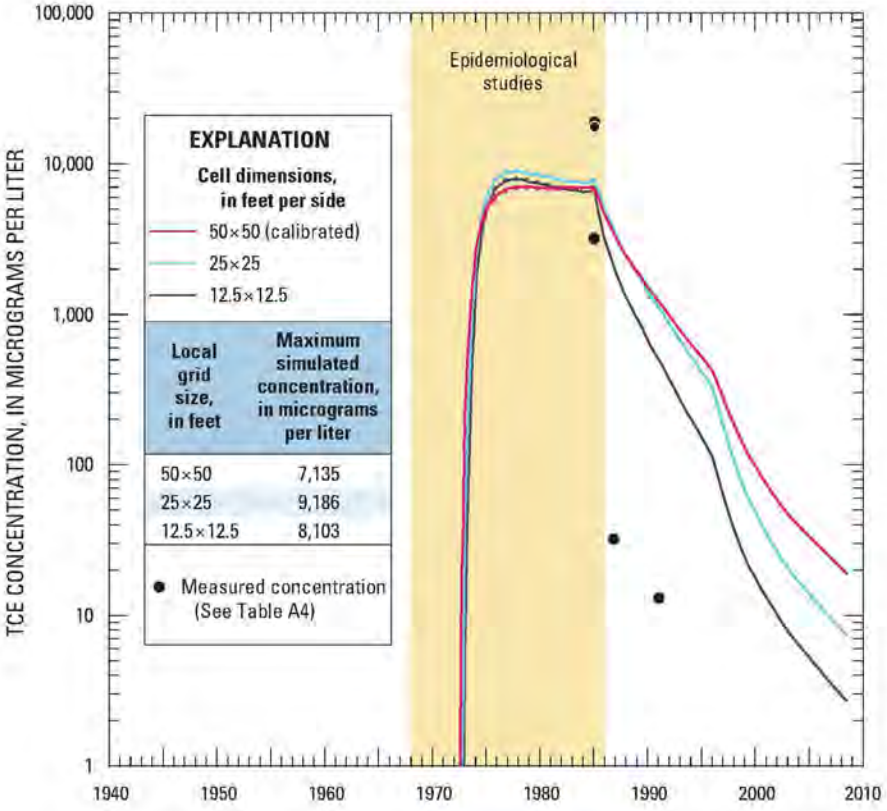

Figure S6.20. Simulated concentrations of trichloroethylene (TCE) in water-supply well HP-651 using finite-difference cell dimensions of 50, 25, and 12.5 feet per side, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. (See Figure S6.1 for well location.)

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Time-Step Size

When conducting fate and transport simulations, numerical instability related to inappropriate temporal discretization (i.e., time-step size) is minimized when the Courant number (C_N) equals 1 or less. For the models described in this supplement, the Courant condition was set to a maximum of 1.[26] The Courant number is defined as

$$C_N = \frac{V\Delta t}{\Delta l} \qquad \text{(S6.10)}$$

where

C_N = Courant number [L^0];
V = simulated groundwater-flow velocity [LT^{-1}];
Δt = stress-period length or time-step size [T]; and
Δl = a characteristic length [L].

The characteristic length of finite-difference numerical models is typically related to grid cell dimensions. The MODFLOW and MT3DMS models applied to the HPHB study area fate and transport model subdomains are uniform at 50 ft per side. Therefore, the characteristic length, Δl, becomes the length of the cell side or the distance between two adjacent cell centroids (50 ft). To minimize and control oscillations of the numerical solution resulting from the temporal discretization, Daus and Frind (1985) indicate that the Courant number (C_N) should be less than or equal to 1. For the HPHB study area groundwater-flow and contaminant fate and transport models, the stress periods were equal to the number of days in a month (i.e., 28, 29, 30, or 31). Except in the immediate vicinity of water-supply wells, groundwater-flow velocities ranged between 0.01 and 0.6 foot per day (ft/d) for the HPIA model subdomain area and between 0.01 and 1 ft/d for the HPLF model subdomain area. Thus, applying Equation S6.10—assuming Δt is the length of the stress period—to each subdomain area yields the following values for Courant numbers:

HPIA subdomain area (Figure S6.2):

$$\frac{0.01\times 28}{50} \le C_N \le \frac{0.6\times 31}{50}$$

$$0.006 \le C_N \le 0.4\,, \qquad \text{(S6.11)}$$

and for the HPLF subdomain area (Figure S6.3):

$$\frac{0.01\times 28}{50} \le C_N \le \frac{1.0\times 31}{50}$$

$$0.006 \le C_N \le 0.6\,. \qquad \text{(S6.12)}$$

This demonstrates that for the HPHB study area, the Courant number was less than 1 throughout the subdomain model areas except in the immediate vicinity of operating water-supply wells.

In the immediate vicinity of operating water-supply wells, simulated velocities were as great as 18 ft/d near well HP-608 in the HPIA area and as great as 10 ft/d near well HP-651 in the HPLF area. Substituting these values of velocity into Equation S6.10—again, Δt is the length of the stress period—results in maximum-value Courant numbers of about 11 and 6 for the HPIA and HPLF fate and transport model subdomain areas, respectively. These Courant numbers—exceeding a value of 1—could be indicative of numerical oscillations leading to inaccurate simulated concentrations. Although the number of time steps (e.g., additional transport steps) was increased to maintain a Courant number of less than 1, an analysis was completed to assess the effect of time discretization into the concentrations at the wells. To assess the effect of numerical oscillations caused by an inappropriate time discretization (that is, too large of a time step), contaminant fate and transport simulations were conducted by assigning 1-day stress periods ($\Delta t = 1$) to the calibrated contaminant fate and transport model for the HPLF subdomain area from November 1, 1984, to January 31, 1985. Pumpage assigned to these months in the calibrated model was assigned to every day of each respective month for the time-step sensitivity analysis. Comparisons of calibrated (30- and 31-day time steps) and simulated (1-day time step) concentrations of PCE and TCE for the days of November 30, 1984, December 31, 1984, and January 31, 1985, for water-supply well HP-651 are listed in Table S6.10. These results indicate that the relative absolute difference in simulated PCE and TCE concentrations at water-supply well HP-651 between the 1-day time step and the 30- and 31-day time steps is typically less than 0.2 percent and never exceeds 0.25 percent. Thus, PCE and TCE concentrations simulated by the HPHB study area contaminant fate and transport models were most likely unaffected by numerical oscillations caused by inappropriate temporal discretization.

[26] The Courant condition is automatically checked for every cell in the computational grid by the MT3DMS code to assure that $C_N \le 1$ for every stress period. If the Courant condition is not met, MT3DMS increases the number of transport time steps within a stress period, thus reducing the value of Δt in Equation 6.10. In most cases, the stress period was discretized by MT3DMS into about 2–5 transport time steps to comply with a Courant condition of less than 1.

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Table S6.10. Simulated tetrachloroethylene and trichloroethylene concentrations at water-supply well HP-651, November 1984–January 1985, using 1-day stress periods and 30- or 31-day stress periods (calibrated model), Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter; Δt, time of stress period]

Contaminant	Simulated elapsed time, in days	Date	[1]Simulated concentration, in µg/L		[2]Absolute relative difference, in percent
			Δt=1 day	Δt=30 or 31 days	
Tetrachloroethylene (PCE)	15,675	Nov. 30, 1984	348.557	347.777	0.22
	15,706	Dec. 31, 1984	337.01	336.601	0.12
	15,737	Jan. 31, 1985	343.498	343.105	0.11
Trichloroethylene (TCE)	15,675	Nov. 30, 1984	6,910.40	6,894.63	0.23
	15,706	Dec. 31, 1984	6,589.20	6,582.72	0.10
	15,737	Jan. 31, 1985	6,779.30	6,772.31	0.10

[1]Simulated PCE and TCE concentrations for $\Delta t = 30$ or $\Delta t = 31$ days are from the calibrated fate and transport model for the Hadnot Point landfill (HPLF) subdomain area.

[2]Absolute relative difference ($|R_C|$) of simulated PCE and TCE concentrations are water-supply wells defined as:

$$|R_C| = \frac{C_{cal} - C_{\Delta t=1}}{C_{\Delta t=1}} \times 100\%,$$

where

C_{cal} is the calibrated PCE or TCE concentration simulated using a time-step size of 30 or 31 days, and

$C_{\Delta t=1}$ is the PCE or TCE concentration simulated using a time-step size of 1 day

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Numerical Solver

During the process of calibrating both the HPIA and HPLF fate and transport models, the third-order, total-variation-diminishing (TVD) solver of MT3DMS was initially employed because it is characterized as being mass conservative and typically produces an accurate solution, free of numerical dispersion. However, the TVD solver "minimizes numerical dispersion at the expense of introducing spurious oscillations" (Zheng and Wang, 1999), which proved to be the case with the HPIA and HPLF models. The artificial oscillations produced negative simulated concentrations, especially along areas of sharp concentration fronts, indicative of an advection-dominated system. To alleviate the oscillation problem, the standard finite-difference solution method was used, which, not unexpectedly, produced a solution characterized by increased numerical dispersion. To assess the quality of the results, the HPIA and HPLF models were run using different solvers. Well HP-651 reconstructed concentrations from the calibrated model, which use the finite-difference solver, were compared with results of simulations obtained by using the TVD solver and the method of characteristics (MOC) solver (Figure S6.21).

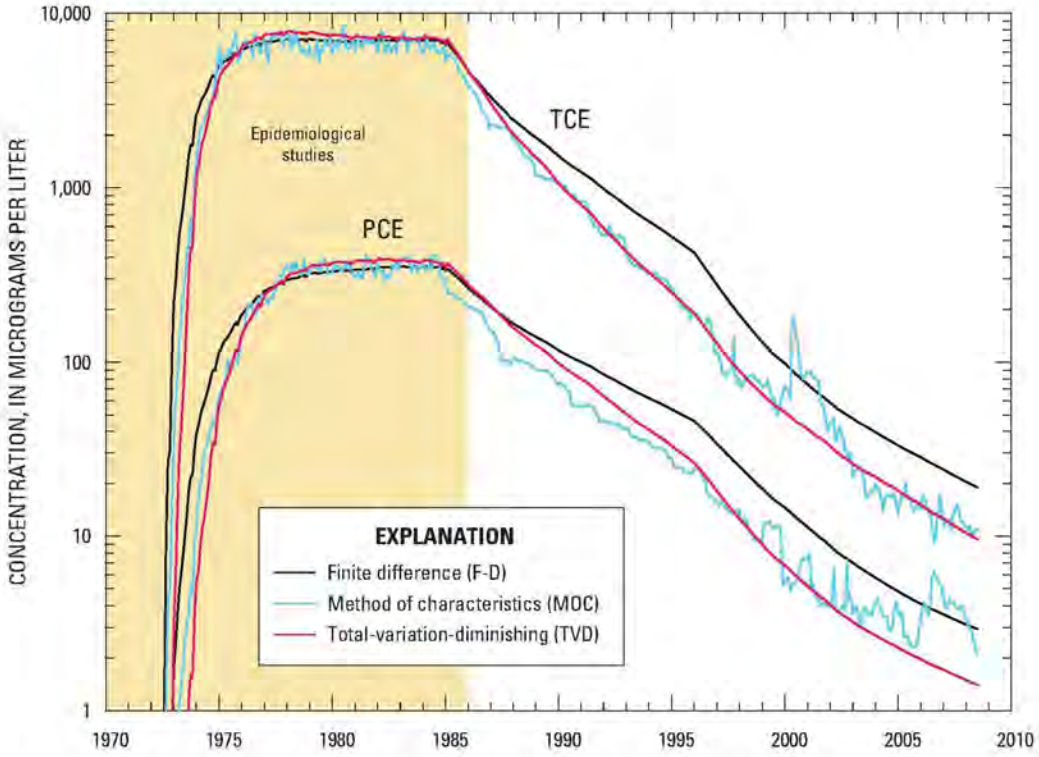

Figure S6.21. Simulated tetrachloroethylene (PCE) and trichloroethylene (TCE) concentrations at water-supply well HP-651 using MT3DMS finite-difference solver (F-D, calibrated model), method of characteristics solver (MOC) and total-variation-diminishing (TVD) solver, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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Trichloroethylene Source-Release Date

Historical records delineating the timing and volume of inadvertent releases of solvents during routine operations, from leaking UST systems, or from disposal of solvent waste, spent dry cleaning filters, or other materials were not available for the HPHB study area. For modeling purposes, a median source-release date of 9 years from the date of UST system installation or site development (in the case of the HPLF area) was used in the contaminant fate and transport models. This source-release date formulation is consistent with empirical data indicating that the median timeframe for leak development in UST systems (typically in piping and joint components) is 9 years from installation date (USEPA 1986, 1987; Gangadharan et al. 1987). UST systems were not the source of contaminants in the HPLF area. However, given the lack of historical information, a similar source-release time frame, in this case 7 years from site development, was applied to HPLF-area sources within the model. The shorter source-release time frame acknowledges that landfill disposal likely encompassed a range of contained and uncontained source materials, in contrast to the engineered tank and piping system sources discussed previously.

To assess the effect of source-release-date variation on TCE concentrations in finished water at the HPWTP, a sensitivity analysis was conducted whereby the source-release date was modified from the calibrated source-release date. For example, a decrease of 5 years from the calibrated median of 9 years indicates a source-release date of 4 years from the estimated installation date for a UST system. Conversely, an increase of 5 years from the calibrated median of 9 years indicates a source-release date of 14 years from the estimated UST installation date.

Four sensitivity analysis simulations were conducted using the HPIA and HPLF area TCE contaminant source-release dates (Table S6.5). For these sensitivity analyses, the calibrated source-release date (9 years for suspected UST system sources and 7 years for HPLF area sources) was decreased by 5 and 9 years and increased by 5 and 9 years (7 years for the HPLF area sources) (Figure S6.22). In the case of the HPLF area sources, the calibrated source-release date was decreased by 7 years, to coincide with Base development in 1941. Results indicate that reconstructed TCE concentrations of finished-water for the HPWTP at the start of the epidemiological studies (January 1968) display little variation, except for a source-release-date increase of 9 years. The maximum reconstructed TCE concentration during the time frame (1968–1985) of the epidemiological studies varies by about 5 percent or less from the calibrated maximum value of 783 µg/L (Figure S6.22). Decreasing the source-release date by 9 years from its calibrated value (Figure S6.22) implies that contaminant leakage in the HPLF area would have started during or immediately following the onset of construction (1941/1942) of USMCB Camp Lejeune, which is not an unrealistic scenario given landfill-construction technologies that existed during the 1940s and 1950s. Results from this scenario indicate that the MCL for TCE in finished water at the HPWTP would have been exceeded during November 1948, compared to the calibrated exceedance date of August 1953. Variations in source-release dates of ±9 years show MCL exceedance-date variations of about 5 years earlier to 14 years later than the calibrated TCE MCL exceedance date (August 1953). In terms of historical reconstruction results of interest to the ATSDR epidemiological studies (finished-water concentrations of TCE during the period 1968–1985), the variation (and uncertainty due to a lack of data) in source-release dates does not appear to have a substantial effect..

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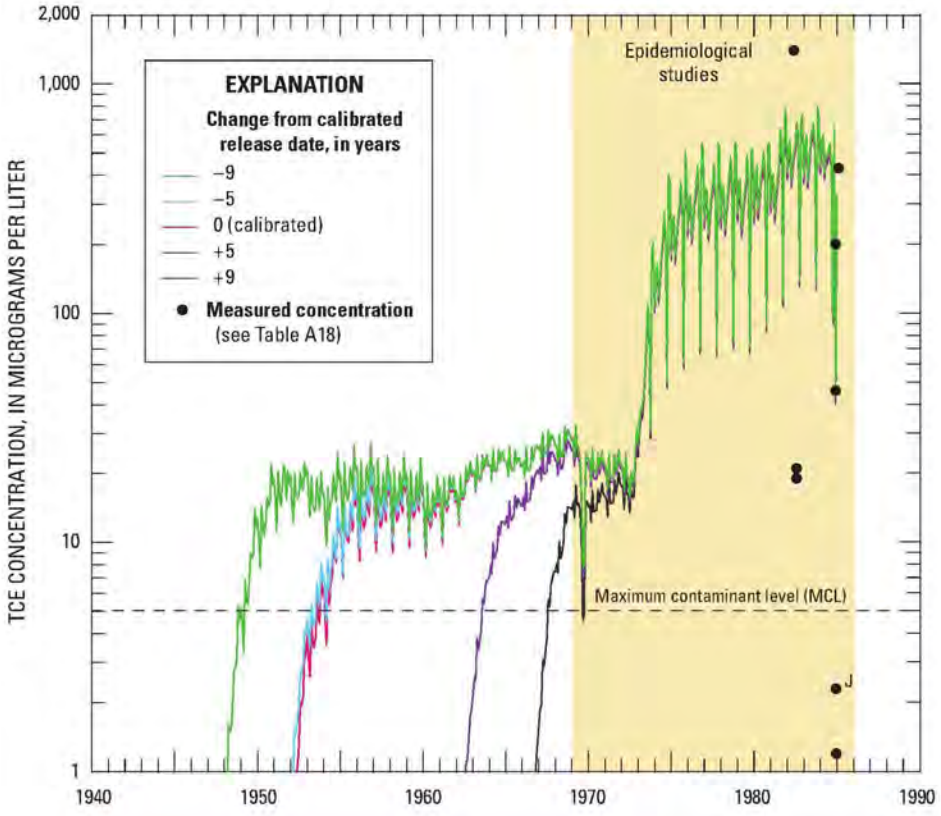

[1]Change from calibrated release date, in years	First month exceeding MCL	Concentration at start of epidemiological study (January 1968), in micrograms per liter	Maximum concentration during epidemiological study period (January 1968–December 1985), in micrograms per liter
−9	November 1948	26	800
−5	April 1953	26	798
0 (calibrated)	August 1953	27	783
+5	August 1963	23	748
+9	August 1967	7	740

[1]Calibrated release date varies by source location (Table S6.5)

Note:
−9 years means 9 years earlier than calibrated-source release date
+9 years means 9 years after calibrated-source release date

Figure S6.22. Reconstructed (simulated) finished-water concentrations of trichloroethylene (TCE) derived from variations in contaminant-source release dates, Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.
[J, estimated concentration]

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Uncertainty Analysis

In order to demonstrate the effect of uncertainty in the pumping schedules of water-supply wells, a Latin hypercube sampling (LHS) methodology was used. LHS is a useful tool for generating a limited number of random samples that are evenly distributed over a multidimensional random field. In this respect, LHS is an ideal approach to overcome the computational expense posed by the Monte Carlo (MC) simulation by reducing the number of simulations required. The LHS technique was first introduced by McKay et al. (1979). Helton and Davis (2003) provide a summary on LHS used for uncertainty analyses of complex systems. LHS was used to model spatial uncertainty in forest landscape simulations by Xu et al. (2005). Lahkim et al. (1999) applied LHS methodology to reduce the number of simulations required for the uncertainty analysis for the exposure and risk analyses in a polluted aquifer.

For this analysis, MATLAB® (version R2012b, 2012) was used to generate the Latin hypercube samples for the pumping schedules of the wells providing groundwater to the HPWTP and the HBWTP (Figure S6.23). The default criterion for LHS is to maximize the minimum distance between points. For this analysis, the number of random variables can be calculated as the product of the number of wells and number of months (i.e., 72 wells×792 months=57,024 for HPWTP, and 24 wells×792 months=19,008 for HBWTP). Replicating the approach described in Maslia et al. (2007, 2009) for conducting a similar uncertainty analysis for the HPHB study area was not computationally feasible even when using the LHS methodology. Therefore, a limited analysis with 10 Latin hypercube samples was conducted. The MATLAB® LHS function that was used generates 10 Latin hypercube samples for the monthly flow produced by all 96 wells included in the analysis. Initially, the values assigned to each well for each month range from 0 to 1. These normalized samples are then

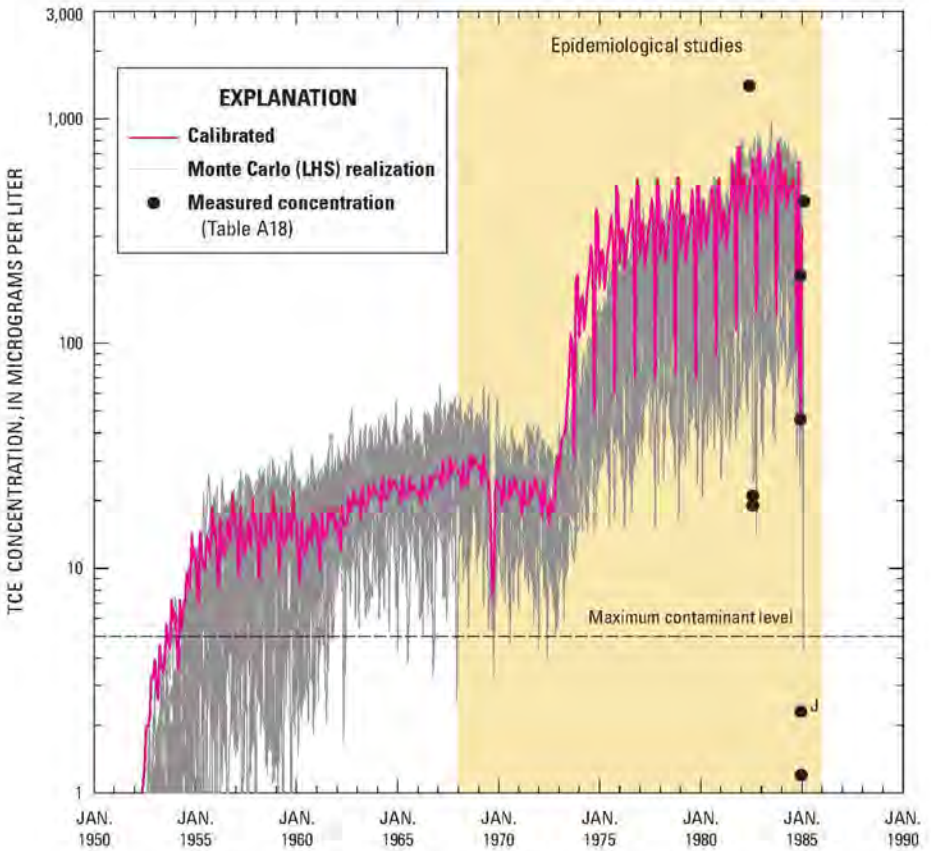

Figure S6.23. Variations in reconstructed (simulated) finished-water concentrations of trichloroethylene (TCE) derived using Latin hypercube sampling (LHS) methodology on water-supply well monthly operational schedules, Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. [J, estimated]

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scaled to the actual monthly flows reported by Telci et al. (2013) by multiplying with a range of flows for each well and each month. These flow ranges were determined by finding the difference between the maximum and minimum flows generated for 1,000 MC Markov Chain scenarios that satisfy conservation of mass at WTP water treatment plant within an error range of ±40 percent. The revised pumping schedules (relative to the calibrated schedules reported in Telci et al. (2013) were used as an input to the contaminant fate and transport models of the HPIA and HPLF area to reconstruct TCE concentrations delivered to the HPWTP by each well. Reconstructed TCE concentrations at the HPWTP derived from applying the LHS methodology to water-supply well monthly operational schedules are shown in Figure S6.23. In this figure, the red line indicates the TCE concentration obtained from the calibrated models. The gray lines indicate the TCE concentration variation over time for the 10 random scenarios obtained by LHS methodology. Results shown in Figure S6.23 indicate that observed data exhibit substantially greater variation than reconstructed concentrations generated by using the LHS-MC uncertainty analysis.

Discussion and Limitations

The purpose of this section is to provide readers with some additional thoughts pertinent to historical reconstruction results and application of models presented herein. All of the limitations that are presented in the Discussion section of Faye (2008) in reference to the TT study area fate and transport model are by extension applicable to the HPIA and HPLF area fate and transport models. Specifically, the water-quality sample records from the HPHB study area, on which assessment of model calibration results are substantially dependent, are subject to the same level of uncertainty and variability as discussed in Faye (2008). The water-quality data used in developing and calibrating the HPIA and HPLF area fate and transport models are tabulated in Faye et al. (2010, 2012), where there is further discussion of water-quality data. The reader is referred to those discussions for a better understanding of the complex nature of the water-quality data for the HPHB study area.

Results of the historical reconstruction process—concentrations at water-supply wells—should be interpreted as the most likely estimate representing monthly mean concentrations. These results represent the last day of the month. For example, for January 1968, the simulated TCE concentration at water-supply well HP-602 of 463 µg/L (Appendix A3) should be interpreted as occurring on January 31, 1968. For groundwater-flow model calibration (Suárez-Soto et al. 2013), sufficient water-level data are documented to apply statistical methods to assess the calibration fit.

For contaminant fate and transport modeling reported herein, however, insufficient water-quality data existed to conduct a statistical analysis for assessment of model calibration fit. In addition, specific data pertinent to the timing of initial deposition of contaminants to the ground or subsurface, chronologies of waste-disposal operations, such as dates and times when contaminants were deposited in the HPLF, or descriptions of the temporal variation of contaminant concentrations in the subsurface generally are not available. Determining these types of source identification and characterization data became part of the historical reconstruction process, whereby the contaminate fate and transport model was used to test source locations, varying concentrations, and beginning and ending dates for leakage and migration of source contaminants to the subsurface and the underlying groundwater-flow system.

Conducting a robust uncertainty analysis using Monte Carlo analysis (e.g., Maslia et al. 2009) requires simulating thousands of realizations. When using available computational equipment, the HPIA and HPLF models have a simulation time of about 6–8 hours for each simulation. The lengthy simulation times and the substantial data limitations therefore make a comprehensive uncertainty analysis computationally prohibitive based on available resources and time limitations. Thus, the ranges of values presented in the sensitivity analysis section of this report assess a limited number of input and output model parameters. The results (i.e., range of concentration) presented in the sensitivity analysis reported herein should not be considered or interpreted as the results of a robust and comprehensive uncertainty analysis, but do provide insight into parameter sensitivity and uncertainty in a qualitative sense.

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Appendix S6.1. Biological Reactions of Selected Contaminants of Concern, Hadnot Point–Holcomb Boulevard Study Area

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[28] Chlorinated volatile organic carbons (VOCs) and benzene, toluene, ethylbenzene, and xylenes (BTEX) were detected in groundwater that was extracted at Installation Restoration Program Sites 6 and 82 (Figure S6.3), Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune. Sites 6 and 82 adjoin one another and together comprise over 200 acres. Site 6 is composed of equipment staging and open storage areas, including Storage Lots 201 and 203. Site 82 is a mostly wooded area that borders Site 6 to the north. Prior to the late 1980s, much of the northern portion of Storage Lot 203 and Site 82 was used for storage, disposal, and handling of hazardous waste and materials. Located in the central and southern portions of Site 6, Storage Lot 201 has been used to stage equipment and material since the 1940s. Lot 201 was also reportedly used to store pesticides and polychlorinated biphenyls until the late 1980s.

At Sites 6 and 82, the measured maximum concentrations of contaminants are 6,500, 180,000, 18,000, 8,070, 187, and 800 micrograms per liter (µg/L) for tetrachlorotheylene (PCE), trichloroethylene (TCE), *cis*-1,2-dichloroethylene (1,2-cDCE), *trans*-1,2-dichloroethylene (1,2-tDCE), 1,1-dichloroethylene (1,1-DCE), and vinyl chloride (VC), respectively (refer to Faye et al. 2010 for measured concentrations at Sites 6 and 82). When considering potential biological processes of PCE and TCE, shown in Figure S6.1.1, the presence of the high concentration of three DCE isomers (1,2-cDCE, 1,2-tDCE, and 1,1-DCE) strongly suggests that the anaerobic biological transformation of PCE and TCE into DCEs occurred in the subsurface at both Sites 6 and 82. The biological dechlorination processes of PCE and TCE have been reported at contaminated sites (Vogel et al. 1987; Semprini et al. 1995; Witt et al. 2002; Jang and Aral 2008).

Aerobic and anaerobic bioreactions of chlorinated VOCs are complicated, and bioreaction rates are difficult to measure in the environment. A first-order kinetic model is often used to express the reductive dechlorination of chlorinated VOCs at contaminated sites (Schmidt et al. 1985; Wiedemeier 1998; Alvarez-Cohen and Speitel 2001; Jang and Aral 2007). In this study, a first-order kinetic model is applied to describe the dechlorination of chlorinated VOCs: PCE, TCE, 1,2-cDCE, 1,2-tDCE, 1,1-DCE, and VC. A first-order kinetic model can be written as:

$$\frac{dC_i}{dt} = -kC_i \qquad \text{(S6.1.1)}$$

where

C_i is the concentration of a target contaminant (M/L^3],
t is time [T], and
k is a first-order rate [T^{-1}].

Typically, the temporal profiles of concentrations of contaminants (i.e., contaminant concentration vs. time) are used to estimate the biodegradation of contaminants. However, the temporal variation of measured contaminant concentrations (or measured concentration data of chlorinated VOCs) at Sites 6 and 82 are the outcome of multiple processes, including advection (or groundwater flow), diffusion and dispersion, dilution, sorption, and biotic and abiotic reactions. In this study, we use a simplified analytical solution, derived from Equation S6.1.1, to estimate the attenuation rates[29] of chlorinated VOCs. Some of the field data and fitted curves used herein are illustrated in Figure S6.1.1, and the calculated attenuation rates of PCE, TCE, 1,2-cDCE, 1,2-tDCE, 1,1-DCE, and VC are presented in Table S6.1.1.

[28] Discussion presented in this appendix was obtained from the Biological Reactions of Target Chlorinated VOCs at Hadnot Point section in Jang and Aral 2009.

[29] Attenuation and bioreaction rates are sometimes used synonymously; however, calculated rates in this appendix should be considered attenuation rates because the calculated rate comprises multiple processes (e.g., advection, dispersion).

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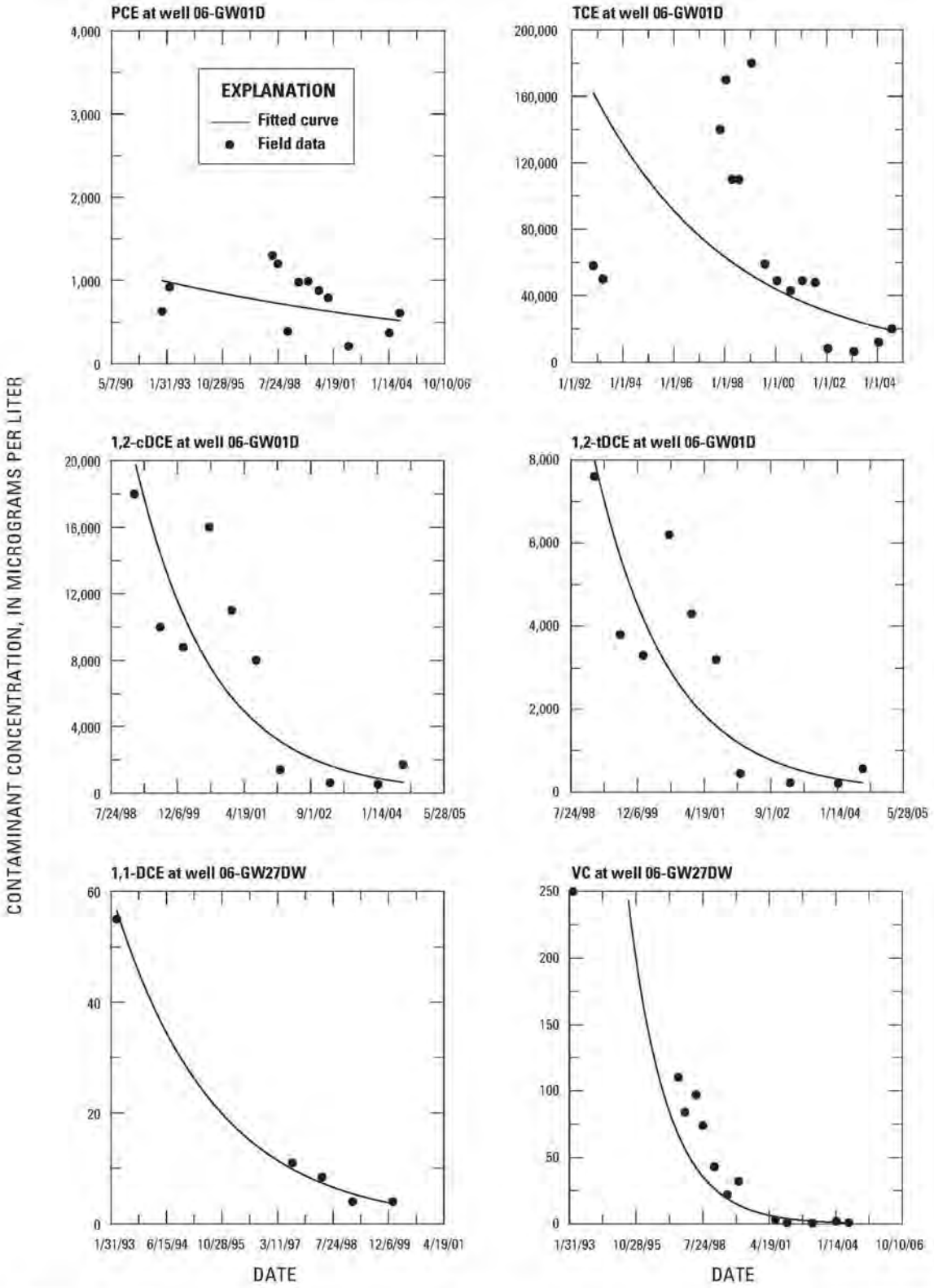

Figure S6.1.1. Field data and fitted curves for tetrachlorotheylene (PCE), trichloroethylene (TCE), *cis*-1,2-dichloroethylene (1,2-cDCE), *trans*-1,2-dichloroethylene (1,2-tDCE), 1,1-dichloroethylene (1,1-DCE), and vinyl chloride (VC). The fitted curves are for a first-order dechlorination kinetics, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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Table S6.1.1. Calculated attenuation rates at selected monitor wells in the Hadnot Point landfill area, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Well number	Attenuation rates (day^{-1})	Half-life, in days	R^2 (root mean square)
Tetrachloroethylene (PCE)			
06-GW01D	1.54×10^{-4}	4,501	0.15
06-GW27DW	9.75×10^{-4}	711	0.84
Trichloroethylene (TCE)			
06-GW01D	3.59×10^{-4}	1,931	0.37
06-GW01DA	6.14×10^{-4}	1,129	0.23
06-GW27DW	1.50×10^{-3}	462	0.93
cis-1,2-dichloroethylene (1,2-cDCE)			
06-GW01D	1.70×10^{-3}	408	0.73
06-GW27DW	2.26×10^{-3}	307	0.67
trans-1,2-dichloroethylene (1,2-tDCE)			
06-GW01D	1.76×10^{-3}	394	0.75
06-GW27DW	2.47×10^{-3}	281	0.63
1,1-dichloroethylene (1,1-DCE)			
06-GW01D	7.36×10^{-4}	942	0.61
06-GW27DW	1.10×10^{-3}	630	0.97
Vinyl chloride (VC)			
06-GW01D	1.22×10^{-3}	568	0.72
06-GW27DW	1.72×10^{-3}	403	0.84

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Appendix S6.2. Results for Sensitivity Analysis for Selected Water-Supply Wells

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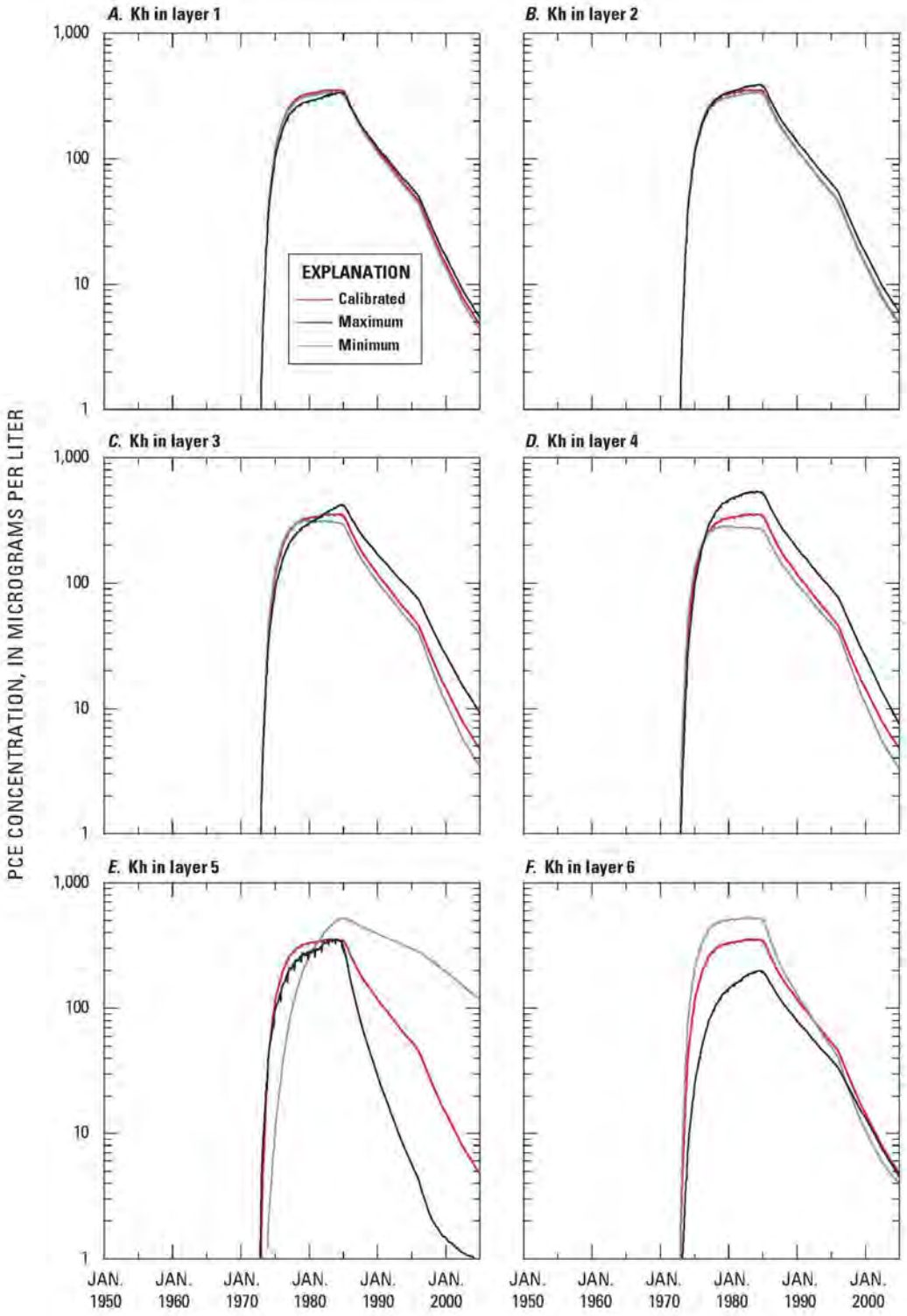

Figure S6.2.1. Tetrachloroethylene (PCE) concentrations at well HP-651 for calibrated value and minimum and maximum calibration-constrained values of K_h in *(A)* layer 1, *(B)* layer 2, *(C)* layer 3, *(D)* layer 4, *(E)* layer 5, and *(E)* layer 6, Hadnot Point landfill area fate and transport model, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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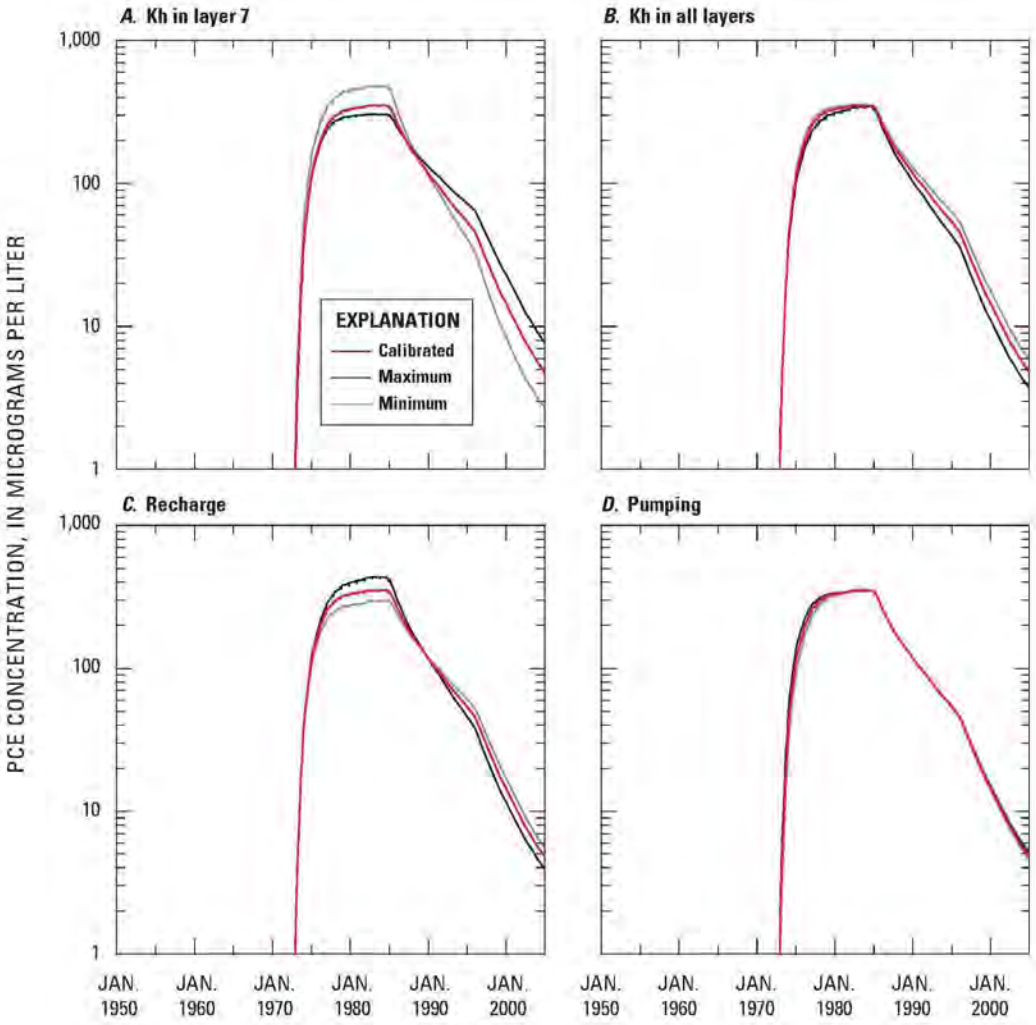

Figure S6.2.2. Tetrachloroethylene (PCE) concentrations at well HP-651 for calibrated value and minimum and maximum calibration-constrained values of *(A)* K_h in layer 7, *(B)* K_h in all layers, *(C)* recharge, and *(D)* water-supply well pumping, Hadnot Point landfill area fate and transport model, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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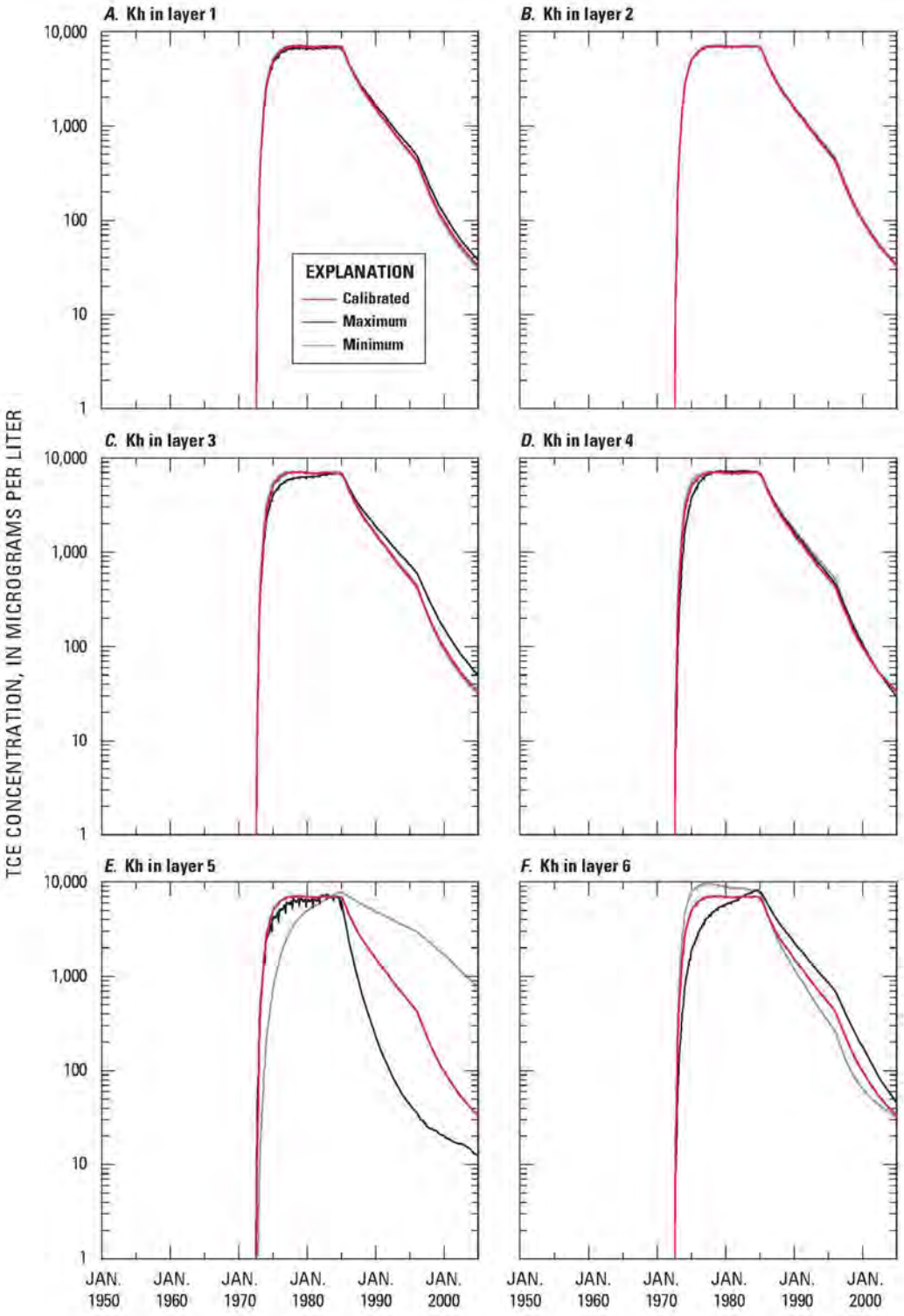

Figure S6.2.3. Trichloroethylene (TCE) concentrations at well HP-651 for calibrated value and minimum and maximum calibration-constrained values of K_h in *(A)* layer 1, *(B)* layer 2, *(C)* layer 3, *(D)* layer 4, *(E)* layer 5, and *(E)* layer 6, Hadnot Point landfill area fate and transport model, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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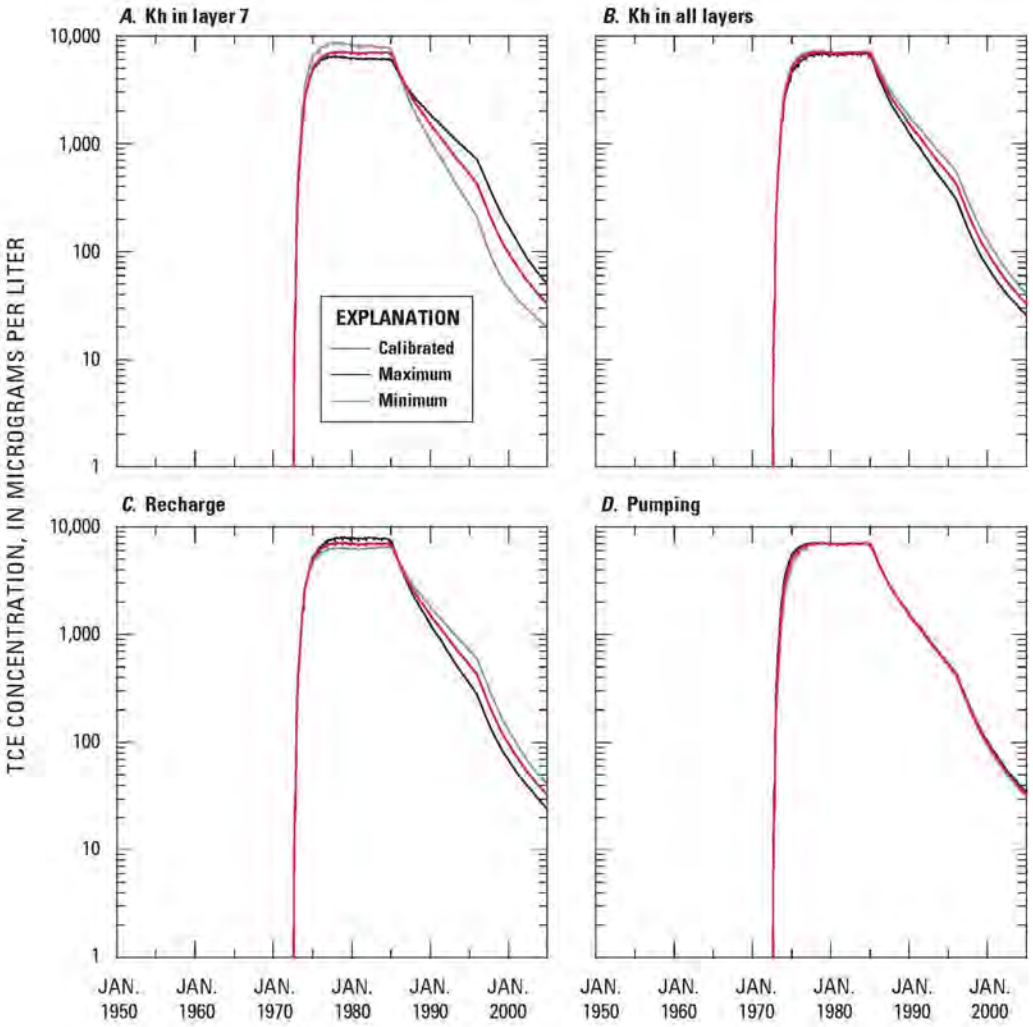

Figure S6.2.4. Trichloroethylene (TCE) concentrations at well HP-651 for calibrated value and minimum and maximum calibration-constrained values of *(A)* K_h in layer 7, *(B)* K_h in all layers, *(C)* recharge, and *(D)* water-supply well pumping, Hadnot Point landfill area fate and transport model, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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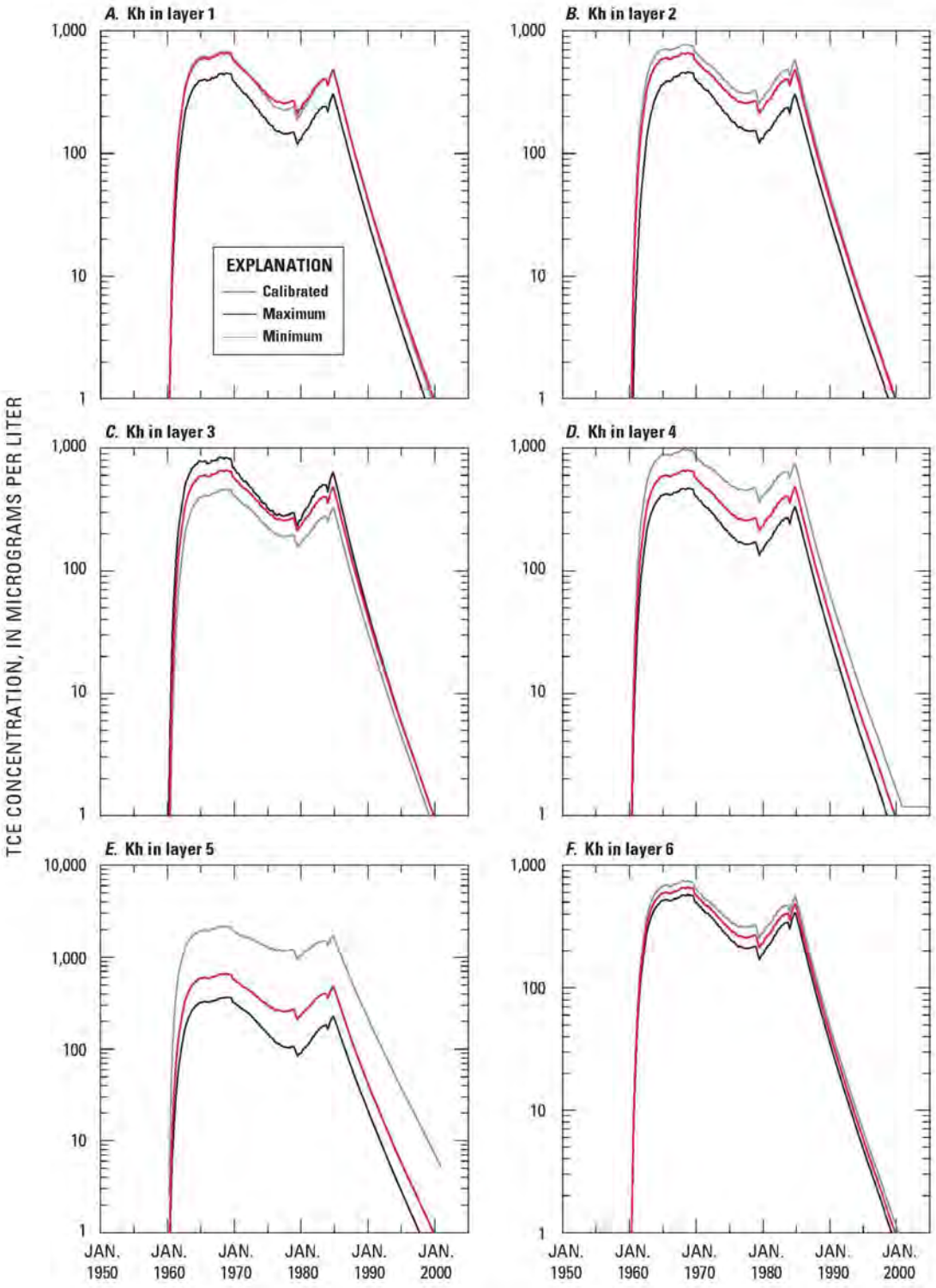

Figure S6.2.5. Trichloroethylene (TCE) concentrations at well HP-634 for calibrated value and minimum and maximum calibration-constrained values of K_h in *(A)* layer 1, *(B)* layer 2, *(C)* layer 3, *(D)* layer 4, *(E)* layer 5, and *(F)* layer 6, Hadnot Point landfill area fate and transport model, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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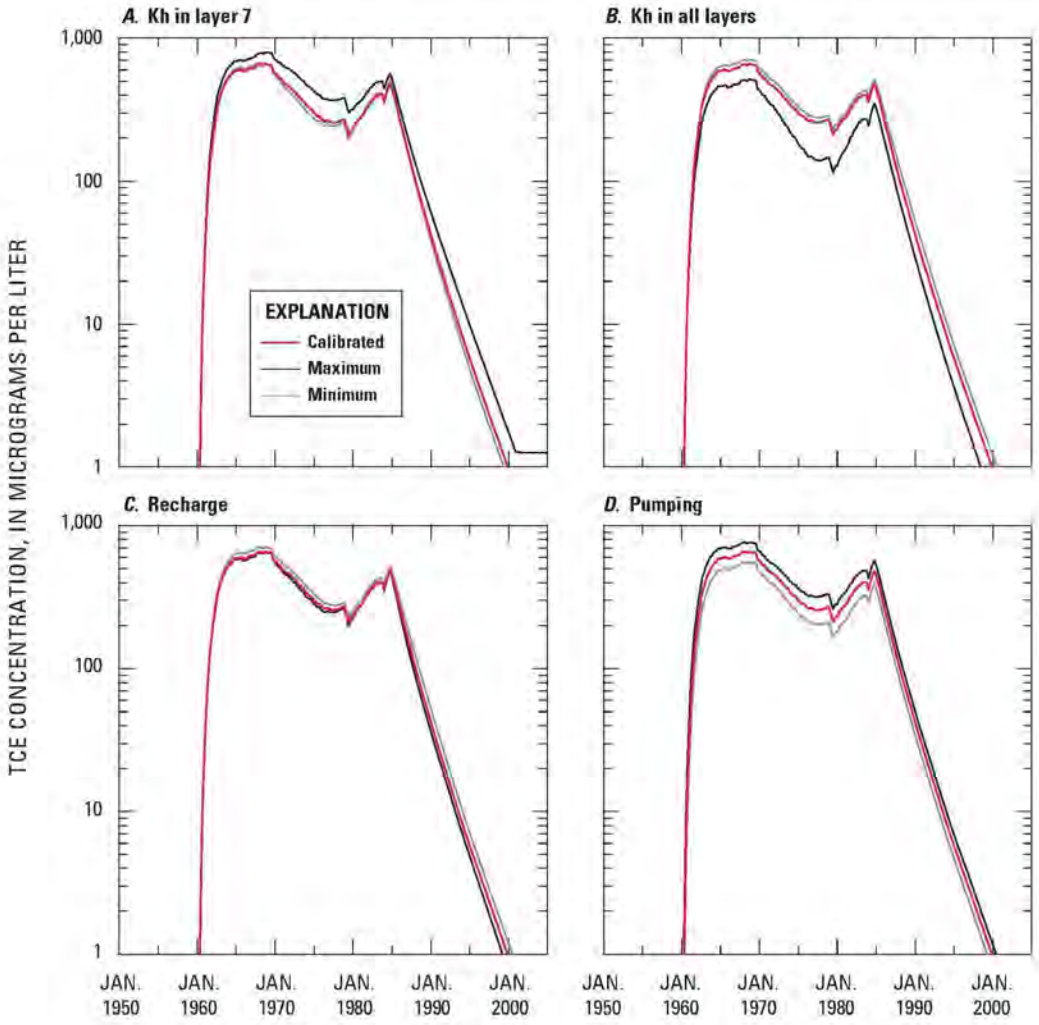

Figure S6.2.6. Trichloroethylene (TCE) concentrations at well HP-634 for calibrated value and minimum and maximum calibration-constrained values of *(A)* K_h in layer 7, *(B)* K_h in all layers, *(C)* recharge, and *(D)* water-supply well pumping, Hadnot Point landfill area fate and transport model, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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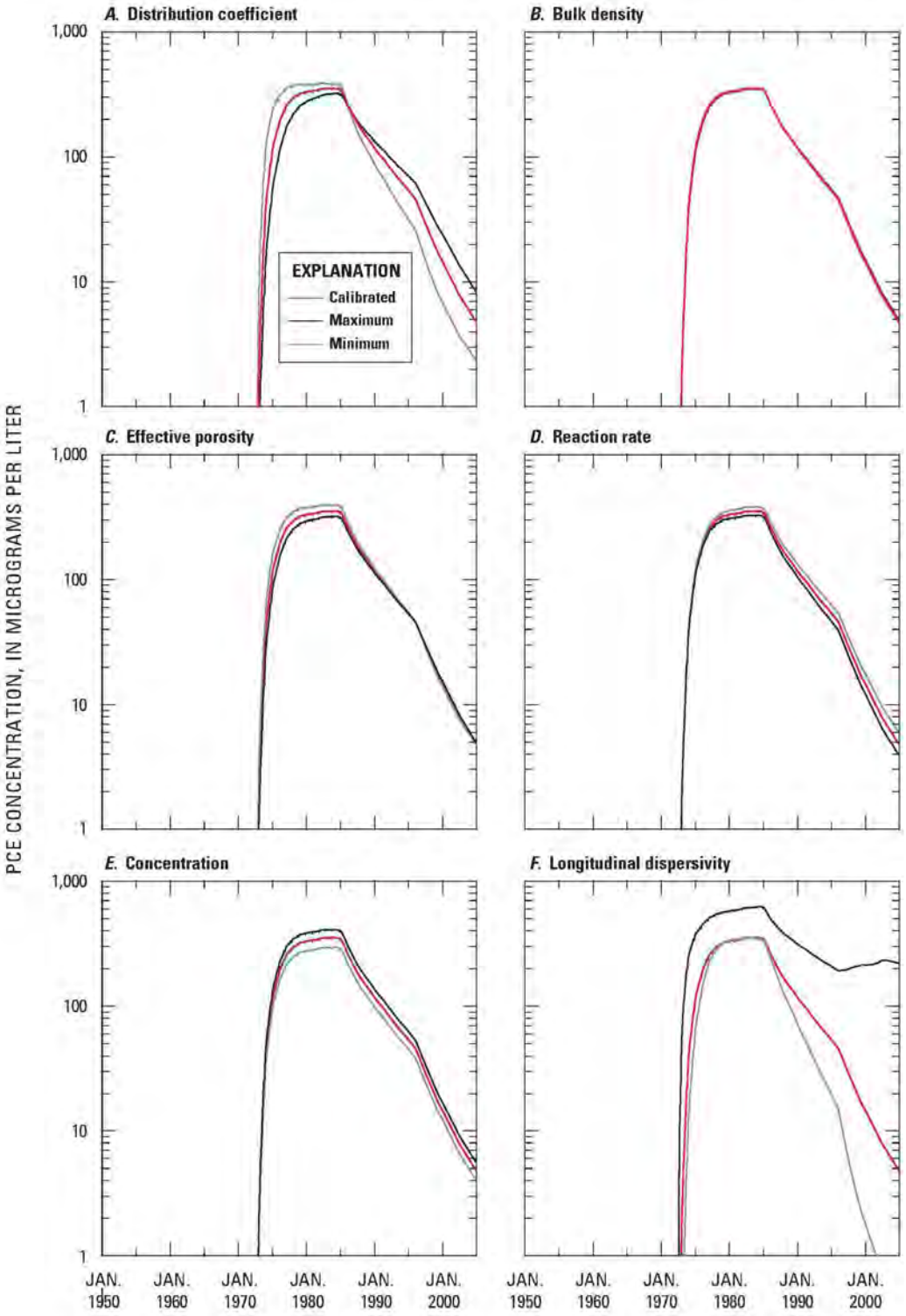

Figure S6.2.7. Tetrachloroethylene (PCE) concentrations at well HP-651 for calibrated value and minimum and maximum values of *(A)* distribution coefficient, K_d; *(B)* bulk density, ρ_b; *(C)* effective porosity, n_E; *(D)* reaction rate, r; *(E)* concentration, C; and *(F)* longitudinal dispersivity, α_L; Hadnot Point landfill area fate and transport model, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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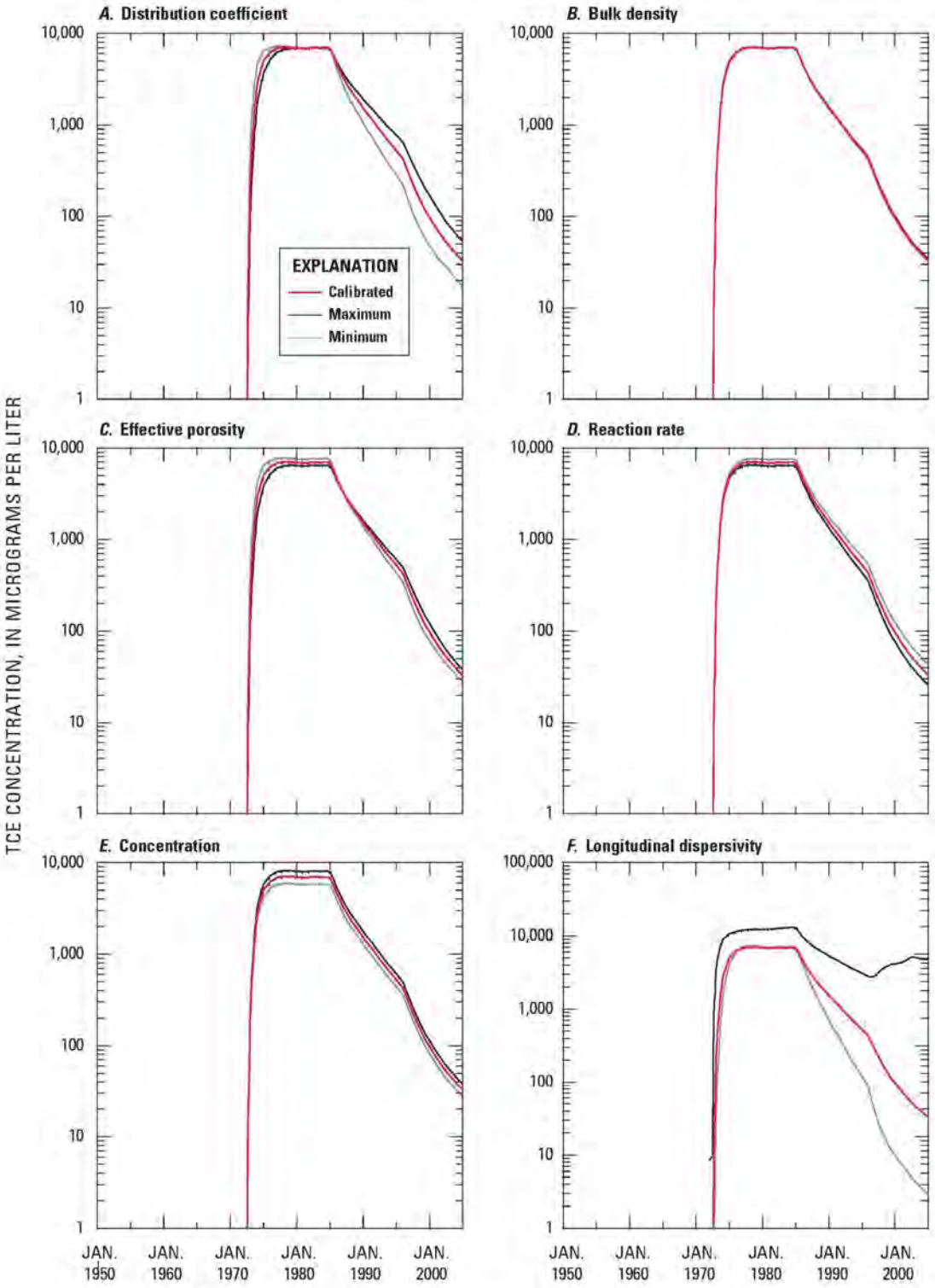

Figure S6.2.8. Trichloroethylene (TCE) concentrations at well HP-651 for calibrated value and minimum and maximum values of *(A)* distribution coefficient, K_d; *(B)* bulk density, ρ_b; *(C)* effective porosity, n_E; *(D)* reaction rate, r; *(E)* concentration, C; and *(F)* longitudinal dispersivitiy, α_L; Hadnot Point landfill area fate and transport model, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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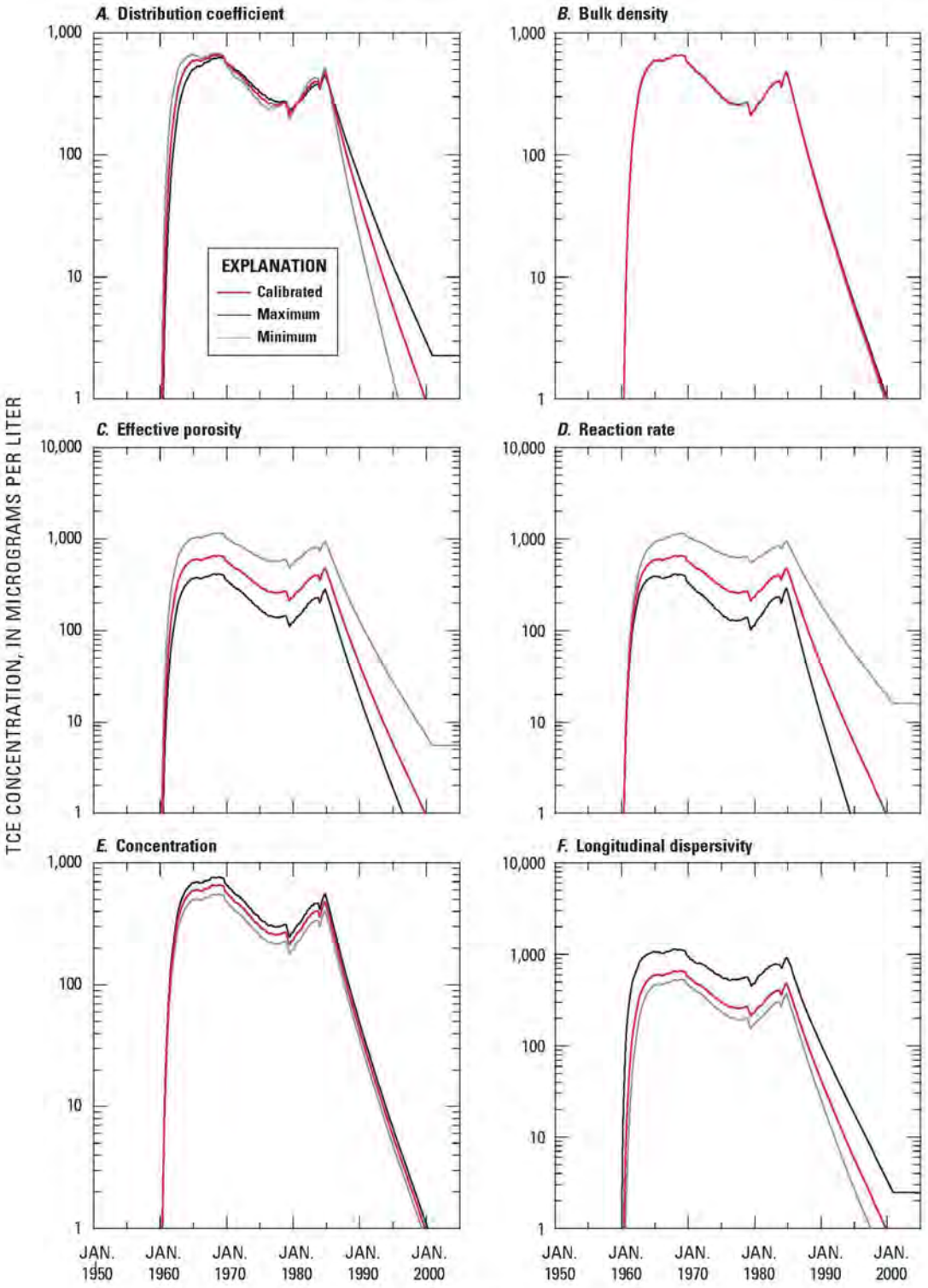

Figure S6.2.9. Trichloroethylene (TCE) concentrations at well HP-634 for calibrated value and minimum and maximum values of *(A)* distribution coefficient, K_d; *(B)* bulk density, ρ_b; *(C)* effective porosity, n_E; *(D)* reaction rate, r; *(E)* concentration, C; and *(F)* longitudinal dispersivity, α_L; Hadnot Point landfill area fate and transport model, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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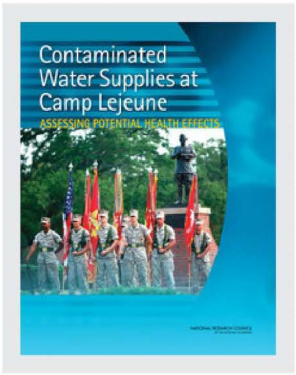

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[1]This study was planned, overseen, and supported by the Board on Environmental Studies and Toxicology.

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Preface

Two water-supply systems on the Marine Corps Base Camp Lejeune in North Carolina were contaminated with the industrial solvents trichloroethylene (TCE) and perchloroethylene (PCE). The contamination appears to have begun in the middle 1950s and continued until the middle 1980s, when contaminated supply wells were shut down. The sources of the contamination were an off-base dry-cleaning establishment and on-base industrial activities. Contaminated water was distributed to enlisted-personnel family housing, barracks for unmarried personnel, base administrative offices, schools, a hospital, industrial areas, and recreational areas.

Many former residents and employees of the base have raised questions about whether health problems that they or members of their families have experienced could be related to their exposure to the contaminated water. A few studies have been performed on former residents of the bases, but they were focused only on selected birth and childhood health outcomes. As directed by Congress, the U.S. Navy requested a study by the National Research Council to review the scientific evidence on associations between historical data on prenatal, childhood, and adult exposures to contaminated water at Camp Lejeune and adverse health effects.

In response to the Navy's request, the National Research Council convened the Committee on Contaminated Drinking Water at Camp Lejeune, which prepared this report. The members of the committee were selected for their expertise in epidemiology, toxicology, exposure analysis, environmental health, groundwater modeling, biostatistics, and risk assessment (see Appendix A for biographic information on the members).

To help the committee in its review, meetings were held in September and November 2007 and September 2008 to gather information from scientists and those who chose to inform the committee regarding their experiences in relation to the water contamination at Camp Lejeune. The committee is grateful to the people who gave presentations on their investigations into the contamination of the water supplies at Camp Lejeune and on general issues related to groundwater modeling, including a series of responses to followup queries from members of the committee: Frank Bove and Morris Maslia, of the Agency for Toxic Substances and Disease Registry (ATSDR); Richard Clapp, of Boston University and a member of ATSDR's community-assistance panel; Marcia Crosse, of the U.S. Government Accountability Office; and Mary Hill, of the U.S. Geological Survey. The committee also thanks the many former residents of and workers at Camp Lejeune who contributed their time to attend the public meetings and share their experiences and concerns (see Appendix B). In particular, the committee acknowledges Jerry Ensminger and Jeff Byron, who served as representatives of people who were unable to attend the meetings. The committee is thankful for the useful input from Amy Kyle, of the University of California at Berkeley, in the early deliberations of this study. It would also like to acknowledge the advice that it received from Michael Luster, formerly with the National Institute for Occupational Safety and Health, who was a consultant to the committee on immunotoxicity issues.

The U.S. Marine Corps provided the committee with support throughout the study. Kelly Dreyer and Scott Williams helped to coordinate a meeting at Camp Lejeune and responded to the committee's requests for background information. The committee is grateful to the staff of the Installation and Environment Department at Camp Lejeune for providing a guided tour of the areas of the base where the sup-

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ply wells and water-treatment plants were and of the residential and work areas that were served by the contaminated water systems.

This report has been reviewed in draft form by persons chosen for their diverse perspectives and technical expertise in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of the independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards of objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We thank the following for their review of this report: John L. Adgate, University of Minnesota; Mary P. Anderson, University of Wisconsin; Richard Clapp, Boston University; Mary C. Hill, U.S. Geological Survey; Margot Krauss, consultant; Lawrence H. Lash, Wayne State University; Rosalind A. Schoof, Integral Consulting, Inc.; Michael A. Stoto, Georgetown University; Clifford Weisel, University of Medicine and Dentistry of New Jersey; and Raymand S. Yang, Colorado State University.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of the report was overseen by the review coordinator, George M. Rusch, Honeywell Inc., and the review monitor, George M. Hornberger, Vanderbilt University. Appointed by the National Research Council, they were responsible for making certain that an independent examination of the report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of the report rests entirely with the author committee and the institution.

The committee is grateful for the assistance of National Research Council staff in preparing the report. In particular, Susan Martel, who served as project director, skillfully coordinated the project and contributed to the committee's report, devoting patient, concerted effort to resolving the many controversies that evolved through the course of the project. Other staff members who contributed are James Reisa, director of the Board on Environmental Studies and Toxicology; Norman Grossblatt, senior editor; Mirsada Karalic-Loncarevic, manager of the Technical Information Center; Tamara Dawson, program associate; and Patrick Baur, research assistant.

The committee members devoted substantial effort to the development of this report through rounds of discussion, deliberation, writing, and rewriting. They came to their task with a wide variety of perspectives based on disciplinary training, research pertaining to the chemicals and health effects of concern, and ideology; but all shared a commitment to bring the best knowledge possible to bear on important health issues and to assist the sponsor and former Camp Lejeune residents by offering an assessment and a scientific perspective that can help to bring this long-standing and sometimes contentious concern closer to a resolution.

This report focuses on what scientific evidence can say about the causal relationship of past exposures and health outcomes. It is important to understand the difference between how scientific evidence is used in this context, compared to how it is used in the context of regulatory risk assessment and prevention. We should be clear that the evaluation we conducted was not for the purposes of regulatory risk assessment, and the prepublication version of this report may not have made this distinction clear enough to all readers. The following excerpt from the 2003 Institute of Medicine report, *Gulf War and Health Volume 2* provides a useful explanation of this important distinction.[2]

> *Most laws enforced by regulatory agencies permit the agencies wide latitude in the choice of data used to prevent future disease or injury. In the present case, however, the goal is not prevention of risk, but rather the use of the best available data to categorize evidence for a relationship between a chemical exposure and the occurrence of an adverse health outcome in humans. Here, precautionary policies have no substantial role (at least not the same way that they have in regu-*

[2]This paragraph was added after the release of the prepublication to clarify an issue that confused some readers of the prepublication.

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lation). Therefore, studies in human populations played the dominant role for the committee in identifying the relevant associations. Experimental evidence may or may not provide support for epidemiologic conclusions.

David A. Savitz, *Chair*
Committee on Contaminated Drinking Water
at Camp Lejeune

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Abbreviations

ALL	acute lymphocytic leukemia
ALS	amyotrophic lateral sclerosis
ATSDR	Agency for Toxic Substances and Disease Registry
AWWA	American Water Works Association
BMI	body-mass index
BTEX	benzene, toluene, ethylbenzene, and xylene
CHAMPS	Naval Health Research Center's Career History Archival Medical and Personnel System
CI	confidence interval
CLW	Camp Lejeune water
CNS	central nervous system
CYP	cytochrome P-450
DCA	dichloroacetic acid
DCE	dichloroethylene
DCVC	*S*-(1,2-dichlorovinyl)-L-cysteine
DCVCS	DCVC sulfoxide
DCVG	*S*-(1,2-dichlorovinyl)glutathione
DCVT	*S*-(1,2-dichlorovinyl)thiol
DEP	Department of Environmental Protection
DNAPL	dense nonaqueous-phase liquid
DOD	U.S. Department of Defense
DP	dipeptidase
EEG	electroencephalograpic
EPA	U.S. Environmental Protection Agency
FMO3	flavin-containing monooxygenase 3
GAO	U.S. Government Accountability Office
GIS	geographic information system
GST	glutathione *S*-transferase
IARC	International Agency for Research on Cancer
IFN-γ	interferon gamma
IL-4	interleukin-4
ILO	International Labor Organization
IOM	Institute of Medicine
JEM	job-exposure matrix
LBW	low birth weight
LMP	last menstrual period
LOAEL	lowest-observed-adverse-effect level
MC	methylene chloride
MCAS	Marine Corps Air Station
MCL	maximum contaminant level

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MCLG	maximum contaminant level goal
MOR	mortality odds ratio
MS	multiple sclerosis
NCDNRCD	North Carolina Department of Natural Resources and Community Development
ND	not detected
NHL	non-Hodgkin lymphoma
NOAEL	no-observed-adverse-effect level
NR	not reported
NRC	National Research Council
NTP	National Toxicology Program
OR	odds ratio
OU	operable unit
PAH	polycyclic aromatic hydrocarbon
PCE	perchloroethylene
PDD	personal delivered dose
PPARα	peroxisome-proliferator-activated receptor alpha
PPT	parts per trillion
PSOpS	Pumping Schedule Optimization System
PVC	polyvinyl chloride
RDD	relative delivered dose
RI	remedial investigation
RR	relative risk
SES	socioeconomic status
SGA	small for gestational age
SIR	standardized incidence ratio
SLE	systemic lupus erythematosus
SMR	standardized mortality ratio
SRR	standardized rate ratio
SSFL	Santa Susana Field Laboratory
STROBE	strengthening the reporting of observational studies in epidemiology
SVOC	semivolatile organic compound
TAL	target analyte list
TCA	trichloroacetic acid
TCE	trichloroethylene
TCE-O-CYP	trichloroethylene-oxide-cytochrome P-450 complex
TCL	target compound list
TCOG	trichloroethanol glucuronide
TCOH	trichloroethanol
TCVC	*S*-(1,2,2-trichlorovinyl)-L-cysteine
TCVCS	*S*-(1,2,2-trichlorovinyl)-L-cysteine sulfoxide
TCVG	*S*-(1,2,2-trichlorovinyl) glutathione
TLBW	term low birth weight
UST	underground storage tank
VA	Department of Veterans Affairs
VC	vinyl chloride
VHL	von Hippel-Landau
VLBW	very low birth weight
VOC	volatile organic compound

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BOXES, FIGURES, AND TABLES

BOXES

FIGURES

TABLES

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Contaminated Water Supplies at Camp Lejeune

ASSESSING POTENTIAL HEALTH EFFECTS

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Public Summary and Context

In the early 1980s, two water-supply systems on the Marine Corps Base Camp Lejeune in North Carolina were found to be contaminated with the industrial solvents trichloroethylene (TCE) and perchloroethylene (PCE). The water systems were supplied by the Tarawa Terrace and Hadnot Point water-treatment plants, which served enlisted-family housing, barracks for unmarried service personnel, base administrative offices, schools, and recreational areas. The Hadnot Point water system also served the base hospital and an industrial area and supplied water to housing on the Holcomb Boulevard water system (full-time until 1972 and periodically thereafter).

This report examines what is known about the contamination of the water supplies at Camp Lejeune and whether the contamination can be linked to any adverse health outcomes in former residents and workers at the base. Because of the technical nature of the report, this public summary is being provided to explain the committee's approach and reasoning, so that people who are not scientists can understand what was done and why. It attempts to place the committee's analysis and findings into the context of a larger discussion about environmental health issues at Camp Lejeune in a way that will be helpful to people who have personal concerns about the situation at the base. It also provides perspective on why the committee was unable to answer some questions.

THE CHARGE TO THE COMMITTEE

The National Research Council (NRC) conducted this review in response to a request from the U.S. Navy, the department under which the Marine Corps operates. The Navy was mandated by the U.S. Congress (Public Law 109-364, Section 318) to request a review by the NRC to address the evidence on whether adverse health outcomes are associated with past contamination of the water supply at Camp Lejeune. The NRC developed specific instructions for the scope of the review ("the charge"). It then recruited and appointed a committee of scientists with diverse but pertinent backgrounds and perspectives to carry out the review.

The charge had several elements. One was to review the scientific evidence about the kinds of adverse health effects that could occur after exposure to TCE, PCE, and other contaminants. The second was to evaluate studies that were performed or that are under way on former residents of the base and to consider how useful it will be to conduct additional studies. The third element was to identify scientific considerations that could help the Navy set priorities on future activities. The responsibility of the committee was to address its charge in a dispassionate, expert, and unbiased way. Analyses and findings were neither subject to oversight nor influenced by the agenda of any of the entities with responsibilities for Camp Lejeune, former or current residents of Camp Lejeune, or any other entity.

THE CONCERNS OF FORMER RESIDENTS AND WORKERS

The committee held three public meetings over the course of its study, two in Washington, DC (September 24, 2007, and September 12, 2008) and one in Camp Lejeune, NC (November 15, 2007). Former residents and other concerned individuals presented oral and written testimonies about their experiences at Camp Lejeune at those meetings. The committee also sought comments from consultants

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working with community groups seeking answers to questions about the water contamination. Although these encounters were not exhaustive in identifying all issues of concern or all perspectives, they gave the committee a chance to hear firsthand from people who have concerns. The committee sincerely appreciates the time and effort that went into the presentations, testimonies, and materials that were provided.

On the basis of the public input, the committee understands that some people believe that the Marine Corps has not responded appropriately to the contamination since it was first discovered. Some believe that the military leadership has not been fully forthcoming in providing data and information about the contamination and about the people who lived in affected areas. Some have concerns about whether information was disclosed or released in timely and appropriate ways. Questions have also been raised about the pace at which investigations have been conducted and whether the investigations are the most appropriate ones. Many expressed an interest in an unbiased and credible review.

Many of the people who addressed the committee have suffered from serious diseases or have family members or friends who have suffered. The committee was moved by the testimonies it heard and understands that some may have been looking for the committee to make a judgment on their particular case. However, science does not allow the committee to determine the cause of a specific case of disease. This may be hard to understand. Why would scientific experts not be able to determine whether a child's birth defect or a parent's cancer diagnosis was due to a chemical exposure? Unfortunately, for diseases that can have multiple causes and that develop over a long period of time, it is generally impossible to establish definitively the cause in individual cases. It was beyond the scope of the committee's charge to try to determine whether any particular case of a disease or disorder is associated with exposure to the water supply at Camp Lejeune.

Some parties contend that the Marine Corps has not done what it should to compensate them or to provide medical care for the harm they believe was caused by their exposure to the contaminated water supplies. In 2007, the U.S. Government Accountability Office (GAO) reported that former residents and employees of Camp Lejeune had filed more than 750 claims against the federal government related to the contamination. GAO also reports that the federal government is awaiting the results of a study on childhood cancers and birth defects before adjudicating claims. It was beyond the scope of the committee's charge to judge whether the military authorities acted appropriately from a legal or ethical perspective or fulfilled their responsibilities to those under their charge. It was also beyond the scope of the committee's charge to determine whether or how the military authorities should address claims made.

THE COMMITTEE'S REVIEW AND FINDINGS

The committee divided its review into two major categories: (1) evaluating the exposures of former residents and workers to the contamination of the Tarawa Terrace and Hadnot Point water-supply systems, and (2) evaluating the potential health effects associated with the water contaminants. The assessments were then considered together to ascertain whether conclusions could be drawn about whether any adverse health outcomes could be attributed to the water contaminants.

Exposures to Former Residents and Workers

The term "exposure" refers to contact with contaminants in air, water, or food that may occur through inhalation, ingestion, or dermal absorption (through the skin). In this case, it refers to drinking water that contains contaminants or using it for other purposes. Bathing and showering are relevant, as well as drinking, because TCE and PCE (and other solvents) can evaporate into the air (volatilize) when present in hot water used for bathing, showering, or washing dishes or clothing and can then be inhaled. All of these routes of exposure affect how the body metabolizes TCE and PCE, how the metabolites are distributed and cleared by the body, and how organ systems respond.

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It is also important to understand the duration of exposure, which is the length of time a person is exposed. An understanding of individual behaviors helps to estimate the degree of exposure that occurred. Water-related behaviors include water-consumption and showering or bathing patterns, but whether such information can be accurately recalled is questionable. The contaminated water systems also supplied nonresidential areas of the base, including schools, workplaces, recreational areas, and a hospital. Water-use patterns and behaviors in these settings are expected to vary substantially from those in residential areas. In addition, residential and nonresidential exposures could overlap, thus, exposing dividuals to contaminated water at multiple locations.

The Water Systems at Camp Lejuene

Figure 1 provides a simplified illustration of a water-supply system at Camp Lejeune. Water-supply wells collected groundwater and pumped it to a water-treatment plant when the wells were turned on. The wells were "cycled," meaning that only a few wells pumped water to the treatment plant at any given time. A few wells that supplied water to the Tarawa Terrace and Hadnot Point systems were contaminated by solvents from sources on and off the base. When the contaminated wells were in service, contaminated water was delivered to the water-treatment plant where water from several wells was mixed and processed before being distributed in the pipes that supplied water to the base. Thus, the contamination of the water supplies varied and was dependent on many factors, such as the time of operation of the contaminated wells, the water treatments used, and the rate at which water was supplied to the base.

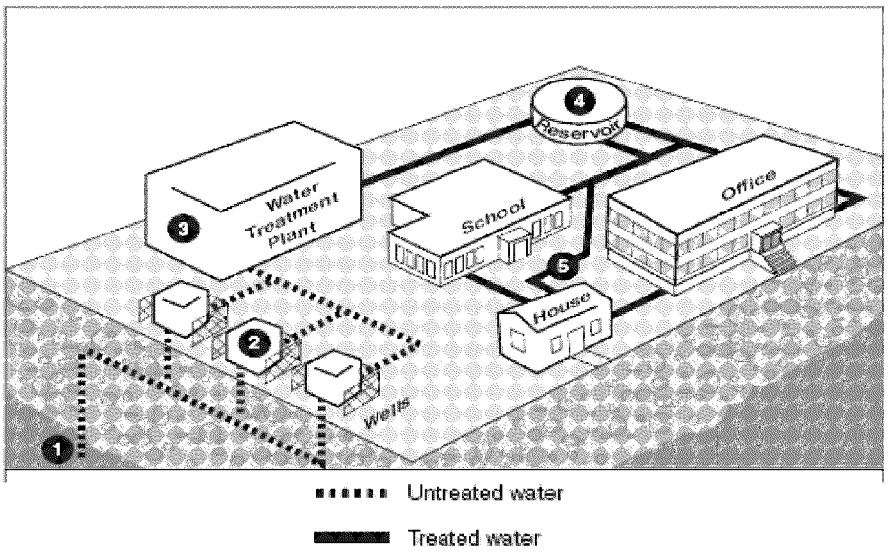

FIGURE 1 Conceptual model of a Camp Lejeune water system. (1) The drinking water at Camp Lejeune is obtained from groundwater pumped from a freshwater aquifer located approximately 180 feet below the ground. (2) Groundwater is pumped through wells located near the water-treatment plant. (3) In the water-treatment plant, the untreated water is mixed and treated through several processes: removal of minerals to soften the water, filtration through layers of sand and carbon to remove particles, chlorination to protect against microbial contamination, and fluoride addition to help to prevent tooth decay. (4) After the water is treated, it is stored in ground and elevated storage reservoirs. (5) When needed, treated water is pumped from the reservoirs and tanks to facilities such as offices, schools, or houses on the base. Source: GAO. 2007. Defense Health Care: Activities Related to Past Drinking Water Contamination at Marine Corps Base Camp Lejeune. GAO-07-276. Washington, DC: U.S. Government Accountability Office.

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Exposure Review

The committee's exposure evaluation involved identifying the contaminants of concern, their sources, and the concentrations estimated to be present in the water supplies over time. For Tarawa Terrace, the committee relied on work by the Agency for Toxic Substances and Disease Registry (ATSDR). ATSDR compiled the available information on the Tarawa Terrace water system and used computer models to simulate how contaminants moved underground, entered water-supply wells, and were distributed in the water supply. Contaminant measurements were only available from 1980 to 1985, so models were needed to make estimates of the concentrations of contaminants in the water supply in the preceding decades.

A similar historical reconstruction has not yet been performed for the Hadnot Point water system. To identify contaminants of concern there, the committee reviewed information on historical activities on the base (for example, building and chemical uses and sites of hazardous-waste storage or disposal) and findings from site investigations and plans for remedial action at waste sites. The committee also reviewed data available from testing records and other documents to get a preliminary characterization of the exposures that occurred. For some of its analyses, the committee focused on samples taken from "mixed water," that is, water mixed from several supply wells at the treatment plant, because those measurements were probably the most representative of the contaminant concentrations that were delivered to the taps on base. As was the case with Tarawa Terrace, contaminant measurements of the Hadnot Point system were only available from 1980 to 1985.

The major contaminants of the Tarawa Terrace and Hadnot Point systems are of a particular form that tends to serve as a continuing source of contamination even after the contaminants are underground. These are called "DNAPLs," which stands for dense nonaqueous phase liquids. DNAPLs are dense, so they have the potential to sink into the deeper aquifers. Such chemicals get trapped in the soil and dissolve slowly into groundwater. The geology of the area makes it probable that DNAPLs that were spilled on the ground or that were leaked or disposed of in the soil got into the groundwater that supplied some of the wells of the two systems.

The dry-cleaning solvent PCE is the primary contaminant of the Tarawa Terrace water-supply system. Spills and improper disposal of PCE by an off-base dry-cleaner contaminated the groundwater collected by on-base supply wells. Other contaminants detected in water-supply wells were TCE, 1,1-dichloroethylene (DCE), *cis*-1,2-DCE, *trans*-1,2-DCE, benzene, toluene, and vinyl chloride. Several of the contaminants (TCE, *cis*-1,2-DCE, *trans*-1,2-DCE, and vinyl chloride) may be the result of degradation of PCE in the soil and groundwater. There was some on-base contamination of the Tarawa Terrace supply system as well.

Sophisticated computer modeling techniques were used by ATSDR to make predictions about the monthly concentrations of PCE to which residents of Tarawa Terrace were exposed. To provide perspective on its estimates, ATSDR compared its monthly estimates with the U.S. Environmental Protection Agency (EPA) maximum contaminant level (MCL) for PCE in drinking water of 5 µg/L, which was established in 1985. The model estimated that starting in November 1957, the concentration of PCE delivered to residents exceeded that MCL and remained well above it until the wells were closed in 1985.

Some of the modeling approaches used by ATSDR were "cutting-edge," meaning that they used computer codes and modeling techniques that are still in the research stage and have yet to be validated. Furthermore, the absence of measurement data for the first 30 years of the contamination period means the predictions, even if based on validated codes and models, cannot be evaluated for accuracy. The actual concentrations may have been higher or lower than the predictions, but that cannot be assessed. Other uncertainties were introduced into the models because assumptions had to be made about how the water system was operating. For example, little information was available on which wells were supplying water at specific time periods, so assumptions had to be made about when the contaminated wells were operating. Another uncertainty is that the models did not take into account the DNAPL form of pollutants. Given the multiple uncertainties and likely variation in contaminant concentrations, the committee con-

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cluded that the Tarawa Terrace modeling predictions should only be used to provide a general estimate of the timeframe and magnitude of exposure.

The contamination of the Hadnot Point system was more complex than Tarawa Terrace. There were multiple sources of pollutants, including an industrial area, a drum dump, a transformer storage lot, an industrial fly ash dump, an open storage pit, a former fire training area, a site of a former on-base dry cleaner, a liquids disposal area, a former burn dump, a fuel-tank sludge area, and the site of the original base dump. The available data on contaminant measurements taken in the 1980s show that TCE and *trans*-1,2-DCE were the contaminants found most often in mixed-water samples, with a few detections of PCE, methylene chloride, and vinyl chloride. The nature of the hazardous-waste sites in the vicinity of the Hadnot Point supply wells suggests that other contaminants may have been present. For example, tests of samples taken from special monitoring wells installed after the contamination was discovered have detected fuel constituents and metals, compounds that were not routinely analyzed in the water samples taken in the 1980s.

Recommendations

- For the purposes of epidemiologic studies, the results of the Tarawa Terrace historical reconstruction can be used to characterize people as being exposed or unexposed on the basis of date and location of residence or workplace. The monthly estimates imply more accuracy than is appropriate and should not be used to characterize exposure of individual people.
- Because any groundwater modeling of the Hadnot Point system will be fraught with considerable difficulties and uncertainties, simpler modeling approaches should be used to assess exposures from the Hadnot Point water system. Simpler modeling will not reduce the uncertainty associated with the estimates, but they have the advantage of providing a broad picture of the timeframe and magnitude of exposure encountered by people who used water from that system more quickly and with less resources than complex modeling exercises.
- To facilitate better understanding of the contamination on the base, the Marine Corps should develop a comprehensive and accessible database of water-quality measurements taken from the base.

Potential Health Effects

The committee undertook four kinds of reviews to determine what kinds of diseases or disorders (adverse health effects) have been found to result from exposure to TCE and PCE: (1) review of epidemiologic studies of solvents and their effects, including studies in occupational and industrial settings and community studies; (2) review of epidemiologic studies of other communities with solvent-contaminated water supplies; (3) review of toxicologicstudies conducted in animals and humans to test for health effects of TCE and PCE; and (4) review of studies conducted specifically on the Camp Lejeune population.

Review of Epidemiologic Evidence on Solvents

Epidemiologic studies examine whether people with greater exposure to particular chemicals have greater frequency of disease than people with lesser or no exposure (also referred to as greater incidence or greater risk of disease). To manage the review of the vast amount of peer-reviewed scientific literature on TCE and PCE, the committee began with a comprehensive review of the epidemiologic studies of those solvents that was conducted by the Institute of Medicine (IOM) in 2003. IOM categorized the evidence according to an established scheme accepted by the Department of Veteran's Affairs in evaluating risks to veterans of the Vietnam War and the Gulf War. These categories are shown in Box 1. The

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BOX 1 Five Categories Used by IOM to Classify Associations

Sufficient Evidence of a Causal Relationship

Evidence from available studies is sufficient to conclude that a causal relationship exists between exposure to a specific agent and a specific health outcome in humans, and the evidence is supported by experimental data. The evidence fulfills the guidelines for sufficient evidence of an association (below) and satisfies several of the guidelines used to assess causality: strength of association, dose-response relationship, consistency of association, biologic plausibility, and a temporal relationship.

Sufficient Evidence of an Association

Evidence from available studies is sufficient to conclude that there is a positive association. A consistent positive association has been observed between exposure to a specific agent and a specific health outcome in human studies in which chance and bias, including confounding, could be ruled out with reasonable confidence. For example, several high-quality studies report consistent positive associations, and the studies are sufficiently free of bias, including adequate control for confounding.

Limited/Suggestive Evidence of an Association

Evidence from available studies suggests an association between exposure to a specific agent and a specific health outcome in human studies, but the body of evidence is limited by the inability to rule out chance and bias, including confounding, with confidence. For example, at least one high-quality study reports a positive association that is sufficiently free of bias, including adequate control for confounding. Other corroborating studies provide support for the association, but they were not sufficiently free of bias, including confounding. Alternatively, several studies of less quality show consistent positive associations, and the results are probably not due to bias, including confounding.

Inadequate/Insufficient Evidence to Determine Whether an Association Exists

Evidence from available studies is of insufficient quantity, quality, or consistency to permit a conclusion regarding the existence of an association between exposure to a specific agent and a specific health outcome in humans.

Limited/Suggestive Evidence of No Association

Evidence from well-conducted studies is consistent in not showing a positive association between exposure to a specific agent and a specific health outcome after exposure of any magnitude. A conclusion of no association is inevitably limited to the conditions, magnitudes of exposure, and length of observation in the available studies. The possibility of a very small increase in risk after exposure studied cannot be excluded.

Source: IOM (Institute of Medicine). 2003. Gulf War and Health, Vol. 2, Insecticides and Solvents. Washington, DC: National Academies Press.

committee identified new studies published from 2003 to 2008 and considered whether they changed the conclusions in the IOM report. The studies included people exposed in occupational situations and in community settings.

IOM's approach to evaluating the literature is to determine whether a "statistical association" exists between the chemicals and diseases and disorders. When studies are conducted properly, a statistical association means that people who are exposed to the chemicals are more likely to have or develop the disease or disorder than people who are not exposed. A statistical association, however, does not establish

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that the chemicals cause the diseases or disorders. Judgment about the quality of each study and additional supporting evidence from other studies are needed. Statistical associations are often represented by numeric estimates, known as "relative risks" or "odds ratios." The estimates describe the relative frequency of disease in groups with higher exposures compared with groups with lower or no exposure. For example, in a study in which individuals are classified as either exposed or unexposed, a relative risk of 2 means that exposed people in the study were twice as likely to develop the disease as people who were not exposed.

As shown in Box 2, all the health outcomes reviewed were placed into one of two categories. The strongest evidence was in the category of *limited/suggestive of an association*, which means that there is some evidence that people who were exposed to TCE or PCE were more likely to have the disease or disorder but that the studies were either few in number or had important limitations. In many cases, the studies could not separate out the effects of individual chemicals because the people were exposed to mixtures. Some of these studies were of highly exposed groups of workers where detection of effects would be expected if present. Such studies might reach conclusions about solvents in general but not about TCE or PCE specifically. For diseases and disorders where the evidence is limited/suggestive of an association, the committee has concluded that the epidemiologic studies give some reason to be concerned that sufficiently high levels of the chemical may cause the disease, but the studies do not provide strong evidence that they actually do so.

The majority of the health outcomes reviewed by the committee were placed into the category of *inadequate/insufficient evidence to determine whether an association exists*, which means that the studies were too few in number, limited in quality, inconsistent, or inconclusive in results to make an informed assessment. It also means that such an association cannot be ruled out. For diseases and disorders in this category, the committee has concluded that the epidemiologic studies cannot tell us whether exposure to the chemicals is associated with the disease or not.

The committee is aware that some health outcomes reported by former residents of the base (for example, male breast cancer and second-generation effects) are not cited in Box 2. The absence of inclusion of specific health outcomes does not mean that such effects are unrelated to exposures from the contaminated water supplies at Camp Lejeune. Rather, those outcomes have not been specifically investigated or, if they were considered, the studies were too small or of insufficient quality to allow conclusions to be drawn.

Review of Epidemiologic Evidence from Community Studies

The committee decided to consider the subset of epidemiologic studies that were conducted in communities exposed to solvents in their water supplies in more detail. Because these studies involved populations and exposure situations that more closely resemble those at Camp Lejeune, some relevant implications might be learned. A few studies reported certain diseases and disorders, such as congenital heart defects, spontaneous abortions, and very low birth weight. However, the studies reported differing effects, so generally they did not confirm each other. In general, the studies had limitations in their design that are unavoidable because of the circumstances that gave rise to them. The limitations include lack of data on levels of contaminants in the water, lack of adequate information about diseases and disorders in the population, and relatively small populations. These factors limit the capacity of such studies to detect associations even if they exist. Limitations in such studies often mean that people in the study communities can only be classified into two groups to reflect exposure to contamination—those exposed and those considered unexposed. Such classification is a crude way to address exposure because it can make it more difficult to detect any effects that might occur. Another common limitation of community studies in general is that they are not able to account for other factors that may affect the likelihood of disease. Furthermore, the studies face the difficult task of addressing diseases that are relatively uncommon. It is harder to find enough cases of uncommon diseases to make comparisons when studying relatively small

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BOX 2 Categorization of Health Outcomes[a] Reviewed in Relation to TCE, PCE, or Solvent Mixtures

Sufficient Evidence of a Causal Relationship

- No outcomes

Sufficient Evidence of an Association

- No outcomes

Limited/Suggestive Evidence of an Association

- Esophageal cancer (PCE)
- Lung cancer (PCE)
- Breast cancer (PCE)
- Bladder cancer (PCE)
- Kidney cancer
- Adult leukemia (solvent mixtures)
- Multiple myeloma (solvent mixtures)
- Myleodysplasic syndromes (solvent mixtures)
- Renal toxicity (solvent mixtures)
- Hepatic steatosis (solvent mixtures)
- Female infertility (with concurrent exposure to solvent mixtures)
- Miscarriage (with exposure to PCE during pregnancy)
- Scleroderma (solvent mixtures)
- Neurobehavioral effects (solvent mixtures)

Inadequate/Insufficient Evidence to Determine Whether an Association Exists

- Oral/pharyngeal cancer
- Nasal cancer
- Laryngeal cancer
- Esophageal cancer (TCE)
- Stomach cancer
- Colon cancer
- Rectal cancer
- Pancreatic cancer
- Hepatobiliary cancer
- Lung cancer (TCE)
- Bone cancer
- Soft tissue sarcoma
- Melanoma
- Non-melanoma skin cancer
- Breast cancer (TCE)
- Cervical cancer
- Ovarian/uterine cancer
- Prostate cancer
- Bladder cancer (TCE)
- Cancer of the brain or central nervous system
- Non-Hodgkin lymphoma
- Hodgkin disease
- Multiple myeloma
- Adult leukemia
- Myelodysplasic syndromes
- Childhood leukemia
- Childhood neuroblastoma
- Childhood brain cancer
- Aplastic anemia
- Congenital malformations
- Male infertility
- Female infertility (after exposure cessation)
- Miscarriage, preterm birth, or fetal growth restriction (from maternal preconception exposure or paternal exposure)
- Preterm birth or fetal growth restriction (from exposure during pregnancy)
- Cardiovascular effects
- Liver function or risk of cirrhosis
- Gastrointestinal effects
- Renal toxicity
- Amyotrophic lateral sclerosis
- Parkinson disease
- Multiple sclerosis
- Alzheimer disease
- Long-term reduction in color discrimination
- Long-term hearing loss
- Long-term reduction in olfactory function

Limited/Suggestive Evidence of No Association

- No outcomes

[a]Outcomes for TCE and PCE unless otherwise specified.

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populations. The committee concluded that the evidence provided by this subset of epidemiologic studies needs further support and confirmation before they can be considered significant on their own.

Review of the Toxicologic Evidence

Toxicologic studies are mainly laboratory experiments, usually conducted on animals. The committee's review on TCE and PCE were in part based on previously published toxicologic reviews but were mainly based on analyses of recently published studies. The studies were analyzed using criteria for good study design and degree of agreement between the conclusions and the data presented. Further, the committee took into consideration the quality and reliability of studies, consistency of findings of similar studies, understanding of the biologic processes, toxicologic significance, dose- and duration-dependence, and understanding of whether effects observed in animals are predictive of human risks. Each chemical was reviewed for effects on the major organ systems—for example, liver, kidneys, lungs, reproductive system, nervous system, and immune system.

In animal experiments, TCE was reported to cause kidney and testicular cancers in rats and liver and lung cancers in mice. PCE was reported to cause liver cancer in mice and mononuclear cell leukemia and kidney cancer in rats. Differences in how these chemicals are handled in the body by rodents and humans, as well as current scientific understanding of how these tumors develop, led the committee to the conclusion that kidney cancer is the most relevant to humans.

For other kinds of adverse health effects, kidney toxicity and liver toxicity were observed in rodents given high doses of TCE and PCE. Effects on male rodent fertility, but not female fertility, were observed. Neither chemical caused birth defects in rats. There were some adverse effects on offspring of pregnant female rats exposed to PCE but to not TCE. Adverse changes in some nervous system measurements were seen in some TCE and PCE studies. TCE causes some effects on the immune system of sensitive strains of mice, but there are few immunotoxicity studies on PCE.

When possible, the committee identified the lowest dose of TCE or PCE at which adverse effects were observed in animal studies (the dose is called the lowest-observed-adverse-effect level or LOAEL). To put these doses in perspective, the committee did a comparison of the doses with approximated doses to former residents that were estimated from concentrations of TCE and PCE measured in mixed water.[1] Because of the known variation in contaminant concentrations, the range used for the comparison included the highest measured concentrations of TCE and PCE in mixed water, one-half those concentrations, and twice the highest measured concentrations. The adverse health effects considered for this comparison were those thought to be most relevant to humans (kidney cancer, renal toxicity, and immunosuppression for TCE, and renal toxicity and neurotoxicity for PCE). This comparison is not an assessment or prediction of risk and can only give a general indication of the degree of difference between doses that caused a response in laboratory animals and doses to former residents of Camp Lejeune. The comparison reflects estimated combined daily doses from all three routes of exposure (ingestion, inhalation, and skin contact) that could have occurred for adults and children at Camp Lejeune. Results of the comparison suggest that the highest levels of either TCE or PCE measured in the mixed-water samples at Camp Lejeune were much lower than the lowest dose that caused adverse effects in the most sensitive strains and species of laboratory animals. The lower levels of exposure may be of some concern for effects on neurotoxicity and immunotoxicity, but further research is needed to evaluate the specific effects of TCE and PCE and whether they are relevant to humans.

Consideration of the Epidemiologic and Toxicologic Evidence Together

The committee considered collectively what is known about adverse health effects that are asso-

[1]A dissenting viewpoint on the conduct of this comparison is provided in Chapter 4.

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ciated with exposure to TCE and PCE from human epidemiologic and animal toxicologic studies. Evidence on similar outcomes reported in animal and human studies were compared to see whether the data were supportive of the potential health consequences of exposure to TCE and PCE in the water supply.

Review of epidemiologic studies on cancer outcomes provided limited/suggestive evidence for an association between chronic exposure to TCE or PCE and kidney cancer and to PCE and cancers of the esophagus, lungs, breast, and bladder. For these outcomes, the toxicologic evidence was strongest for kidney cancer.

Noncancer effects that were found to be similar in humans and laboratory animals included adverse effects on the liver, kidneys, and nervous and immune systems. In the epidemiologic literature, toxic effects on the liver and kidneys appeared to be related to short-term inhalation of high concentrations of solvents as opposed to longer-term exposure at lower concentrations. Support for these effects observed in toxicologic studies come from rodents exposed to high concentrations of TCE and PCE. For kidney effects, adverse findings were only found in male rats. Epidemiologic studies of occupational exposure to mixed solvents showed limited/suggestive evidence of neurobehavioral effects, and toxicologic studies of TCE showed some decrements in neurobehavioral outcomes. For effects on the immune system, epidemiologic studies showed limited/suggestive evidence for an association with mixed solvent exposure for certain immunologically mediated diseases. Toxicologic studies also showed that TCE can affect the immune system, as shown by immunosuppression and worsening of preexisting autoimmune diseases. These findings are shown in Table 1. The absence of other diseases and disorders in the table does not mean that such outcomes are irrelevant or unworthy of study, but that the findings for them were inconsistent between the toxicologic and the epidemiologic evidence or were not addressed in the available studies.

Review of Camp Lejeune Studies

Only a few studies have been conducted on the Camp Lejeune population, and these have focused on health effects in people who were exposed as children or while their mothers were pregnant with them. One study evaluated pregnancy outcomes among women who lived in base housing from 1968 to 1985.

Although the water contamination probably began before 1968, ATSDR selected 1968 as its starting point because electronic birth certificates became available that year. ATSDR compared data on premature births, births of babies who were small relative to other babies from pregnancies of similar duration (small for gestational age), and birth weights between mothers who were exposed and those who were unexposed. Whether mothers were exposed was determined by where they lived on the base when the child was born, not taking into account whether they moved during the pregnancy. Two analyses were performed; one that evaluated residents of Hadnot Point and Tarawa Terrace and one that focused only on Tarawa Terrace residents.

In both analyses, no clear associations were found between mean birth weight, preterm birth, or small for gestational age. However, a comparison of subgroups within the Tarawa Terrace population found a weak association between PCE exposure and small-for-gestational-age births for children of women over 35 or of women who had prior miscarriages. However, a limitation of this conclusion is that the decision to perform this analysis was added after the original design of the study. It was not one of the hypotheses or theories set out before the study. Therefore, scientists give this finding less weight.

The findings from these analyses are no longer valid. After the study was completed, ATSDR discovered that that a residential area it classified as unexposed (Holcomb Boulevard) received water from the Hadnot Point system for the first 4 years of the study period, and the study results must be reanalyzed to correct for this mistake in classification. ATSDR has indicated that it will reanalyze the results of the study using exposure estimates from its groundwater modeling of the Tarawa Terrace and Hadnot Point systems.

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TABLE 1 Similar Health Effects Found in Epidemiologic and Toxicologic Studies

Effects	Epidemiologic Evidence	Toxicologic Evidence
Kidney cancer	Limited/suggestive for TCE and PCE	TCE and PCE (limited to male rats)
Liver toxicity	Limited/suggestive for solvents and hepatic steatosis[a]	TCE and PCE (liver damage)
Kidney toxicity	Limited/suggestive for solvents	TCE and PCE (limited to male rats)
Neurobehavioral effects	Limited/suggestive for solvents (effects on visuomotor and motor function, fatigue, headache, deficits in concentration)	TCE: central nervous system depression, attention deficits, deficits in visual discrimination, altered visual evoked potentials[b] PCE: anesthetic effects; changes in behavior and neurochemical markers
Immunologic effects	Limited/suggestive for solvents and glomerulonephritis[c] and scleroderma[d]	TCE: sensitization, immunosuppression, influence autoimmune disease (in sensitive strains of mice)

[a]Hepatic steatosis is fatty accumulation in the liver.
[b]Electrical response recorded by a skull electrode after a visual stimulus (e.g., a flash).
[c]Glomerulonephritis is a disease that affects kidney function.
[d]Scleroderma is a disease resulting in abnormal growth of connective tissue.

ATSDR also has a study under way on prenatal exposure to water-supply contaminants and birth defects and childhood cancer. The specific outcomes being studied are childhood leukemia, childhood non-Hodgkin lymphoma, spina bifida, anencephaly, cleft lip, and cleft palate. These outcomes are rare, and given the number of study participants, it appears that the statistical power of this study could limit its ability to detect associations. The study is also awaiting the completion of groundwater modeling of the Hadnot Point water system so that differences in exposure can be assessed.

Recommendations

- The committee recommends that ATSDR go forward with reanalyzing its study of birth outcomes to correct for errors in exposure classification without awaiting the results of groundwater modeling of the Hadnot Point system. For the reasons given earlier, such modeling is unlikely to yield reliable quantitative estimates of exposure that would refine exposure classification for epidemiologic study.
- Despite the committee's concerns about the statistical power of the study of birth defects and childhood cancer, it recommends that the study be completed as soon as possible. Simpler approaches to groundwater modeling should be performed to support the exposure classification in the study rather than performing the same type of complex groundwater modeling that was performed for Tarawa Terrace.

The Feasibility and Utility of Future Studies of the Camp Lejeune Population

ATSDR has evaluated the feasibility of conducting three additional studies of the Camp Lejeune population, including a health survey and studies that would evaluate deaths from all causes and cancer incidence among former residents and workers. ATSDR identified some of the same diseases and disorders identified in the committee's review as being of interest. These included kidney cancer, lung cancer, breast cancer, scleroderma, liver disease, kidney disease, and spontaneous abortion. ATSDR also identified additional outcomes of possible interest for its study.

Difficulties with performing the studies are identifying, locating, and recruiting the study participants and obtaining reliable health information on them in an efficient manner. The committee found that

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although ATSDR did consider the major issues bearing on the feasibility of the proposed studies and proposed reasonable approaches to conducting the studies, there remain serious, unresolved questions about the feasibility and ultimate value of the studies. For example, it is not clear that the cancer incidence study could be performed successfully, because it is contingent on the cooperation of many state cancer registries. Even with cooperation, the statistical power to compare groups of interest across the range of outcomes has yet to be assessed. Statistical power is also an issue with the mortality study.

The committee also reviewed ATSDR's plans for a health survey that was generated in response to a congressional directive. The survey would seek information on residential history and various health outcomes. Although the survey could contribute to designing future studies at Camp Lejeune, its success depends on getting adequate participation (at least 60%). Even if satisfactory participation is achieved, there are concerns that there could be bias in the reported data because people who have experienced disease or illness are more likely to participate in the survey.

After reviewing the study plans and feasibility assessments, the committee concluded that most questions about whether exposures at Camp Lejeune resulted in adverse health effects cannot be answered definitively with further scientific study. There are two main reasons for this. First, it is not possible to reliably estimate the historical exposures experienced by people at the base. Second, it will be difficult to detect any increases in the rate of diseases or disorders in the study population. Most of the health effects of concern are relatively rare, which means that very large numbers of people are needed to detect increased cases. Although the total number of people who have lived at Camp Lejeune while the Tarawa Terrace and Hadnot Point water supplies were contaminated is sizable, the population is still unlikely to be large enough to detect effects, other than common diseases or disorders, of concern. Another factor is that the population was relatively young, so many who would be studied are in an age range in which chronic diseases are rare. Yet another factor is that the people tended to live on the base for a relatively short time, resulting in a small increase in risk of disease at most, making it difficult to rule out other exposures or factors that could have contributed to disease or illness. All these factors make it unlikely that the proposed studies, even if the notable uncertainties about feasibility are resolved favorably, will produce results of sufficient certainty to resolve the question of whether Camp Lejeune residents suffered adverse health effects from exposure to contaminated water.

The available scientific information does not provide a sufficient basis for determining whether the population at Camp Lejeune has, in fact, suffered adverse health effects as a result of exposure to contaminants in the water supplies. On the one hand, several lines of scientific reasoning suggest such effects are unlikely to have occurred. The evidence includes a substantial body of research on the toxicology of TCE and PCE that indicate that the exposures required to cause adverse effects in laboratory animals were much larger than the highest measurements available on the Camp Lejeune water supplies; evidence that humans have lower sensitivity to TCE and PCE than rodents; epidemiologic data largely from occupational settings with higher, longer-term exposures to TCE and PCE that has not generated compelling evidence of adverse health effects; and the relatively short-term, intermittent nature of the exposures incurred at Camp Lejeune. On the other hand, the possibility that health effects have been produced by the contaminant exposures at Camp Lejeune cannot be ruled out. Some effects of TCE or PCE exposure might have occurred below the level of detection in toxicologic studies, which focused on single contaminant exposures at high doses, used genetically homogeneous animal strains, and necessarily involved extrapolation across species. In addition, the population exposed at Camp Lejeune is more diverse and possibly more susceptible than those who have been exposed to TCE and PCE in occupational settings, and the actual concentrations of PCE and TCE and the presence of additional water contaminants are poorly documented and could thus be higher or more complex than the limited historical measurements suggest. There were divergent views among the committee members about the probability that each would assign to whether adverse health effects have in fact occurred, but there was consensus among them that scientific research is unable to provide more definitive answers to that question.

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Conclusion and Recommendation

- It cannot be determined reliably whether diseases and disorders experienced by former residents and workers at Camp Lejeune are associated with their exposure to contaminants in the water supply because of data shortcomings and methodological limitations, and these limitations cannot be overcome with additional study. Thus, the committee concludes that there is no scientific justification for the Navy and Marine Corps to wait for the results of additional health studies before making decisions about how to follow up on the evident solvent exposures on the base and their possible health consequences. The services should undertake the assessments they deem appropriate to determine how to respond in light of the available information.

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Summary

In the early 1980s, two water-supply systems on the Marine Corps Base Camp Lejeune in North Carolina were found to be contaminated with the industrial solvents trichloroethylene (TCE) and perchloroethylene (PCE). The water systems were supplied by the Tarawa Terrace and Hadnot Point water-treatment plants, which served enlisted-family housing, barracks for unmarried service personnel, base administrative offices, schools, and recreational areas. The Hadnot Point water system also served the base hospital and an industrial area and supplied water to housing on the Holcomb Boulevard water system (full-time until 1972 and periodically thereafter).

PCE was the primary contaminant found in the wells serving the Tarawa Terrace system. The chemical was used by an off-base dry cleaner (ABC One-Hour Cleaners), and the groundwater became contaminated with PCE as a result of spills and improper disposal practices. Contamination of the wells from that source is estimated to have begun as early as 1953, the year when dry-cleaning operations began. There were also other on-base sources of contamination in the Tarawa Terrace system that had a smaller impact on the water supply. The contamination of the Hadnot Point water supply was more complex and involved multiple sources and multiple contaminants. The primary contaminant found in those wells since monitoring began in the 1980s was TCE. It is likely that multiple sources contributed to the TCE contamination, including on-base spills at industrial sites and leaks from underground storage tanks and drums at dumps and storage lots. The Hadnot Point water-treatment plant began operating in 1943, but no estimates have yet been made of when the contamination began. Wells in both systems that were contaminated in the early 1980s were closed in the period November 1984–May 1985, and the entire Tarawa Terrace water-treatment plant was closed in 1987.

There has been considerable public controversy over the potential health consequences for former residents who were exposed to the contaminated water. TCE and PCE are known to have toxic effects in animals and in humans, so it is important to understand the scale and extent of exposure that occurred at the base to assess effects on the health of former residents. Only a few studies have been performed specifically on former residents of the base. To supplement those evaluations and to help to inform decisions about addressing health claims, the U.S. Navy was directed by Congress (Public Law 109-364, Section 318) to ask the National Research Council to address independently questions about whether any health outcomes are associated with past contamination of the water supply at Camp Lejeune. The National Research Council assembled a multidisciplinary committee of environmental scientists, toxicologists, epidemiologists, and biostatisticians to review the scientific evidence on associations between adverse health effects and historical data on prenatal, childhood, and adult exposures to contaminated drinking water at Camp Lejeune. The committee was asked to focus its attention on toxicologic and epidemiologic literature on TCE and PCE and to consider studies of Camp Lejeune residents and other populations exposed to the contaminants of concern and proposals for additional studies of Camp Lejeune residents.

To address its task, the committee divided its investigation into two major categories: assessing exposure to contaminants in the water supply and assessing the possible health effects associated with the contaminants. The reviews were then integrated to ascertain whether conclusions could be drawn about the likelihood that outcomes in people who lived or worked in the affected areas of the base were caused by the contaminated water supplies. The contribution of past and current studies of the Camp Lejeune population was evaluated, as was the potential contributions of future research on this population.

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EXPOSURE-ASSESSMENT EVALUATION

To understand the exposures that occurred because of the contamination of water supplies at Camp Lejeune, it is important to characterize the contamination—including its location, magnitude, duration, and variability—and the individual water-use patterns and other water-related behavior of the population that was exposed. The first component involves identifying the contaminants of concern, their sources, and their estimated concentrations in any particular water-supply system over time. The second component is to characterize how members of the population may have been exposed to the contaminated water supply at home, at work, and in other settings through water consumption, dermal contact, and inhalation of volatile compounds during showering, bathing, dishwashing, and other activities. Such factors are important determinants of exposure and are likely to vary widely in the population.

Water-Supply Contamination

The Tarawa Terrace and Hadnot Point water-supply systems began operating in 1952 and 1943, respectively. From a conceptual standpoint, their operations were similar. Water-supply wells collected groundwater and pumped it to a water-treatment plant. The wells were "cycled," meaning that only a subset of wells pumped water to the treatment plant at any given time. A few wells on both systems were contaminated. When those wells were operating, they delivered contaminated water to the treatment plant, where it was mixed with water from other wells and processed before being distributed on the base. Over the years, wells were added and some were taken temporarily offline or were closed for various reasons. Thus, concentrations of contaminants to which people were exposed varied substantially on a short-term and long-term basis.

The residential areas served by the two water systems were primarily enlisted family housing and barracks for unmarried service personnel. Thus, many of the exposed were young families and people of reproductive age. The population was also transient, with some people living on the base for a few months for training or for a few years for longer assignments.

Tarawa Terrace

The committee reviewed the available data on the exposures that occurred at Camp Lejeune. For Tarawa Terrace, the Agency for Toxic Substances and Disease Registry (ATSDR) performed a historical reconstruction of contamination scenarios and used its model to estimate the concentrations of chemical contaminants that occurred during different periods. ATSDR's historical reconstruction involved investigation into operations of the off-base dry cleaner, on-base operations, operation of water-supply wells and water-treatment plants, water-monitoring data, groundwater flow, and other data relevant to providing a chronology of events related to the contamination. The primary contaminant identified as present at Tarawa Terrace is PCE. PCE is typically degraded by natural processes in the soil and groundwater to TCE, *trans*-1,2-dichloroethylene (1,2-DCE), and vinyl chloride. Groundwater models were used to reconstruct the migration of PCE from the dry cleaners to the water-supply wells serving Tarawa Terrace, and then mixing models were used to predict monthly concentrations of PCE and its degradation products in finished water (groundwater that was treated at a water-treatment plant for delivery to residences) from 1957 to 1985. Because the models were based on several simplifying assumptions and were calibrated by using a small number of water-quality measurements taken during a narrow window (1980-1985) of the total contamination period, considerable uncertainty is associated with the predictions. Some of the uncertainty was characterized when ATSDR performed statistical analyses to calculate the probability that its exposure estimates were reasonable. To gain some perspective on its estimates, ATSDR compared its monthly estimates with the U.S. Environmental Protection Agency (EPA) maximum contaminant level (MCL) for PCE in drinking water of 5 µg/L that was established in 1985. The model estimated that starting in No-

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vember 1957, the concentration of PCE delivered to residents exceeded that MCL and remained well above it until the wells were closed in 1985.

The committee concluded that ATSDR applied scientifically rigorous approaches to address the complex groundwater-contamination scenario at Tarawa Terrace. The outcome of the modeling was monthly estimates of the concentrations of contaminants in the water supply to which people could have been exposed. Although ATSDR recognized and tried to account for the limitations and uncertainties associated with its models, the committee judges that—because of the sparse set of water-quality measurements, the need to make unverifiable assumptions, and the complex nature of the PCE source—it is virtually impossible to estimate exposure to historical levels of PCE and its degradation products accurately. Reporting precise values based on model predictions gives the misleading impression that the exposure of the former residents and workers at Tarawa Terrace during specific periods can be accurately defined. It is the committee's judgment that ATSDR's model is best used for estimating exposure categories qualitatively. From that perspective, a single exposure category of "exposed" appears to be applicable to persons who resided or worked at Tarawa Terrace during 1957-1985.

Hadnot Point

The water-supply contamination scenario for Hadnot Point is much more complex than that for Tarawa Terrace because there were multiple sources and contaminants. The extent of contamination has not yet been characterized, inasmuch as historical reconstruction or groundwater modeling has not yet been performed for Hadnot Point. The committee therefore relied on site descriptions of source areas, laboratory reports and other documentation of supply-water sampling, and results of monitoring of groundwater wells that were installed as part of remedial investigations to characterize likely exposures. Numerous sites have been identified as possibly contributing to the contamination of the groundwater, including an industrial area, a drum dump, a transformer storage lot, an industrial fly-ash dump, an open storage pit, a former fire training area, a site of a former on-base dry cleaner, a liquid-disposal area, a former burn dump, a fuel-tank sludge area, and the site of the original base dump. TCE appears to be the primary contaminant of concern on the basis of measurement data from the 1980s, but many other chemicals had the potential to contaminate the water supply, given the nature of activities at sites near the supply wells. Other chemicals measured in the water supply included PCE, vinyl chloride, 1,1-DCE, 1,2-DCE, methylene chloride, benzene, and toluene. Sampling performed in the early 1990s as part of remedial investigations also detected metals in monitoring wells, but little if any metal analysis was conducted for the timeframe of interest (1943-1985), and the committee did not review such data. Qualitative evidence suggests that the potential magnitude of groundwater contamination appears to have been much higher at Hadnot Point than at Tarawa Terrace.

ATSDR plans to perform a historical reconstruction of estimates of the concentrations of water-supply contaminants at Hadnot Point similar to the one performed for Tarawa Terrace. On the basis of its review of Hadnot Point water-system contamination, the historical groundwater modeling performed for Tarawa Terrace, and ATSDR's preliminary plans for historically reconstructing exposures that occurred at Hadnot Point, the committee recommends that simpler models be used instead of complex groundwater models. In particular, the use of conceptual models based on hydrogeologic characterization studies coupled with mass-balance calculations or analytic models should be given serious consideration because they can be performed relatively quickly and can be used to achieve a crude characterization of the degree and timeframe of contamination of the aquifer. Groundwater-modeling studies using public-domain MODFLOW-family tools should be performed only after establishing a clear need for a study. To support further analyses, the committee also recommends that the Marine Corps create and maintain a comprehensive public database of water-quality measurements for all environmental media samples collected across the base in the course of investigating the nature and extent of contamination at Camp Lejeune. The database should include information on where samples were taken, sampling dates, analytes meas-

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ured, laboratory quality-control information (including limits of detection), and other information relevant to exposure assessment.

Water-Use Patterns and Behavior

Places and dates of residence are key determinants of likely exposure at Camp Lejeune, but individual behaviors also affect the magnitude of exposure. Such behavior includes water consumption, showering or bathing patterns, and other water-related behavior (such as dishwashing). Such information is not available in archival records, and it is far too remote in time for accurate recall. A study in progress evaluating birth defects and childhood cancers is collecting self-reported water-use information from surviving mothers of offspring in the study, but the data are not yet available. The contaminated water systems also supplied nonresidential areas of the base, including schools, workplaces, recreational areas, and a hospital. Water-use patterns and behavior in those setting are expected to differ substantially from residential uses and behavior. In addition, the residential and nonresidential exposures could overlap, and people could have been exposed to contaminated water at multiple locations.

HEALTH-EFFECTS EVALUATION

The committee considered a wide spectrum of potential health effects that are known or suspected to be associated with TCE and PCE by surveying the scientific literature on the contaminants and the health problems reported by former residents and workers of Camp Lejeune. The scientific literature reviewed included reports of toxicologic experiments with the solvents in laboratory animals; of epidemiologic studies of workers and communities exposed to TCE, PCE, and mixed solvents; and of studies of the Camp Lejeune population. Studies on how the chemicals are processed and distributed in the body of laboratory animals and humans were also reviewed and compared. Those lines of research were considered separately and then considered together to determine the health outcomes that were of greatest concern. The health effects on which there was convergent information from the toxicologic and epidemiologic literature, even if not perfectly concordant, were considered by the committee to be of most interest.

Epidemiologic Evidence

In evaluating the epidemiologic literature, the committee adopted a categorization scheme developed by the Institute of Medicine (IOM) for determining whether data indicate a statistical association between chemicals and various health outcomes. IOM's approach was developed to evaluate exposure of veterans of the Vietnam War and the Gulf War and is used by the Department of Veterans Affairs to make decisions about compensation. The five categories in the scheme are limited/suggestive evidence of no association, inadequate/insufficient evidence to determine whether an association exists, limited/suggestive evidence of an association, sufficient evidence of an association, and sufficient evidence of a causal relationship. Among the five categories, only two were judged to be applicable to the literature on TCE and PCE: *limited/suggestive evidence of an association* and *inadequate/insufficient evidence to determine whether an association exists*. In the category of limited/suggestive, the evidence suggests an association between exposure to a chemical and a specific health outcome in human studies, but the body of evidence is limited by the inability to rule out chance and bias, so there is incomplete support of any association and insufficient basis for inferring a *causal* association. In the category of inadequate/insufficient, the available evidence is of insufficient quantity, quality, or consistency to support a conclusion about the existence of an association.

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Overall, the committee did not find sufficient evidence to justify causal inference for any of the health effects it reviewed. The committee concluded that there was limited/suggestive evidence of an association between chronic exposure to TCE or PCE and cancers of the breast, bladder, kidneys, esophagus, and lungs. The epidemiologic literature was also judged to provide limited/suggestive evidence of an association between TCE or PCE and hepatic steatosis and acute tubular necrosis related to chronic exposure at high concentrations but not to chronic exposure at low concentrations. Studies also showed some evidence of an association between solvent exposure and acute glomerulonephritis. Findings of human studies were not sufficiently consistent to draw any firm conclusions about reproductive outcomes, but a few studies showed a potential association with male infertility, and there was a suggestion of an association between solvents in general and reduced fermale fecundability (the ability to conceive). The epidemiologic evidence provides some indication that solvent exposure during but not before pregnancy is associated with increased risk of miscarriage but not with preterm birth or reduced birth weight, and there is no direct evidence on perinatal mortality. The epidemiologic evidence on paternal exposure to TCE and adverse pregnancy outcome was inadequate/insufficient to determine whether an association exists. Human evidence on chronic exposure to TCE or PCE and the risk of congenital malformations was also judged to be inadequate to support conclusions about associations. Overall, there was limited/suggestive evidence of an association between principally inhalation exposure to solvents and neurobehavioral outcomes, with the most support for effects on visuomotor and motor function, fatigue, headache, and deficits in concentration; most of these effects were reported concurrently with exposure, and there has been little study of whether effects persist after exposure ceases. Epidemiologic studies have provided some support of two immunologically mediated outcomes—chronic glomerulonephritis and scleroderma. In each case, there is limited/suggestive evidence of an association with mixed solvent exposure and, for scleroderma, some indication of an association specifically with TCE.

Toxicologic Evidence

Animal cancer studies of TCE at maximally tolerated doses revealed liver and lung cancers in mice and kidney and testicular cancers in male rats. Similar cancer studies of PCE exposure revealed liver cancers in mice and mononuclear-cell leukemia and kidney cancer in male rats. These tumors were in most instances species-, gender-, and strain-specific. Malignant liver tumors were seen in only one strain of one sensitive species, the $B6C3F_1$ mouse. Studies revealed that metabolic and mechanistic similarities between rodents and humans are such that highly exposed workers might develop TCE- and PCE-induced kidney tumors but appear to be much less susceptible than rats.

Review of noncancerous health outcomes in studies of TCE and PCE exposure indicated increased lung toxicity in mice, and hepatic and renal toxicity was reported after high exposure in rodents. Metabolism of TCE and PCE in rodents is qualitatively similar to that in humans but is quantitatively different and results in greater susceptibility of rodents to these compounds. Other studies revealed that rodent liver, kidney, and lung cells are more sensitive than equivalent human cells. Toxicologic studies reported adverse effects on indicators of male fertility in rats and mice exposed to TCE and PCE, respectively, at high doses, but there was little evidence of female infertility even at high concentrations. The toxicologic data constitute strong evidence that neither solvent is associated with congenital malformations in rats. Adverse pregnancy outcomes were not seen in toxicologic studies of maternal exposure to TCE in rats. A reduction in number of litters and increased perinatal mortality were observed in studies of mating pairs of rats and mice. Pregnancy outcomes after maternal inhalation exposure of rats to PCE indicate a reduction in intrauterine growth. Auditory deficits, reduction in performance of tasks, and other neurologic effects were reported in rats exposed to high TCE concentrations. Changes in visual evoked potentials in rabbits and decreased wakefulness in rats were reported in response to inhalation exposure to TCE. A few studies have reported neurobehavioral changes and altered brain neurochemistry in rats in response to inhalation exposure to PCE. TCE caused allergic sensitization in animal studies, including contact dermatitis and exacerbation of asthma. Toxicologic studies have shown exacerbation of autoim-

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mune diseases in a genetically modified mouse model and immunosuppression after TCE exposure. Inhalation of PCE reduced innate bactericidal activity in mice subjected to inhaled microorganisms, but little information was available on the potential of PCE to suppress the immune system or to induce autoimmune diseases.

Integrated Consideration of the Epidemiologic and Toxicologic Evidence

Convergence of the epidemiologic and toxicologic evidence was considered to identify health outcomes of greatest interest and plausibility as potential consequences of exposure to TCE and PCE in the water supply. This approach supplemented IOM's categorization approach by explicitly considering how the toxicologic evidence adds to the weight of evidence in characterizing health risks posed by TCE and PCE. The complementary strengths and weaknesses of the two bodies of literature provide important information on outcomes that are most deserving of attention. Review of epidemiologic studies of cancer outcomes provides limited/suggestive evidence of an association between chronic exposure to TCE or PCE and cancers of the breast, bladder, kidneys, esophagus, and lungs. Among those outcomes, positive concordance with the toxicologic evidence was strongest for kidney cancer observed in workers exposed to TCE, sometimes at doses where acute neurotoxicity was observed.

For noncancer outcomes, some convergence was found for toxic effects on the liver and kidneys of rodents and humans. Rodents exposed to high concentrations of TCE and PCE exhibited hepatic damage and renal tubular-cell damage. Epidemiologic studies also found limited/suggestive evidence of an association with hepatic steatosis (fatty accumulation in the liver) and sensitive measures of acute renal tubular necrosis. Such damage was associated with chronic high-level exposure to solvents but not with chronic low-level exposure.

Separate toxicologic evidence and epidemiologic evidence of associations between exposure to solvents and reproductive outcomes were found, but there was little convergence for specific reproductive outcomes. For example, toxicologic studies of high doses have reported adverse effects on indicators of male fertility in rats exposed to TCE and mice exposed to PCE; human studies were not consistent enough to support any firm conclusions, but a few studies showed a potential association with male infertility. The human data on female fertility were suggestive of an association between solvents and the ability to conceive, but there was little evidence of an association in the toxicologic literature to support female infertility even at high doses. Although the epidemiologic evidence of an association between chronic exposure to TCE or PCE and congenital malformations was judged to be inadequate to support conclusions, the toxicologic data provide strong evidence that neither solvent is associated with congenital malformations in rats. Reduction in fetal weight after maternal exposure of rats to PCE was observed in one toxicologic study; this outcome is considered somewhat analogous to the human outcome of "small for gestational age" (SGA), for which the epidemiologic data are inadequate/insufficient for determining whether an association exists.

Toxicologic studies report effects of exposure to high doses of TCE on the nervous system, such as central nervous system depression, attention deficits, alterations in visual evoked potentials, and other neurologic outcomes. Neurologic effects in toxicologic studies of PCE include anesthetic effects at high doses and changes in behavior and neurochemical markers at lower doses. Epidemiologic studies provide limited/suggestive evidence of an association between inhalation exposure to solvents and neurobehavioral effects; most of the reported effects were concurrent with exposure, and there has been little study of whether neurobehavioral effects persist after exposure ends.

Regarding effects on the immune system, toxicologic studies in sensitive strains of mice indicate that TCE can act as a skin sensitizer, modulate existing asthma, produce immunosuppression, and influence autoimmune diseases. Immunotoxic data on PCE are less abundant, with only a suggestion of effects on allergic sensitization and immunosuppression. Epidemiologic studies show limited/suggestive evidence of an association between mixed solvent exposure and two immunologically mediated outcomes,

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chronic glomerulonephritis and scleroderma. There is some indication of a specific association between TCE and scleroderma.

The committee is aware that some other health outcomes reported by former residents of the base (for example, male breast cancer and second-generation effects) are not cited above. The absence of inclusion of specific health outcomes does not mean that such effects should be excluded from further consideration of the Camp Lejeune population. Rather, it indicates that those outcomes have not been specifically investigated, or if they were considered, the studies were too small or of insufficient quality to support inferences.

Exposure Estimates in the Context of the Toxicologic and Epidemiologic Evidence

Perspective is needed in evaluating the exposures that occurred at Camp Lejeune. For example, some exposures are described as being "high" and others as being "low." To understand the meaning of those descriptors, it is important to understand what is being compared. For example, ATSDR compared exposures with EPA's MCL of 5 µg/L for PCE. In 1985, EPA classified PCE as a probable human carcinogen, and its policy is to assign a public health goal of zero exposure for such chemicals. The analytic feasibility of measuring PCE was considered in the setting of the MCL, and 5 µg/L was selected because it was judged to be the lowest concentration that could be reliably detected. Thus, the MCL is not based on toxicologic or epidemiologic data.

In epidemiologic studies, "high" exposures tend to occur in occupational situations where TCE and PCE are used routinely. Inhalation is usually the primary route of exposure in occupational scenarios, with skin exposure a less important route. Exposure tends to be much lower in community studies than in occupational studies and to involve exposure by the oral, dermal, and inhalation routes.

In toxicologic studies, exposure is usually expressed in terms of vapor concentration for inhalation exposure (parts per million) and dose for oral exposure (milligrams per kilogram of body weight per day). Lowest-observed-adverse-effect levels (LOAELs) were identified from the animal toxicologic studies for different adverse health effects. In some cases, a no-observed-adverse-effect level was also identified. The committee compared LOAELs with a range of estimated daily intakes that may have occurred at Camp Lejeune. Adverse health outcomes used in the evaluation were renal toxicity, renal cancer, neurotoxicity, and immune-related health effects—adverse outcomes in animals judged to be most relevant to humans on the basis of metabolic, mechanistic, and epidemiologic studies. Because of known variation in contaminant concentrations at Camp Lejeune, the range of exposures considered included the highest measured concentrations of TCE and PCE in finished water, half those concentrations, and twice those concentrations. Results of a toxicologic hazard evaluation[1] indicate that the lowest doses that elicited adverse health effects in animals are much greater than the doses to children and adults that may have occurred, as estimated from the highest measurements taken of the Camp Lejeune water supplies. Thus, in the context of human occupational and animal studies, potential exposure of human populations at Camp Lejeune is described as being "low." Although such comparisons afford a general frame of reference, they should be considered as just one facet of the health-effects evaluation. There are limitations in extrapolating the results of toxicologic studies, in which laboratory animals are exposed to high concentrations under controlled conditions, to human exposure scenarios where exposure varies in concentration and duration. Even community studies cannot be directly extrapolated to the Camp Lejeune population, because the Camp Lejeune population was much more transient than the nonmilitary populations studied in the other scenarios; moreover, other contaminants or other risk factors were probably present in both cases.

[1]A dissenting viewpoint on the conduct of this evaluation is provided in Chapter 4.

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Past and Current Studies of the Camp Lejeune Population

Two analyses of the Camp Lejeune population have been completed by ATSDR, both of which focused specifically on health risks to children who were exposed in utero and considered measures of fetal growth and duration of gestation. No clear associations were found between exposure and mean birth weight, preterm birth, and SGA, although one study conducted a subgroup analysis and reported an increased risk of SGA in infants born to older mothers or mothers who had prior fetal losses. Weaknesses in both studies limit the ability to draw definitive conclusions—most important, weaknesses in exposure assessment. Place of residence at the time of birth was used to categorize people as exposed or unexposed despite the potential for migration in or out over the course of pregnancy. It was discovered after the study was completed that an area that was considered unexposed (Holcomb Boulevard) had received water from a contaminated system (Hadnot Point) for the first 4 years of the study period, so the study results became invalid. ATSDR plans to reanalyze its study with corrected exposure information; the committee views this as a useful effort that can be completed rapidly without awaiting water-modeling results.

An ATSDR study of the effect of prenatal exposure on birth defects and childhood cancers is under way. In addition to many of the same methodologic concerns as in the studies of fetal growth and preterm birth, the current study has limited statistical power to detect associations with congenital defects or childhood cancer, and it does not consider exposures in infancy or early childhood. The results of that study await completion of ATSDR's water modeling at Hadnot Point. As noted above, the committee recommends that simpler or conceptual groundwater modeling be performed for the analysis of Hadnot Point and that the results of that effort be applied to the completion of the case-control study of congenital defects and childhood cancer.

Future Studies of the Camp Lejeune Population

ATSDR has evaluated the feasibility of conducting three additional studies of the Camp Lejeune population, including a health survey and studies that would evaluate deaths from all causes and cancer incidence among former residents and workers. ATSDR identified some of the same diseases and disorders identified in the committee's review as being of interest. These included kidney cancer, lung cancer, breast cancer, scleroderma, liver disease, kidney disease, and spontaneous abortion. ATSDR also identified additional outcomes of possible interest for its study.

The proposed health survey was generated in response to a congressional directive. The survey would seek information on residential history and various health outcomes, and could be used to support the other two studies. The survey's success depends on getting adequate participation (at least 60%). Even if satisfactory participation is achieved, there are concerns that there could be bias in the reported data, because people who have experienced disease or illness are more likely to participate in the survey.

There are a number of difficulties with performing the mortality and cancer incidence studies, including identifying, locating, and recruiting the study participants and obtaining reliable health information on them in an efficient manner. The committee found that although ATSDR considered the major issues bearing on the feasibility of the studies and proposed reasonable approaches to address them, there remain serious, unresolved questions about the feasibility and ultimate value of the studies. For example, it is not clear that the cancer incidence study could be performed successfully, because it is contingent on the cooperation of many state cancer registries. Even with cooperation, the statistical power to compare groups of interest across the range of outcomes has yet to be assessed. Statistical power is also an issue with the mortality study. The quality of exposure assessment remains problematic as well. On the basis of information reviewed, the committee considers it unlikely that the proposed studies, even if the notable uncertainties about feasibility are all resolved favorably, will produce results of sufficient certainty to resolve the question of whether Camp Lejeune residents suffered adverse health effects from contaminated water.

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OVERARCHING CONCLUSIONS AND RECOMMENDATIONS

Conclusions

- The available scientific information does not provide a sufficient basis for determining whether the population at Camp Lejeune has, in fact, suffered adverse health effects as a result of exposure to contaminants in the water supplies. On the one hand, several lines of scientific reasoning suggest such effects are unlikely to have occurred. The evidence includes a substantial body of research on the toxicology of TCE and PCE that indicates that the exposures required to cause adverse effects in laboratory animals were much larger than the highest measurements available on the Camp Lejeune water supplies; evidence that humans have lower sensitivity to TCE and PCE than rodents; epidemiologic data largely from occupational settings with higher, longer-term exposures to TCE and PCE that has not generated compelling evidence of adverse health effects; and the relatively short-term, intermittent nature of the exposures incurred at Camp Lejeune. On the other hand, the possibility that health effects may have been produced by the contaminant exposures at Camp Lejeune cannot be ruled out. Some effects of TCE or PCE exposure might have occurred below the level of detection in toxicologic studies, which focused on single contaminant exposures at high doses, used genetically homogeneous animal strains, and necessarily involved extrapolation across species. In addition, the population exposed at Camp Lejeune is more diverse and possibly more susceptible than those that have been exposed to TCE and PCE in occupational settings, and the actual concentrations of PCE and TCE and the presence of additional water contaminants are poorly documented and could thus be higher or more complex than the limited historical measurements suggest. There were divergent views among the committee members about the probability that each would assign to whether adverse health effects have in fact occurred, but there was consensus among them that scientific research is unable to provide more definitive answers to that question.
- Additional research on potential health effects of water contamination at Camp Lejeune are unlikely to provide definitive information on whether exposure to it resulted in adverse health effects. Limitations in population size, data availability, and data quality cannot be overcome. Those limitations are due in part to the lack of documentation of exposure and the difficulty in assessing the health events that residents experienced after they were exposed. Even if ATSDR's planned work goes forward successfully, the outcome of the efforts is unlikely to determine conclusively whether Camp Lejeune residents were adversely affected by exposure to water contaminants.
- Because of the historical and complex nature of the contamination that occurred at Camp Lejeune and the availability of few empirical data on concentrations in water supplies, only crude estimates of exposure can be obtained. Even with the use of reasonable and, in some cases, advanced approaches, limitations in data availability and quality cannot be overcome. Thus, only a general conclusion can be drawn that the Tarawa Terrace and Hadnot Point water-supply systems were contaminated and that residents and workers were exposed to the contaminants in a highly variable manner. Additional work should make it possible to assign exposure categories of exposed and unexposed based on time and residence with reasonable certainty.

Recommendations

Additional research on the affected population should be only one of several potential responses by the Marine Corps to the water-contamination at Camp Lejeune. Given the likelihood that such studies would extend for many years and their expected inability to deliver definitive information on whether the water-supply contamination at Camp Lejeune caused adverse health effects, efforts to address and resolve the concerns associated with the documented contamination should not be deferred until such research is completed. Policy changes or administrative actions that would help to resolve the controversy should proceed in parallel with the studies (if they are continued) rather than in sequence.

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Introduction

Camp Lejeune is a U.S. Marine Corps base that covers about 233 square miles in Onslow County, North Carolina. It was established in the early 1940s and is the site of six major Marine Corps commands and two U.S. Navy commands, including reconnaissance, intelligence, infantry, artillery, and amphibious units. In the early 1980s, the Marine Corps discovered that the drinking-water systems that supplied two areas of housing at Camp Lejeune (Tarawa Terrace and Hadnot Point) were contaminated with volatile organic compounds (VOCs). The major contaminants of concern were identified as the solvents trichloroethylene (TCE) and perchloroethylene (PCE).[1]

Investigation into the drinking-water contamination began in 1980, when a routine test was conducted for trihalomethanes, which are produced as byproducts of water-treatment processes. Results indicated that other contaminants were present, including TCE, PCE, and other VOCs. Further investigation revealed that wells serving Tarawa Terrace were contaminated with PCE from an off-base dry-cleaning operation because of accidental spills and improper disposal of PCE. The contamination probably began when dry-cleaning operations began in 1953 (Maslia et al. 2007). The wells serving the Hadnot Point water system had multiple sources of contamination and multiple contaminants, the most important of which was TCE. Sources of the contamination included on-base spills at industrial sites and leaks from underground storage tanks and drums at dumps and storage lots. The Hadnot Point water-treatment plant began operating in 1943, but no estimates have yet been made of when the contamination might have begun. The contaminated wells in both systems were removed from service during 1984-1985.

The residential areas served by the Tarawa Terrace and Hadnot Point water systems consisted primarily of enlisted-personnel family housing and barracks for unmarried service personnel. Thus, many of the exposed were young members of families and people of reproductive age. Both water systems also served base administrative offices, schools, and recreational areas. In addition, the Hadnot Point water system served the base hospital and an industrial area, periodically supplemented water supply to the Holcomb Boulevard system in summer months (Bove and Ruckart 2008), and temporarily supplied water to the Holcomb Boulevard water system for a 2-week period during an emergency in 1985 (GAO 2007). The number of people that lived or worked in the areas served by the contaminated water systems has not yet been determined.

There has been considerable controversy over the drinking-water contamination at Camp Lejeune. Questions have been raised about when the contamination was discovered, whether appropriate action was taken by the Marine Corps and the Department of the Navy (the department under which the Marine Corps operates), and whether information about the contamination was disclosed in timely and appropriate ways. Some people who became ill or whose families or friends became ill or died have sought to learn whether the contaminated drinking water might be to blame. They have also questioned whether the investigations that were conducted were the most appropriate ones and whether studies that

[1]PCE is also known as tetrachloroethylene or Perc.

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are under way will answer their questions definitively. Hundreds of former residents and employees of Camp Lejeune have filed claims with the Department of the Navy.

Several investigations have been performed on issues related to the discovery of the contamination at Camp Lejeune. A brief overview of the investigations follows.

INVESTIGATIONS

Camp Lejeune Studies

Health Investigations

A sequence of health investigations and studies were conducted by the Agency for Toxic Substances and Disease Registry (ATSDR) after the U.S. Environmental Protection Agency (EPA) added Camp Lejeune to its National Priorities List in October 1989. A public-health assessment evaluated exposures and potential risks at three sites on the base, including the sites served by the contaminated drinking-water systems (ATSDR 1997a). ATSDR judged that exposure to VOCs in drinking water was unlikely to pose health risks to adults but raised questions about risks to children who may have been exposed in utero. A followup study found no overall association between exposure and pregnancy outcome but reported that male infants were small for their gestational age (ATSDR 1998). Similarly, Sonnenfeld et al. (2001) found no overall association with pregnancy outcome but reported that infants of some groups of mothers who were exposed during pregnancy had lower birth weights.

ATSDR is now studying children born at Camp Lejeune in 1968-1985 to determine whether exposure to VOCs in drinking water is related to specific birth defects and childhood cancers. Health effects under consideration include spina bifida, anencephaly, cleft lip, cleft palate, childhood leukemia, and childhood non-Hodgkin lymphoma. The study will also include modeling of the contaminants and water-supply systems in an attempt to provide better estimates of which study participants might have been exposed and at what concentrations. The water modeling conducted to date and ATSDR's health studies are evaluated in Chapters 2 and 8, respectively.

Other Investigations

Several federal inquires on the contamination of the water supplies at Camp Lejeune were conducted. The inquiries were not health investigations or evaluations of scientific issues but rather were focused on activities surrounding the discovery and handling of the situation. A short summary is presented here to give the reader some background, but the issues are outside the scope of the current report and the investigations were not used or evaluated by the committee. One inquiry was conducted in 2004 by a panel chartered by the Marine Corps to review the facts surrounding the discovery of the drinking-water contamination and actions taken (Drinking Water Fact-Finding Panel for Camp Lejeune 2004). The panel found that the Marine Corps responded appropriately with the information available and found no evidence that an attempt was made to cover up evidence of the contamination. However, the panel concluded that the Navy should have been more aggressive in providing technical expertise to the Marine Corps so that it could understand the significance of the contamination, that communication between Camp Lejeune officials and between base officials and Navy technical support was not always adequate, and that communication with former residents did not provide enough details to characterize the contamination fully.

EPA conducted two inquiries. One, completed in 2005, was the EPA Office of Inspector General's investigation into complaints about EPA's response to Freedom of Information Act requests about the Camp Lejeune contamination and other issues regarding EPA's responsibilities. The Office of Inspector General found that EPA's responses to the information requests were not handled appropriately but

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also found that the other complaints were without merit or were outside the purview of EPA. The second EPA inquiry was conducted in 2003-2005 by its Criminal Investigation Division, which sought to determine whether any violations of federal laws had occurred, reasons for funding delays, and whether records and data were falsified or mishandled. The division was critical of some actions taken by Marine Corps and Navy officials but found that no federal laws were violated. The case was also forwarded to the Department of Justice for evaluation, which decided not to seek criminal prosecution.

The U.S. Government Accountability Office (GAO 2007) also assessed activities related to drinking-water contamination at Camp Lejeune. In its report to Congress, GAO described efforts to identify and address the contamination, activities that resulted from the discovery of the contamination, the government's actions, and the design of the current ATSDR study.

Contaminant Studies

The two drinking-water contaminants of greatest concern—TCE and PCE—are environmental contaminants used in occupational settings and commonly found at hazardous-waste sites. The two solvents have similar metabolites that are thought to be largely responsible for the toxicity observed after exposure. Studies have shown that TCE and PCE can have a number of adverse health effects, including cancer, when animals are exposed under experimental conditions. Epidemiologic studies of workers exposed to the solvents in occupational settings have been conducted, and there is a growing body of literature on community exposures to TCE and PCE in drinking water. In addition, several federal and state agencies have conducted or are conducting human health risk assessments or analyses of TCE and PCE. For example, ATSDR has released toxicologic profiles of TCE (ATSDR 1997b) and PCE (ATSDR 1997c), the International Agency for Research on Cancer has an evaluation of dry-cleaning and chlorinated solvents (IARC 1995), the California Environmental Protection Agency has a public-health goal for PCE in drinking water (Cal EPA 2001), and EPA is updating its human health risk assessments of TCE and PCE.

The Institute of Medicine (IOM 2003) performed a comprehensive assessment of the long-term adverse health outcomes associated with exposure to various solvents as part of its evaluation of agents to which Gulf War veterans were exposed, including TCE and PCE. The literature used in the IOM assessment consisted primarily of occupational studies of workers chronically exposed to solvents. Few of the studies included women or children. Animal data were used for making judgments about the biologic plausibility of associations but were not used as part of the weight-of-evidence approach.

In 2006, the National Research Council published *Assessing the Human Health Risks of Trichloroethylene: Key Scientific Issues* (NRC 2006); it was based on a study sponsored by EPA, which was seeking guidance on updating its risk assessment of TCE. The report examined issues critical for developing an objective, scientifically based health risk assessment of TCE. As indicated above, EPA has not yet released a revised risk assessment of TCE.

COMMITTEE'S TASK

At the request of Congress, the Navy sponsored this study by a committee of the National Research Council to review the scientific evidence on associations between adverse health effects and historical data on prenatal, childhood, and adult exposures to contaminated drinking water at Camp Lejeune, North Carolina. The committee was asked to assess the strength of evidence in establishing a link or association between exposure to TCE, PCE, and other drinking-water contaminants and each adverse health effect suspected to be associated with such exposure. For each health effect reviewed, the committee was to determine, to the extent practicable with the available scientific data, whether a statistical association between contaminant exposure and the health effect exists, whether a plausible biologic mechanism or other evidence of a causal relationship between contaminant exposure and effect exists, the strength of

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evidence for a causal inference for each health effect, and other scientific considerations that may help the Navy to set priorities for future activities.

The committee's review was to include an evaluation of the toxicologic and epidemiologic literature on adverse health effects of TCE and PCE, including studies of populations exposed to similar concentrations of the contaminants of concern; risk-assessment reports from government agencies; recent literature reviews by the National Research Council, IOM, and other groups; completed and current ATSDR studies at Camp Lejeune; and published meta-analyses. In its evaluation of previous and current health studies of residents of Camp Lejeune, the committee was asked to review the appropriateness of the study question, design, analysis, results, and conclusions.

COMMITTEE'S APPROACH

To address its task, the committee held two public meetings in September and November 2007 to gather information from the sponsor and other parties knowledgeable about the contamination and related issues. The Marine Corps made presentations on the drinking-water contamination at Camp Lejeune and addressed questions about the scope of work. Presentations were also made by ATSDR on its past and current health studies of former residents and on its current groundwater modeling activities to estimate the exposures that occurred historically at the base. GAO reported on its investigation into actions taken by various agencies in response to the discovery of the contamination. Representatives of ATSDR's community-assistance panel informed the committee about the panel's activities and about the specific health concerns raised by former residents. There were also open-microphone sessions to hear from former residents and employees of the base about their concerns and to learn about information that they had that was relevant to the study. The committee visited Camp Lejeune to get firsthand information on the affected housing areas; information on the location of wells, water-treatment plants, and base boundaries; and other site information to use in its evaluation. A third public meeting was held in September 2008 to hear about ATSDR's assessment of the feasibility of conducting additional epidemiologic studies.

The current report expands on previous reviews of the Camp Lejeune drinking-water contamination by providing an assessment of multiple lines of research to ascertain the likelihood that exposure to the contaminated water supply is associated with adverse health effects. The evidence reviewed included exposure evaluations performed by other organizations, raw data on the contaminants measured in the water supply, studies of contaminants in laboratory animals, studies of human populations exposed to the contaminants, and studies of the Camp Lejeune population.

As specified in the task, the committee also took advantage of the comprehensive literature reviews and health risk assessments that were performed by other agencies. The report by IOM (2003) figured prominently in the committee's evaluation of the epidemiologic evidence because it provided a comprehensive review of the epidemiologic research on TCE and PCE and individual health outcomes and categorized the evidence according to an established scheme accepted by the Department of Veterans Affairs in evaluating risks to veterans of the Vietnam War and the Gulf War. The committee updated IOM's review, modified categorizations where appropriate, reviewed literature on pregnancy outcomes in women exposed during pregnancy (a population excluded from IOM's review because pregnant women are not deployed), and expanded on IOM's approach by explicitly considering how evidence from the animal literature adds to the weight of evidence and by considering the exposures that were likely to have occurred at Camp Lejeune.

The committee also considered the possible contribution of additional research to inform Marine Corps decisions about what actions to take about the past water-supply contamination and its possible contribution to scientific knowledge. The committee approached that question by considering possible research activities, evaluating their feasibility, and assessing whether the results would substantively inform decisions by the Marine Corps or contribute to scientific knowledge.

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ORGANIZATION OF THE REPORT

The report first discusses the individual elements of the committee's review of the drinking-water contamination at Camp Lejeune (Chapters 2-7) and then considers the elements together to draw conclusions about whether particular health outcomes can be linked to the exposures that occurred. Chapter 2 evaluates what is known about the possible exposures of the populations that lived or worked in areas served by the contaminated water systems. On the basis of what is known about the primary contaminants of concern, Chapter 3 discusses some of the biochemical changes that occur after the contaminants enter the body and how they or their metabolic products are transported in the body; it also considers populations that might be more susceptible to effects of the contaminants, lifestyle factors that affect how the contaminants interact in the body, and how the contaminants interact with each other and with other chemicals in the body. In reviewing what adverse health effects might result from exposure to the contaminants, the committee first reviews the toxicology literature in Chapter 4, which involves primarily studying effects in animals given the contaminants under experimental conditions. Chapter 5 reviews studies of human subjects who were exposed to the same chemicals that contaminated the Camp Lejeune drinking-water system, mainly studies of occupational exposure. Chapter 6 evaluates studies of populations exposed to similar contaminants via drinking water to see whether any inferences that would be applicable to the Camp Lejeune situation can be drawn. The toxicologic and epidemiologic evidence is considered together in Chapter 7 to determine the strength of the available evidence on particular health outcomes. Chapter 8 deals specifically with studies of exposure and health effects in former residents of Camp Lejeune, including completed, current, and proposed studies by ATSDR.

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2

Exposure to Contaminants in Water Supplies at Camp Lejeune

This chapter describes the scenarios of exposure to contaminants in the water supplies at Marine Corps Base Camp Lejeune and identifies gaps in understanding of the exposures of people who lived or worked on the base while the water supplies were contaminated. First, exposure assessment for epidemiologic studies is discussed to set forth concepts that will be used in other chapters that review epidemiologic evidence (see Chapters 5 and 6). Then, an overview of the water-supply contamination scenarios at Camp Lejeune and important considerations for characterizing them are presented, including hydrogeologic features of the site, the base's water-treatment plants and distribution systems, contaminated areas, and water-quality measurements. Finally, information on the Tarawa Terrace and Hadnot Point water systems is evaluated.

EXPOSURE ASSESSMENT FOR EPIDEMIOLOGIC STUDIES

In public health, the term *exposure* refers to contact with an agent (such as environmental contaminant) that occurs at the boundary between a person and the environment. *Exposure assessment* can be defined as the qualitative or quantitative determination or estimation of the magnitude, frequency, duration, and rate of exposure of a person or a population to a chemical (ILSI 2000). Often, the focus is on identifying one or more exposure pathways and, for each exposure pathway, the source, the environmental medium through which the contaminant is transported and possibly transformed, the receptor (individual or population), how contact occurs, and the route of exposure. The goal is to determine how much of a contaminant is absorbed and at what rate (the dose) so that an assessment can be made as to whether the absorbed contaminant produced or might produce an adverse biologic effect (Lioy 1990). The possible routes of exposure are inhalation, if the contaminant is present in the air; ingestion, through food, drinking, or hand-to-mouth behavior; and dermal absorption, if the contaminant can be absorbed through the skin. In the field of exposure science, research has been focused on developing methods for quantifying the uncertainty and error in the exposure assessments and on correcting the assessments for such error or uncertainty when possible. New methods are being developed to account for cumulative exposure to multiple chemicals (ILSI 2000), as are probabilistic models for cumulative and aggregate exposure assessment (for example, Nieuwenhuijsen et al. 2006) and the application of exposure modeling based on geographic information systems (Nuckols et al. 2004; Mindell and Barrowcliffe 2005; Beale et al. 2008).

A well-designed epidemiologic study should have the capability to evaluate exposure in relation to an appropriate latent period of a disease and to evaluate critical windows of exposure. In most epidemiologic studies, exposure cannot be measured directly or completely, and surrogate information is used to classify study subjects into exposure groups. Good surrogates for exposure elucidate the variation

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in exposure in the study population while minimizing exposure misclassification (error). Misclassification of exposure is of particular concern in environmental-epidemiology studies because the health effects of environmental exposures tend to be small, and it is usually difficult to accurately estimate exposure to environmental contaminants, which can occur by multiple pathways and in multiple locations. Furthermore, environmental exposures are often at low concentrations, which make biases due to exposure misclassification more likely to affect epidemiologic results. If misclassification of exposure is not differential by health outcome, it commonly biases risk estimates toward the null (that is, toward finding no association) and can cause associations to be missed (Copeland et al. 1977; Flegal et al. 1986). To evaluate the degree of misclassification in an epidemiologic study, it is important to consider the ability of an exposure metric to correctly classify the magnitude of exposure in the study population and to differentiate between those who are exposed at magnitudes that could result in adverse health effects (sensitivity) and those who are exposed at lower magnitudes (specificity). It is important to maximize specificity when the prevalence of exposure in the study population is low and to maximize sensitivity when the prevalence of exposure is high (Nuckols et al. 2004).

Exposure assessment for epidemiologic studies of the effects of water-supply contamination includes two components. The first is estimation of the magnitude, duration, and variability of contaminant concentrations in water supplied to consumers. An important consideration is hydrogeologic plausibility: an association between a contaminant source and exposure of an individual or population cannot exist unless there is a plausible hydrogeologic route of transport for the contaminant between the source and the receptor (Nuckols et al. 2004). The second component is information on individual water-use patterns and other water-related behaviors that affect the degree to which exposures occur, including drinking-water consumption (ingestion) and dermal contact and inhalation related to the duration and frequency of showering, bathing, and other water-use activities. Water use is an important determinant of variability of exposure to water-supply contaminants, particularly if it varies widely in the study population. Ideally, exposure-assessment strategies include both components, but in practice it may be difficult to obtain either adequately.

A number of approaches have been used to assign exposures in studies of health effects of water-supply contamination. They have ranged from measures of exposure defined by geographic region or job classification (group-level or ecologic exposure) to more sophisticated measures that yield individual exposure estimates. Selecting an optimal approach for a given study is dictated in part by the epidemiologic-study design, the size and geographic extent of the affected population, and the quantity and quality of available exposure-related data. The approaches that have been used in epidemiologic studies of water-supply contamination are more fully described in Chapter 6. The following sections provide information on the water-supply contamination and exposure scenarios at Camp Lejeune.

WATER-SUPPLY CONTAMINATION AT CAMP LEJEUNE

In the early 1940s, the U.S. Marine Corps constructed a water-distribution piping system at Camp Lejeune. The source of water in the system was, and continues to be, groundwater wells. The water-treatment processes, distribution systems, and contributing wells have been modified to accommodate the additional demand due to population growth and to improve water quantity and quality. Four water systems—Hadnot Point, Tarawa Terrace, Marine Corp Air Station, and Holcomb Boulevard—have supplied water to most of the residences and workplaces (see Figure 2-1). Other water-distribution systems on the base are Onslow Beach, Courthouse Bay, Rifle Range, and Camp Johnson.

In late 1984 and early 1985, Marine Corps authorities removed a number of supply wells from service in the Tarawa Terrace and Hadnot Point systems after concluding that they were contaminated with solvents (GAO 2007). The sources of contamination of the two systems were different. Investigation into the source of perchloroethylene (PCE) contamination of the Tarawa Terrace water system concluded

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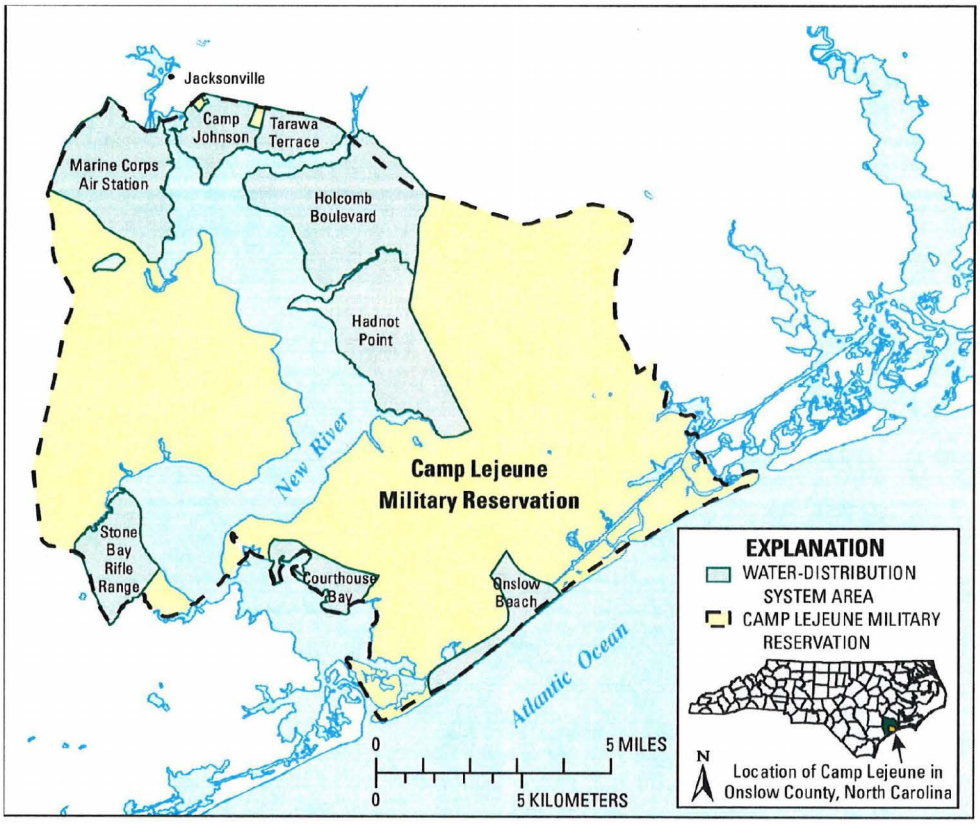

FIGURE 2-1 Water-distribution systems serving U.S. Marine Corps Base, Camp Lejeune, North Carolina. Source: Maslia 2005.

that it was due to waste-disposal practices at ABC One-Hour Cleaners, an off-base dry-cleaning facility (Shiver 1985). The dry-cleaning site was classified as a federal hazardous-waste site during March 1989 under the Comprehensive Environmental Response, Compensation, and Liability Act, commonly known as the Superfund Act, and remedial investigation began in 1990 (Faye and Green 2007). The Agency for Toxic Substances and Disease Registry (ATSDR) completed an extensive water-modeling study to predict the extent of contamination (spatially and temporally) in the period January 1951–January 1994 (Faye 2008; see discussion of the modeling later in this chapter). Quantitative estimates of contaminant concentrations in the water supply from that modeling effort will be used in current and planned ATSDR epidemiologic studies of the Camp Lejeune population.

A report from the U.S. Government Accountability Office (GAO 2007) states that the sources of contamination at Hadnot Point are uncertain but are likely to include many on-base sites, including landfills and base operations where solvents and other compounds were disposed of or used. ATSDR plans to do a historical reconstruction for the Hadnot Point water-distribution system to estimate the extent of groundwater contamination of wells and the extent to which water supplies of housing and public buildings served by this system were contaminated (M. Maslia, ATSDR, personal commun., March 12, 2008).

The committee is not aware of any extensive studies concerning potential contamination of wells serving other water-supply systems on the base. Those wells directly serve the Holcomb Boulevard, Marine Corps Air Station, Courthouse Bay, Camp Johnson, Camp Geiger, and Rifle Range water-supply systems and several smaller systems. Some water-supply systems are connected (for example, Holcomb Boulevard and Hadnot Point), and Bove and Ruckart (2008) documents some reports of intermittent delivery of water from the Hadnot Point system to the Holcomb Boulevard system.

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Hydrogeologic Features of Exposure at Camp Lejeune

On the basis of geophysical data and lithologic logs, several productive aquifers were found to exist beneath Camp Lejeune. The geologic cross-sectional details on the site, as reported in Harden et al. (2004), are summarized in Figure 2-2. The aquifers include the Castle Hayne aquifer and two other deep aquifers beneath the Beaufort confining unit, the Beaufort and Peedee aquifers. All the water-supply wells were installed within the Castle Hayne aquifer, so site characterization efforts focused on understanding the hydrostratigraphy of the upper three hydrogeologic units: the surficial aquifer, the Castle Hayne confining unit, and the Castle Hayne aquifer. Each unit is known to have multiple subunits that consist of seams of clay, silt, and sandy beds (as indicated in Figure 2-2). The sections below summarize the available hydrogeologic data for the three units.

Surficial Aquifer

The thickness of the surficial aquifer at Camp Lejeune ranges from 0 to 73 ft and averages about 25 ft (Cardinell et al. 1993). The largest observed thickness occurs in the southeastern part of Camp Lejeune. The aquifer consists of interfingered beds of sand, clay, sandy clay, and silt of both Quaternary and Tertiary age. The clay and silt beds that occur in the surficial aquifer are thin and discontinuous. The aquifer is often classified into several subunits; and the extent and depth of the subunits can vary among locations. For example, in the vicinity of Tarawa Terrace, three minor units have been identified in the surficial aquifer (the Brewster Boulevard unit, the Tarawa Terrace unit, and the Upper Castle Hayne River bend unit). Review of available cross-sectional hydrogeologic data does not indicate any distinct demarcation between the subunits; hence, they were conceptualized as a single surficial unit in groundwater-flow models (Faye and Valenzuela 2007). According to Winner and Coble (1989), the surficial aquifer is composed of more than 90% sand in the eastern part of the base and about 70-90% sand in the western part. The aquifer is directly recharged by infiltration from rainfall that ranged from 28 to 70 in/year during 1952-1994. Tant et al. (1974) found that the soils in Camp Lejeune have good infiltration capacity. Effective groundwater recharge is estimated to range from 6.6 to 19.3 in/year. The estimated average hydraulic conductivity of the surficial aquifer in the Camp Lejeune area is about 50 ft/day (Winner and Coble 1989). Conceptually, groundwater in the shallow surficial aquifer moves from areas of high hydraulic head in interstream divides toward areas of low hydraulic head at surface-water discharge areas (Harden et al. 2004).

Castle Hayne Confining Unit

The Castle Hayne confining unit lies beneath the surficial aquifer, and this clayey unit is conceptualized as the top confining layer of the Castle Hayne aquifer. However, the lithostratigraphic top of Castle Hayne aquifer is not continuous, and the thickness of the confining layer ranges from 0 to 26 ft, averaging about 9 ft where present. Harned et al. (1989) concluded that no continuous confining unit or clay bed appears to separate the surficial and Castle Hayne aquifers except in the easternmost side of the Hadnot Point area. Furthermore, the thickness and distribution of the confining clay layers observed in various cross sections summarized by Harned et al. (1989) and Cardinell et al. (1993) are similar. The thin (5-10 ft) and discontinuous clay layers observed in several cross sections indicate that the degree of hydrologic connection between the aquifers could be substantial (Harned et al. 1989). The vertical hydraulic conductivity of the confining material, where present, is estimated to range from 0.0014 to 0.41 ft/day (Cardinell et al. 1993).

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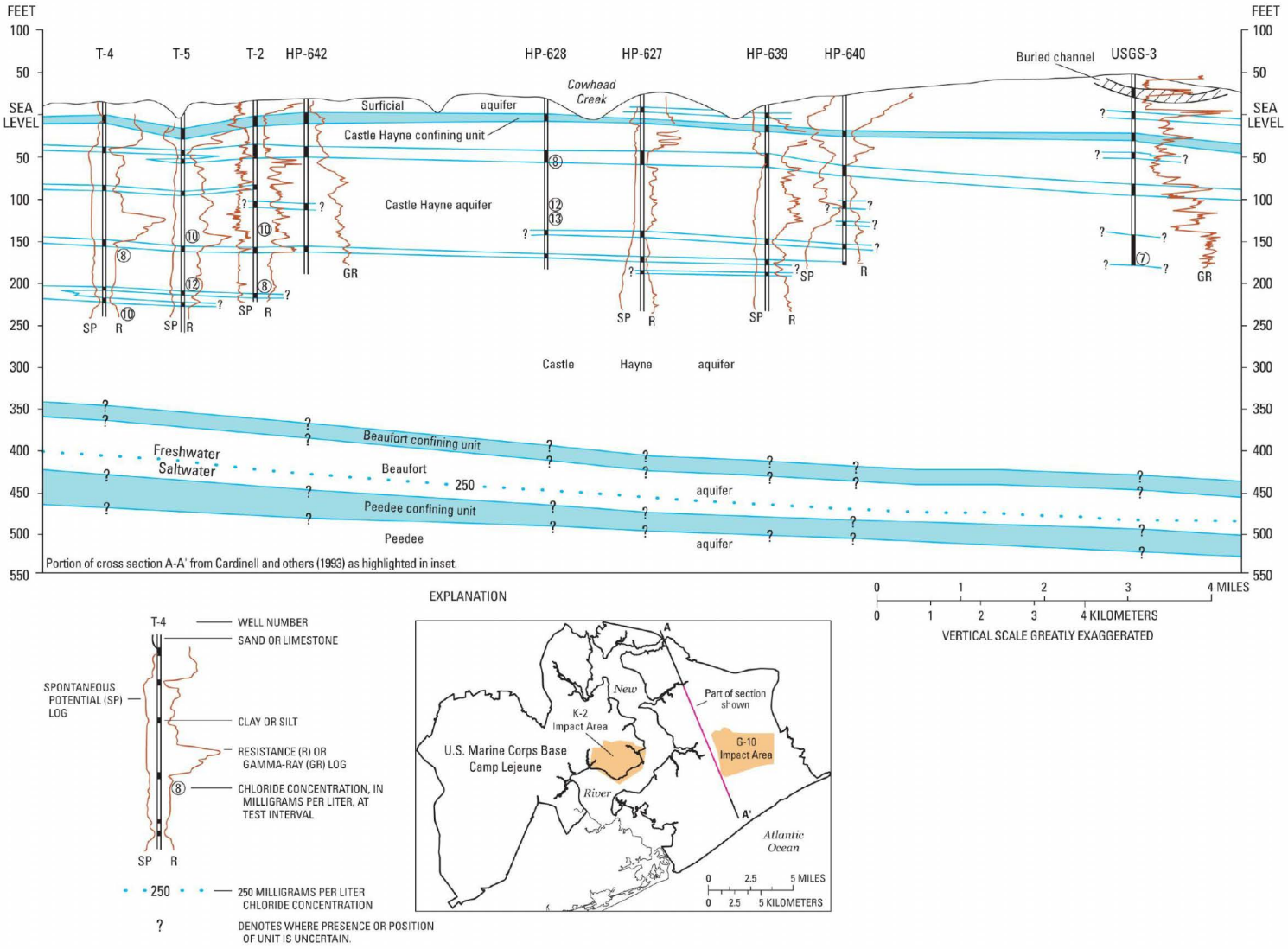

FIGURE 2-2 Geologic cross section of Camp Lejeune. Source: Harden et al. 2004.

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Castle Hayne Aquifer

The thickness of the Castle Hayne aquifer can range from about 200 to 400 ft. The aquifer is thinnest in the area of Camp Geiger in the northwest corner of the base and thickest in the eastern boundary. The bottom of the Castle Hayne aquifer is bounded by a regionally continuous clay unit, which is designated the Beaufort confining unit. All the groundwater-extraction wells in the base are in the Castle Hayne aquifer. The aquifer consists primarily of beds of sand, shell, and limestone (Winner and Coble 1989). The highly conductive material decreases from west to east across Camp Lejeune. The estimated hydraulic conductivity of the aquifer ranges from 14 to 91 ft/day (Cardinell et al. 1993). A portion of water from the surficial aquifer is able to infiltrate (move through or around) the upper confining unit, and this serves as the primary mechanism for recharging the Castle Hayne aquifer. Harned et al. (1989) also observed that in interstream areas the water level in the surficial aquifers can be 2-6 ft higher than the Castle Hayne aquifer and that the high vertical gradients can induce considerable vertical recharge. There is also some evidence of a potential for recharge of the Castle Hayne aquifer through the lower confining unit from the Beaufort aquifer (Cardinell et al. 1993). Finally, several paleostream channels have been identified within the Castle Hayne aquifer; these highly permeable, sandy channel beds can have considerable influence in local groundwater recharge, transport, and discharge patterns.

Characteristics of Source Zones

Predicting the dynamics of contaminant transport from contaminant source zones requires the use of groundwater models that simulate a complex set of fate and transport processes. Results from these models should be interpreted in light of a conceptual framework that integrates the chemical and geologic complexities in sources and receptors to establish a relationship between the contaminant source and the groundwater wells. An example of such a source-receptor conceptual model for a waste site contaminated with volatile organic compounds (VOCs) like PCE or TCE is illustrated in Figure 2-3.

At a typical waste site, spent VOCs are present in the unsaturated zone (a partially saturated soil layer above the water table) in the form of dense nonaqueous-phase liquids (DNAPLs). Pure-phase VOCs are DNAPLs that do not mix with water and have an "oily" texture. They can be trapped in soil pore spaces, and their dissolution (dissolving process) is limited by a complex set of mass-transfer processes (Miller et al. 1991; Jackson 1998; Clement et al. 2004b). Furthermore, considerable spatial variability in DNAPL mass distribution in a source region is almost inevitable; consequently, mass detection at DNAPL-contaminated field sites is extremely difficult and uncertain (Abriola 2005).

Laboratory-scale tank studies have indicated that under typical groundwater-flow conditions the DNAPL dissolving process will be limited by various mass-transfer processes, so concentrations of only about 10-20% of the maximum solubility level can be obtained (Clement et al. 2004a). Furthermore, waste DNAPLs, similar to the ones disposed of at Camp Lejeune, may mix with other chemicals that limit the mass-transfer kinetics further and lead to considerable reduction in solubility (Clement et al. 2002). Therefore, the presence of even a small volume of DNAPL can contaminate a large volume of groundwater for several decades as DNAPL continues to dissolve.

Figure 2-3 illustrates various possible pathways for groundwater contamination from a DNAPL source. If the quantity of the waste product (DNAPL) is high enough, the waste will migrate downward and penetrate the water table. The vertical migration will eventually cease, and the DNAPL will be trapped in the pore spaces or will pool over low permeable clay layers. The DNAPL phase will slowly dissolve into the water phase, and the dissolved plume will be transported toward the extraction wells. The migration patterns of DNAPL contaminants will also be highly influenced by local hydrogeologic conditions. The presence of low-permeability units (such as the Castle Hayne confining unit or any clay units) would limit vertical migration of both DNAPL and dissolved contaminants. At Camp Lejeune, all

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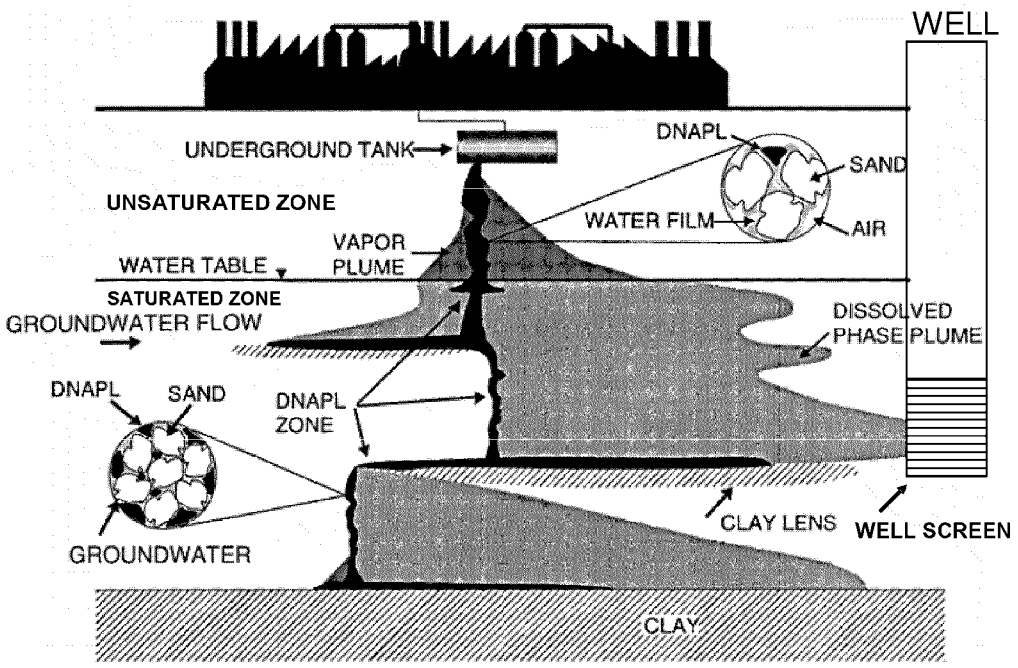

FIGURE 2-3 Conceptual model of DNAPL transport. The well is shown at an exaggerated scale. Source: Modified from Jackson 1998. Reprinted with permission; copyright 1998, *Hydrogeology Journal*.

the groundwater-supply wells are beneath the surficial aquifer. Therefore, the ability of the contaminants to reach the receptor (well screen) at the site depends on local groundwater gradients, on the thickness (or existence) and geometry of the low-permeability clay or silt zones between the source and the well, and on the geometry of the hydrostratigraphic units. The presence of a thick clay unit between the source and the receptor retards transport; however, strong pumping could induce vertical gradients and enhance contaminant transport.

Water-Treatment Plants and Distribution System

A chronology of the water-supply systems providing water to the residential areas at Camp Lejeune from 1941 to 2000 is presented in Table 2-1. At various times, four systems have been the primary sources of water for residences other than barracks at Camp Lejeune since the first system was put into service: Hadnot Point, Tarawa Terrace, Marine Corps Air Station, and Holcomb Boulevard. Several smaller systems have supplied or still supply other areas of the base that have relatively low populations. For each system, a set of supply wells pumped water to a centralized water-treatment plant, where the water was mixed before distribution to housing areas, public buildings (such as schools), businesses, and workplaces.

Figure 2-4 provides an illustration of a conceptual model of a water-supply system at Camp Lejeune. Water-supply wells collected groundwater and pumped it to the water-treatment plant when the wells were turned on. Not all the wells operated at the same time. The wells were "cycled," meaning that only a few wells pumped water to the treatment plant at any given time. Water from several wells was mixed at the treatment plant and processed before being distributed in the pipes that supplied water to the base. Limited historical information is available on the pumping schedules of the wells or the water-treatment techniques that were used.

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In general, the water-treatment processes used by the Marine Corps generally included coagulation, sedimentation, filtration (with sand or anthracite), and lime softening (Marine Corps, personal commun., May 22, 2008). The American Water Works Association (AWWA) reported that efficiency of removal of VOCs would be poor (0-20%) without lime softening and poor to fair (0-60%) with lime softening, of synthetic organic chemicals poor to good (0-80%), and of metals good to excellent (80-100%) except for chromium^{+6} (less than 20%) (AWWA 1995). Actual removal efficiencies are site-specific and depend on how each water-treatment plant is operated.

TABLE 2-1 Water Supply of Housing Areas, Camp Lejeune, North Carolina (1941-2000)

Housing Area	Water-Treatment Plant	Dates of Service
Family housing areas		
Courthouse Bay	Courthouse Bay	1942-2000
Berkeley Manor	Hadnot Point	1961-1971
	Holcomb Boulevard	1972-2000
Hospital Point	Hadnot Point	1947-2000
Knox Trailer Park	Tarawa Terrace	1952-1986
	Holcomb Boulevard	1987-2000
Knox Trailer Park Expanded	Holcomb Boulevard	1989-2000
Marine Corps Air Station	Marine Corps Air Station	1958-2000
Midway Park	Hadnot Point	1943-1971
	Holcomb Boulevard	1972-2000
Paradise Point Cape Cod	Hadnot Point	1948-1971
	Holcomb Boulevard	1972-2000
Paradise Point Capehart	Hadnot Point	1962-1971
	Holcomb Boulevard	1972-2000
Paradise Point Cracker Box	Hadnot Point	1947-1971
	Holcomb Boulevard	1972-2000
Paradise Point general officer housing	Hadnot Point	1943-1971
	Holcomb Boulevard	1972-2000
Paradise Point two-story housing	Hadnot Point	1943-1971
	Holcomb Boulevard	1972-2000
Rifle Range housing	Rifle Range	1942-1993
	Onslow County	1994-2000
Tarawa Terrace I and II	Tarawa Terrace	1952-1986
	Holcomb Boulevard	1987-2000
Watkins Village	Holcomb Boulevard	1978-2000
Barracks subcamps (not individual barracks)		
Camp Geiger	Camp Geiger	1941-1976
	Marine Corps Air Station	1977-2000
Camp Johnson	Camp Johnson	1941-1986
	Holcomb Boulevard	1987-2000
Courthouse Bay	Courthouse Bay	1941-2000
French Creek	Hadnot Point	1943-2000
Hadnot Point	Hadnot Point	1943-2000
Rifle Range	Rifle Range	1941-1993
	Onslow County	1994-2000

Source: Marine Corps, personal commun., March 13, 2008.

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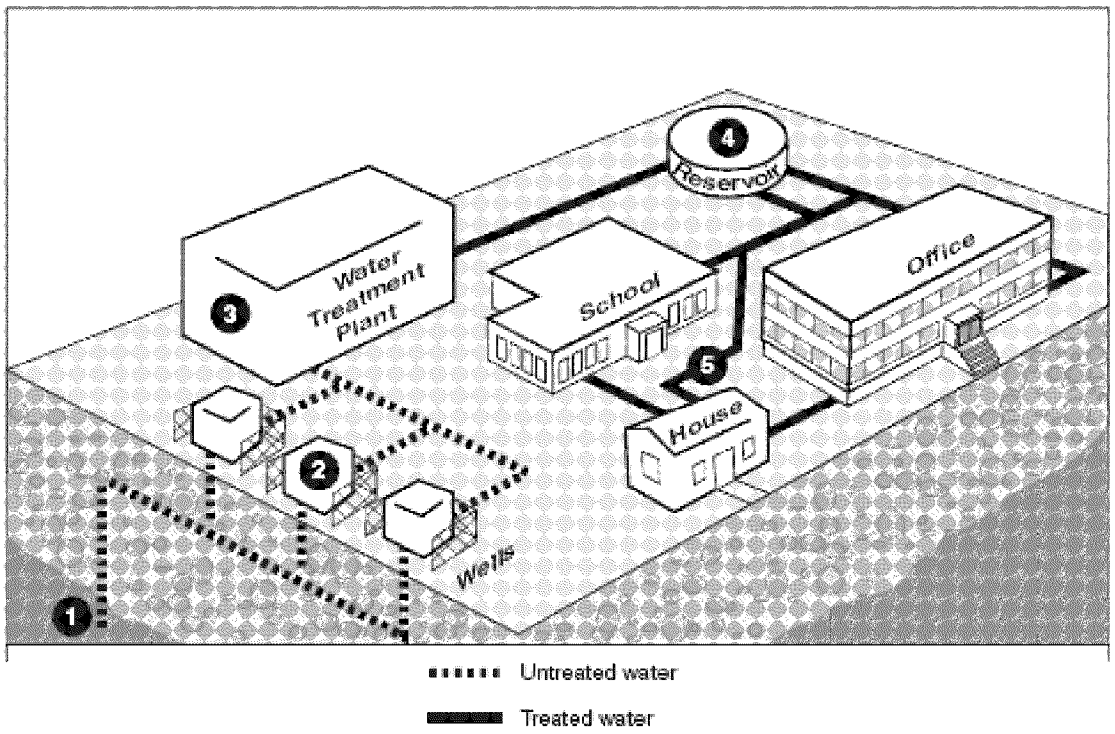

FIGURE 2-4 Conceptual model of a Camp Lejeune water system. (1) The drinking water at Camp Lejeune is obtained from groundwater pumped from a freshwater aquifer located approximately 180 ft below the ground. (2) Groundwater is pumped through wells located near the water-treatment plant. (3) In the water-treatment plant, the untreated water is mixed and treated through several processes: removal of minerals to soften the water, filtration through layers of sand and carbon to remove particles, chlorination to protect against microbial contamination, and fluoride addition to help prevent tooth decay. (4) After the water is treated, it is stored in ground and elevated storage reservoirs. (5) When needed, treated water is pumped from the reservoirs and tanks to facilities, such as offices, schools, and houses on the base. Source: GAO 2007.

Review of Contaminated Areas

The committee evaluated data on hazardous-waste site locations and characteristics in the vicinity of the water-supply well and residential service locations for the water systems listed in Table 2-1 (Baker Environmental, Inc 1999, CH2M Hill and Baker Environmental, Inc 2005). Table 2-2 summarizes the contaminants found in soil or groundwater at waste sites near supply wells. Details of the contamination near supply wells serving Tarawa Terrance and Hadnot Point are presented later in this chapter. Waste sites in the vicinity of other water-supply areas are described briefly in Appendix C (Table C-1).

COMMITTEE'S WATER-SUPPLY EVALUATION APPROACH

The committee focused its attention on the Tarawa Terrace and Hadnot Point water-supply systems. The systems were evaluated differently because much more work had been done to characterize the contamination of the Tarawa Terrace system than that of the Hadnot Point system. For Tarawa Terrace, the committee relied exclusively on reports by ATSDR (Faye 2007; Lawrence 2007; Faye and Green 2007; Faye and Valenzuela 2007; Maslia et al. 2007; Faye 2008; Jang and Aral 2008; Wang and Aral 2008). The reports included analyses of the water-quality data conducted in conjunction with ATSDR's

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TABLE 2-2 Contaminants Found in Soil or Groundwater at Hazardous Waste Sites Near Water-Supply Wells

Water System	Approximate Number Identified Hazardous-Waste Sites	Contaminants Detected in Soils (S) or Monitoring Wells (M, D)
Tarawa Terrace	2	Chlorinated solvents (S ,M, D) BTEX (S, M)
Hadnot Point	13	Pesticides (S, M) Polychlorinated biphenyls (S) Metals (S, M) Chlorinated solvents (S, M, D) Fuel compounds (M) Benzene (M) Toluene (M) Ethylbenzene (M) Xylenes (M) BTEX (M) Petroleum products (S, M) Volatile compounds (S) Semivolatile compounds (S)
Holcomb Boulevard	5	Pesticides (S, M) Volatile and semivolatile compounds (S, M) Metals (M)
Marine Corps Air Station	6	Volatile and semivolatile compounds at two locations (S, M) Pesticides at one location (S, M)
Rifle Range	2	VOCs (M)
Camp Geiger	13	Chromium (M) Lead (M) VOCs (M)
Camp Johnson	2	None

Abbreviations: BTEX = benzene, toluene, ethylene, and xylene; D = deeper wells in Castle Hayne aquifer, source of water-supply wells; M = shallow wells, surficial aquifer, or soil vadose zone.
Sources: Baker Environmental, Inc 1999; CH2M Hill and Baker Environmental, Inc 2005.

water-quality modeling. For Hadnot Point, the committee conducted its own review of information that was in the public record. The committee used multiple sources, including the 2007 GAO report, remedial investigation reports (Baker Environmental, Inc 1993, 1994, 1995), data summarized in the "Camp Lejeune water"(CLW) documents (CD accompanying Maslia et al. 2007), and planning documents from ATSDR (Maslia 2008). The goal was to get an understanding of the contamination of water supplies serving Hadnot Point residents, including which VOCs were of potential concern and the degree to which contaminant concentrations in the water supply varied. In consulting the CLW documents, the committee focused on contaminant measurements taken while the contaminated wells were operating, including measurements of the water-supply wells and from the water-treatment plant and distribution system. As noted earlier, water from the supply wells was mixed at the water-treatment plant before distribution. Because all water samples from the distribution system were taken after water from multiple supply wells was mixed, they were categorized as "mixed" water samples. Sampling of mixed water occurred before and after water was treated or "finished." Samples taken from mixed water give a better indication of the concentrations of contaminants delivered to the tap than samples taken from supply wells. However, water-quality data on the individual supply wells shed light on the wells that were contaminated and permit preliminary documentation of the extent of contamination.

In determining its approach to evaluating the water-quality data on Hadnot Point, the committee wrestled with reporting data that have not been collected by a process that involved standard quality-assurance procedures. The process that was used for abstraction of the water-quality data (see Appendix

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C) did not consider multiple aspects of the data, including the sampling strategy, methods for sample collection and analysis, chain of custody of samples, recording and interpretation of detection or quantitation limits, and duplication of sampling results in source documents. Thus, the data cited are only for illustrative purposes, and references to the primary documents are provided to facilitate additional work.

TARAWA TERRACE WATER SUPPLY

Discovery and Investigation of the Contamination at Tarawa Terrace

The Tarawa Terrace water-supply system began operations in 1952. Seven wells initially supplied water to the system, and more wells were added over the years. A total of 16 wells served the system at some time between 1952 and 1987. The wells operated on a cycled schedule. Wells were taken offline or were closed for various reasons between 1962 and 1987 (Maslia et al. 2007).

During August 1982, a routine analysis with gas chromatography-mass spectrometry (to screen the water samples collected from the Tarawa Terrace water-treatment plant for chlorination byproducts) indicated high concentrations of halogenated hydrocarbons, a class of VOCs (Faye and Green 2007). Further analysis confirmed the presence of PCE in finished water at 76-104 µg/L (Faye and Green 2007). Sporadic sampling in 1982-1985 also indicated detectable concentrations of TCE, which is a degradation byproduct of PCE.

In January 1985, the North Carolina Department of Natural Resources and Community Development (NCDNRCD) began routine sampling of water from supply wells TT-23, TT-25, and TT-26 and finished water from the water-treatment plant (Faye 2008). The data indicated varied PCE and TCE contamination. For example, PCE ranged from nondetectable to 132 µg/L and from 3.8 to 1,580 µg/L in wells TT-23 and TT-26, respectively. Wells TT-23 and TT-26 were temporarily removed from service in February 1985. Later, well TT-26 was closed permanently, and well TT-23 was used intermittently for several days during March and April 1985 and finally shut down in April 1985 (GAO 2007). From January to September 1985, samples were taken from wells TT-30, TT-31, TT-52, TT-54, and TT-67, and PCE and its degradation products were not detected.

In April 1985, NCDNRCD conducted extensive field investigation to map the PCE plume and identify the contaminant source. On the basis of that investigation, the northwest edge of the plume was determined to be close to ABC One-Hour Cleaners. A shallow monitoring well installed close to the cleaners detected an extremely high PCE concentration of 12,000 µg/L (Faye and Green 2007). Such a high concentration is an indication of a source region that contains pure-phase PCE (the highest possible concentration of PCE in water is about 110,000 µg/L). Further investigations revealed that ABC One-Hour Cleaners had routinely used PCE in dry-cleaning operations since 1953. Shiver (1985) reported that PCE releases from various accidental spills entered the septic system through a floor drain. Furthermore, spent PCE was routinely put through a filtration-distillation process that produced dry still bottoms (sludge). Until about 1982, such waste products were used to fill potholes in a nearby alleyway. The exact date of the termination of those disposal practices is unknown; ATSDR estimates that they ceased in 1985 (Faye and Green 2007).

Several on-base sources and episodes were documented. Faye and Green (2007) report that a "strong gasoline type odor" was noted at water-supply well TT-53 during October 1986 while personnel from the U.S. Geological Survey (USGS) conducted a routine well reconnaissance. The well was not in service at the time. The gasoline contamination was traced to various spills and leaks from 12 underground storage tanks (USTs) associated with various buildings in the Tarawa Terrace shopping center. For example, on September 21, 1985, a catastrophic failure discharged about 4,400 gal of unleaded gasoline to the subsurface. A review of past releases indicated that small leaks of gasoline products probably occurred at the site beginning in the 1950s. As of May 4, 1987, more than 2 ft of floating gasoline was determined to be present above the water table in the vicinity of Building TT-2453.

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Investigation of groundwater contamination due to sources other than the ABC One-Hour Cleaners began after 1990 (Faye and Green 2007). The investigations focused on above-ground petroleum-storage tanks, buildings that housed filling stations, and USTs. The above-ground tanks were between State Route 24 and the railroad tanks near water-supply wells TT-27 and TT-55. They were constructed in 1942 and stored petroleum until about 1980, when they were converted to waste-oil storage. Most of the remedial investigations of buildings and USTs focused on areas in or near the Tarawa Terrace shopping center. Information on the installation, use, and release histories of the USTs is sparse. At least some of the tanks may have been constructed as early as the 1950s. High concentrations of benzene and toluene were measured in samples taken from monitoring wells, and several benzene plumes were mapped as a result of those investigations (see Faye and Green 2007, Table E9 and Figures E7 and E9).

Other Contaminants of Concern at Tarawa Terrace

PCE is the primary contaminant at the Tarawa Terrace site, but other contaminants have been detected in supply wells, including TCE, 1,1-dichloroethylene (DCE), *cis*- and *trans*-1,2-DCE, benzene, toluene, and vinyl chloride. Many of these contaminants—including TCE, DCE, and vinyl chloride—may have resulted from degradation of PCE. Microorganisms in the subsurface degrade PCE to TCE under favorable anaerobic conditions. TCE later degrades to DCE (primarily *cis*-1,2-DCE [Bradley 2003]); similarly, DCE degrades to vinyl chloride and eventually to ethane, an innocuous degradation product (Bradley 2003; Clement et al. 2000; Clement et al. 2002). Some of the chlorinated compounds (including TCE, DCE, and vinyl chloride) can also be aerobically oxidized to yield carbon dioxide (Clement et al. 2000; Bradley 2003). At the ABC One-Hour Dry Cleaners site, water samples from monitoring wells in the waste-disposal zone contained TCE at concentrations up to 690 µg/L and total DCE at up to 1,200 µg/L on April 23, 1992 (Faye and Green 2007). The highest measured concentrations of TCE and total DCE in the Tarawa Terrace supply wells were 62 µg/L (estimated value on July 11, 1991) and 92 µg/L (measured value on January 16, 1985), respectively (Faye and Green 2007).

Water-Quality Data on the Tarawa Terrace System

ATSDR (Faye and Green 2007) lists 16 wells that served the Tarawa Terrace water-supply system. Two of them (TT-26 and TT-23 [also referred to as TT New Well]) were shut down on February 8, 1985, because of PCE contamination (GAO 2007). However, well TT-23 was used briefly after that date—at least on March 11-12, 1985, and on April 22, 23, and 29, 1985 (GAO 2007). ATSDR indicates that the well was removed from service in May 1985. Table 2-3 presents the PCE concentrations found in samples taken from various supply wells, including TT-23 and TT-26. Well TT-26 was highly contaminated. The highest concentration (1,580 µg/L) was obtained while the well was in service. Concentration decreased appreciably after the well was taken off line and then increased. Well TT-23 also showed evidence of PCE contamination. Again, the highest concentration was found after a period of regular operation in January 1985, and concentration was lower in later periods; notably, concentration was higher after 24 h of continuous operation (on March 12, 1985) than at the beginning of that period of service.

Measurements of mixed water samples suggest that supply wells TT-23 and TT-26 were major contributors to contamination of the Tarawa Terrace water supply. ATSDR (Faye and Green 2007) summarized results of analyses of PCE, TCE, and *trans*-1,2-DCE measured in water samples collected from May 1982 to October 1985 at the Tarawa Terrace water-treatment plant and locations (some unknown) throughout the water-distribution system (see Table 2-4). TCE and *trans*-1,2-DCE were not measured in all water samples (indicated by a "-" in the table). PCE ranged from undetected to 215 µg/L; the highest reported concentration was in a water sample collected from storage tank STT-39A on February 11, 1985, several days after wells TT-23 and TT-26 were removed from service. With the exception of that sample,

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TABLE 2-3 Observed Concentrations of PCE in Tarawa Terrace Water-Supply Wells

Sample Date	PCE, µg/L	Detection Limit, µg/L
Supply well TT-23		
Jan. 16, 1985	132	10
Feb. 12, 1985	37	10
Feb. 19, 1985	26.2	2
Feb. 19, 1985	ND	10
Mar. 11, 1985	14.9	10
Mar. 11, 1985	16.6	2
Mar. 12, 1985	40.6	10
Mar. 12, 1985	48.8	10
Apr. 9, 1985	ND	10
Sept. 25, 1985	4[a]	2
July 11, 1991	ND	10
Supply well TT-25		
Feb. 5, 1985	ND	10
Apr. 9, 1985	ND	10
Sept. 25, 1985	0.43[a]	10
Oct. 29, 1985	ND	10
Nov. 4, 1985	ND	10
Nov. 12, 1985	ND	10
Dec. 3, 1985	ND	10
July 11, 1991	23	10
Supply well TT-26		
July 16, 1985	1,580	10
Feb. 12, 1985	3.8	10
Feb. 19, 1985	64	10
Feb. 19, 1985	55.2	10
April 9, 1985	630	10
June 24, 1985	1,160	10
Sept. 25, 1985	1,100	10
July 11, 1991	350	10
Supply well TT-30		
Feb. 6, 1985	ND	10
Supply well TT-31		
Feb. 6, 1985	ND	10
Supply well TT-52		
Feb. 6, 1985	ND	10
Supply well TT-54		
Feb. 6, 1985	ND	10
July 11, 1991	ND	5
Supply well TT-67		
Feb. 6, 1985	ND	10
Supply well RW1		
July 12, 1991	ND	2
Supply well RW2		
July 12, 1991	760	2
Supply well RW3		
July 12, 1991	ND	2

[a]Estimated value.
Abbreviation: ND = not detected.
Source: Adapted from Maslia et al. 2007.

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TABLE 2-4 Summary of Selected Analyses for PCE, TCE, and *trans*-1,2-DCE in Water Samples Collected at Tarawa Terrace Water-Treatment Plant and Tarawa Terrace Addresses

Sample Location or *Event*	Date	PCE, µg/L	TCE, µg/L	*Trans*-1,2-DCE, µg/L	Detection Limit, µg/L
Tap water at Bldg. TT-2453	May 27, 1982	80	—	—	Unknown
Tap water at Bldg. TT-2453	July 28, 1982	104	—	—	Unknown
TTWTP Bldg. TT-38	July 28, 1982	76	—	—	Unknown
TTWTP Bldg. TT-38	July 28, 1982	82	—	—	Unknown
Tap water; address unknown	Feb. 5, 1985	80	8.1	12	Unknown
Well TT-26 shut down	Feb. 8, 1985				
Well TT-23 initially shut down[a]	Feb. 8, 1985				
TTWTP Tank STT-39	Feb. 11,1985	215	8	12	10
TTWTP Bldg. TT-38	Feb. 13, 1985	ND	ND	ND	10
TTWTP Bldg. TT-38	Feb. 19, 1985	ND	ND	ND	2
TTWTP Bldg. TT-38	Feb. 22, 1985	ND	ND	ND	10
TTWTP Bldg. TT-38	Mar. 11, 1985	ND[a]	ND[a]	ND[a]	2
TTWTP Bldg. TT-38	Mar. 12, 1985[b]	6.6[a]	ND[a]	ND[a]	10
TTWTP Bldg. TT-38	Mar. 12, 1985[b]	8.9[a]	ND[a]	ND[a]	2
TTWTP Bldg. TT-38	Mar. 12, 1985[c]	20[a]	1.1[a]	1.2[a]	2
TTWTP Bldg. TT-38	Mar. 12, 1985[c]	21.3[a]	ND[a]	ND[a]	10
TTWTP Bldg. TT-38	Apr. 22, 1985	1[a]	4.1[a]	ND[a]	10
TTWTP Bldg. TT-38	Apr. 23, 1985	ND[a]	1.4[a]	ND[a]	10
TTWTP Bldg. TT-38	Apr. 29, 1985	3.7[a]	ND[a]	—	10
Well TT-23 ceases to operate	May 1985				
TTWTP Bldg. TT-38	May 15, 1985	ND	ND	ND	10
TTWTP Bldg. TT-38	July 1, 1985	ND	ND	ND	10
TTWTP Bldg. TT-38	July 8, 1985	ND	ND	ND	10
TTWTP Bldg. TT-38	July 23, 1985	ND	ND	ND	10
TTWTP Bldg. TT-38	July 31, 1985	ND	ND	ND	10
TTWTP Bldg. TT-38	Aug. 19, 1985	ND	ND	ND	10
TTWTP Bldg. TT-38	Sept.11, 1985	ND	ND	ND	10
TTWTP Bldg. TT-38	Sept. 17, 1985	ND	ND	ND	10
TTWTP Bldg. TT-38	Sept. 24, 1985	ND	ND	ND	10
TTWTP Bldg. TT-38	Oct. 29, 1985	ND	ND	ND	10

[a]Intermittent operation of well TT-23 after February 8, 1985, including at least March 11 and 12 and April 22, 23, and 29, 1985.
[b]Samples collected downstream of TTWTP reservoir after well TT-23 operated for 24 h.
[c]Samples collected upstream of TTWTP reservoir after well TT-23 operated for 24 h.
Abbreviations: — = constituent not determined; ND = not detected; TTWTP = Tarawa Terrace water-treatment plant.
Source: Adapted from Table E12 of Faye and Green 2007.

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quantified samples were collected on dates when TT-23 or TT-26 was contributing to the water supply. Most of the analytic results listed in Table 2-4 had nondetectable concentrations of TCE and *trans*-1,2-DCE, but not all samples were tested for these chemicals. Before February 8, 1985, those compounds were measured in only one water sample, which contained TCE at 8.1 µg/L and *trans*-1,2-DCE at 12 µg/L. Similar concentrations of TCE and *trans*-1,2-DCE (8 and 12 µg/L, respectively) were reported in the water-storage tank sample (STT-39A, February 11, 1985).

Faye and Green (2007) also summarized analytic results for benzene and toluene in finished-water samples collected at the Tarawa Terrace water-treatment plant in 1985 (see Table 2-5). Benzene reportedly ranged from "not detected" to 2 µg/L and toluene from "not detected" to 4 µg/L; all concentrations were below the stated laboratory detection limit of 10 µg/L. (The accuracy of values below the detection limit is less certain.) It is notable that all samples in which benzene and toluene were detected were taken after February 8, 1985, the date when the two contaminated wells were closed, except for one sample with detection of benzene taken on March 11, 1985, during a period in which well TT-23 was temporarily back in service). The low concentrations (below the detection limit) of benzene and toluene in finished water and high measurements at a few monitoring wells (Faye and Green 2007) suggest that TT-23 and TT-26 may not have been the only source of VOC contamination in the Tarawa Terrace water-supply system. Analytic results on samples collected in 1986 from the Tarawa Terrace water-treatment plant are available (for example, on a CD accompanying Maslia et al. 2007) but have yet to be summarized.

Groundwater Fate and Transport Modeling

ATSDR performed a historical reconstruction and analysis of the contamination of the Tarawa Terrace water-supply system. It involved analyses of groundwater flow, contaminant fate and transport (of PCE and its decay products; benzene and other petroleum contaminants were not considered), and distribution in the water system. This section provides a brief review of the groundwater-modeling efforts reported in a series of ATSDR reports, including Chapters A, B, C, D, E, F, G, and H, that were made available to the committee (Faye 2007; Faye and Green 2007; Faye and Valenzuela 2007; Lawrence 2007; Maslia et al. 2007; Faye 2008; Jang and Aral 2008; Wang and Aral 2008).

Description of ATSDR's Modeling Efforts for Tarawa Terrace

ATSDR personnel used the USGS model MODFLOW to simulate groundwater flow at the site (Faye and Valenzuela 2007) and the U.S. Environmental Protection Agency (EPA) model MT3DMS to simulate PCE transport (Faye 2008). MODFLOW is a three-dimensional finite-difference code that is capable of simulating groundwater head distribution under both steady-state and transient-flow conditions. MT3DMS is a three-dimensional transport model that is directly coupled to MODFLOW. MODFLOW and other MODFLOW-family transport codes are well-established public-domain codes that are routinely used in court cases to simulate the fate and transport of dissolved chemicals (Denton and Sklash 2006); however, they invoke several assumptions for simulating complex DNAPL contaminants, such as PCE. For example, MT3DMS can predict the transport only of dissolved contaminants, so a key approximation was made to represent the mass dissolved from the DNAPL source. To apply MT3DMS, ATSDR replaced the highly complex DNAPL contaminated source zone with a hypothetical model node where PCE was injected directly into the saturated aquifer formation at a constant rate (1.2 kg/day).

ATSDR in collaboration with personnel from the Georgia Institute of Technology also used a groundwater simulation and optimization tool, the Pumping Schedule Optimization System (PSOpS), to evaluate the effect of pumping-schedule variations on PCE arrival at water-supply wells (Wang and Aral

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Contaminated Water Supplies at Camp Lejeune: Assessing Potential Health Effects

TABLE 2-5 Benzene and Toluene Concentrations in Water Samples Collected at Tarawa Terrace Water-Treatment Plant[a]

Site Name	Date	Benzene, µg/L	Toluene, µg/L
TTWTP Bldg. TT-38	Feb. 13, 1985	ND	ND
	Feb. 22, 1985	ND	ND
	Mar. 11, 1985	1.6	—
	Apr. 22, 1985	ND	ND
	Apr. 23, 1985	ND	ND
	May 15, 1985	ND	ND
	July 1, 1985	ND	ND
	July 8, 1985	ND	ND
	July 23, 1985	ND	ND
	July 31, 1985	ND	ND
	Aug. 19, 1985	ND	ND
	Sept. 11, 1985	ND	4
	Sept. 17, 1985	ND	ND
	Sept. 24, 1985	ND	ND
	Oct. 29, 1985	ND	ND
	Dec. 2, 1985	2	—
	Dec. 18, 1985	1	—
TTWTP tank SST-39A	Feb. 11, 1985	ND	ND

[a]Detection limit for all analyses was 10 µg/L.
Abbreviations: — = constituent not determined; ND = not detected; TTWTP = Tarawa Terrace water-treatment plant.
Source: Faye and Green 2007.

2008). In addition, the team used a multiphase transport simulator, TechFlowMP, which has the capability to use first-order biodegradation kinetics to simulate the fate and transport of PCE and its byproducts TCE, DCE, and vinyl chloride (Jang and Aral 2008). Unlike the MODFLOW and MT3DMS codes, the PSOpS and TechFlowMP codes lack validation by a broad spectrum of practicing geoscientists in an open-source environment.

ATSDR combined the hydrostratigraphic units above the Castle Hayne aquifer and modeled them as a single unconfined layer. The modelers assumed this layer to be underlain by a local confining layer. The permeable Castle Hayne aquifer formation, where all the water-supply wells are, is assumed to be below that confining layer. In the model, the Castle Hayne aquifer formation is divided into five distinct units. The details of all the modeled hydrogeologic units, their assumed thicknesses, and the corresponding model layer numbers that represent the units are summarized in Table 2-6. In both MODFLOW and MT3DMS, the subsurface was conceptualized as a fully saturated flow environment with seven layers that represented various hydrogeologic conditions. The model parameters used in the flow and transport models are summarized in Table 2-7. The boundary conditions of the models included generalized head boundary in the northern and northeastern edges of the model, no flow boundary in the western edge (which followed a natural divide), and constant head boundary conditions in the southern edge and part of the southeast direction. On the basis of rainfall data, an average recharge to the aquifer was estimated to be 13.2 in/year. The DNAPL source zone was represented by using a model node where PCE was injected continuously into the unconfined model layer-1 of the saturated zone at a constant rate of 1.2 kg/day (Faye 2008).

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TABLE 2-6 Assumed Thickness and Layer of Castle Hayne Aquifer Units

Geologic Unit	Thickness, ft	Layer No.
Tarawa Terrace unit (surficial layer)	8-30	1
Tarawa Terrace confining unit (surficial layer)	8-20	1
Upper Castle Hayne aquifer-River Bend unit (surficial layer)	16-56	1
Local confining unit	7-17	2
Upper Castle Hayne aquifer-lower unit	8-30	3
Middle Castle Hayne aquifer confining unit	12-28	4
Middle Castle Hayne aquifer	32-90	5
Lower Castle Hayne aquifer confining unit	18-30	6
Lower Castle Hayne aquifer	41-64	7
Beaufort confining layer	Bottom boundary	N/A

Source: Modified from Faye and Valenzuela 2007.

ATSDR calibrated the MODFLOW and MT3DMS models for Tarawa Terrace by using a "hierarchical process" that included the simulation of the following four successive scenarios: (1) predevelopment (before the 1950s) flow conditions without pumping, (2) transient flow conditions involving pumping, (3) fate and transport of the PCE plume, and (4) concentration of PCE at the Tarawa Terrace water-treatment plant and water-distribution system. The first two steps involved flow modeling exclusively, and the latter two steps involved combined modeling of groundwater flow and PCE transport. The groundwater-flow patterns and PCE concentration contours predicated for the surficial layer (model layer 1) for December 1984 is shown in Figure 2-5. The results of the PCE modeling study with MT3DMS indicated that the vast majority of the PCE that reached Tarawa Terrace water-treatment plant came from well TT-26. The model results show that PCE at well TT-26 exceeded EPA's current maximum contaminant level (MCL) for drinking water of 5 µg/L as early as January 1957 and that a corresponding breakthrough of PCE in well TT-23 occurred roughly in December 1974 (Faye 2008). The model-predicted groundwater concentrations and the simulated extraction rates were used in a mixing model to evaluate the flow-weighted PCE concentration at the water-treatment plant. Those estimates indicated that the concentration of PCE in the water-treatment plant output exceeded the MCL during October or November 1957 and that the concentrations remained above the MCL until the termination of pumping at well TT-26 in 1985. On the basis of ATSDR's model results, the estimated maximum concentration of PCE at the Tarawa Terrace water-treatment plant was 183 µg/L in March 1984. In the period November 1957-February 1987, the average concentration of PCE at the plant was 70 µg/L.

The estimated PCE concentration range should, however, be interpreted with considerable caution because comparison of the model predictions with measured data at various locations, as summarized in Table 2-8 and by Faye (2008), shows that the model predictions systematically overpredicted the point measurements in samples from supply wells TT-23 and TT-25. Also, the model results show a monotonically increasing trend, whereas the measured data are highly random. It is important to note that comparison of monthly averaged model predictions with point measurements from various locations is problematic, although this practice is not uncommon in calibration of groundwater models like this application by ATSDR (Faye 2008). Clearly, the model predictions are influenced by temporal and spatial averaging effects. In the model, the temporal variations in pumping stresses are averaged over a month, and the temporal variations in the DNAPL source release rate are averaged over a year, whereas the data on the wells' water quality represent a single time and are relevant on a much shorter time scale—hours instead of months. Similarly, spatial variations in concentration are averaged over a relatively large control volume represented by the model grid cells (the typical volume of a computational cell in layer 1 is about 100,000 ft^3), whereas the water-quality data represent spatial variations on the scale of the control volume represented by the well (estimated at about 10-1,000 ft^3).

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TABLE 2-7 Calibrated Model Parameter Concentrations Used to Simulate Groundwater Flow and Contaminant Fate and Transport in Tarawa Terrace and Vicinity

Model Parameter[a]	Model Layer[b]						
	1	2	3	4	5	6	7
Predevelopment groundwater-flow model (conditions before 1951)							
Horizontal hydraulic conductivity, K_H (ft/day)	12.2-53.4	1.0	4.3-20.0	1.0	6.4-9.0	1.0	5.0
Ratio of vertical to horizontal hydraulic conductivity, K_V/K_H[c]	1:7.3	1:10	1:8.3	1:10	1:10	1:10	1:10
Infiltration (recharge), I_R (in./year)	13.2	—	—	—	—	—	—
Transient groundwater-flow model(January 1951–December 1994)							
Specific yield, S_y	0.05	—	—	—	—	—	—
Storage coefficient, S	—	4.0×10^{-4}	4.0×10^{-4}	4.0×10^{-4}	4.0×10^{-4}	4.0×10^{-4}	4.0×10^{-4}
Infiltration (recharge), I_R (in./year)	6.6-19.3	—	—	—	—	—	—
Pumpage, Q_k (ft^3/day)	[d]	—	[d]	—	0	—	0
Fate and transport of PCE model (January 1951–December 1994)							
Distribution coefficient, K_d (ft^3/g)	5.0×10^{-6}	5.0×10^{-6}	5.0×10^{-6}	5.0×10^{-6}	5.0×10^{-6}	5.0×10^{-6}	5.0×10^{-6}
Bulk density, ρ_b (g/ft^3)	77,112	77,112	77,112	77,112	77,112	77,112	77,112
Effective porosity, n_F	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Reaction rate, r (d^{-1})	5.0×10^{-4}	5.0×10^{-4}	5.0×10^{-4}	5.0×10^{-4}	5.0×10^{-4}	5.0×10^{-4}	5.0×10^{-4}
Mass-loading rate[e], $q_S C_S$ (g/day)	1,200	—	—	—	—	—	—
Longitudinal dispersivity, α_L (ft)	25	25	25	25	25	25	25
Traverse dispersivity, α_T (ft)	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Vertical dispersivity, α_V (ft)	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Molecular-diffusion coefficient, D* (ft^2/day)	8.5×10^{-4}	8.5×10^{-4}	8.5×10^{-4}	8.5×10^{-4}	8.5×10^{-4}	8.5×10^{-4}	8.5×10^{-4}

[a]Symbolic notation used to describe model parameters obtained from Chiang and Kinzelbach (2001).
[b]Refer to Chapter B (Faye 2007) and Chapter C (Faye and Valenzuela 2007) reports for geohydrologic framework corresponding to appropriate model layers; aquifers are model layers 1, 3, 5, and 7; confining units are model layers 2, 4, and 6.
[c]For model cells simulating water-supply wells, vertical hydraulic conductivity (K_v) equals 100 ft/day to approximate gravel pack around well.
[d]Pumpage varies by month, year, and model layer; refer to Chapter K report (Maslia et al. in press) for specific pumpage data.
[e]Introduction of contaminant mass began in January 1953 and ended in December 1984.
Abbreviations: — = not applicable; d^{-1} = 1/day.
Source: Maslia et al. 2007.

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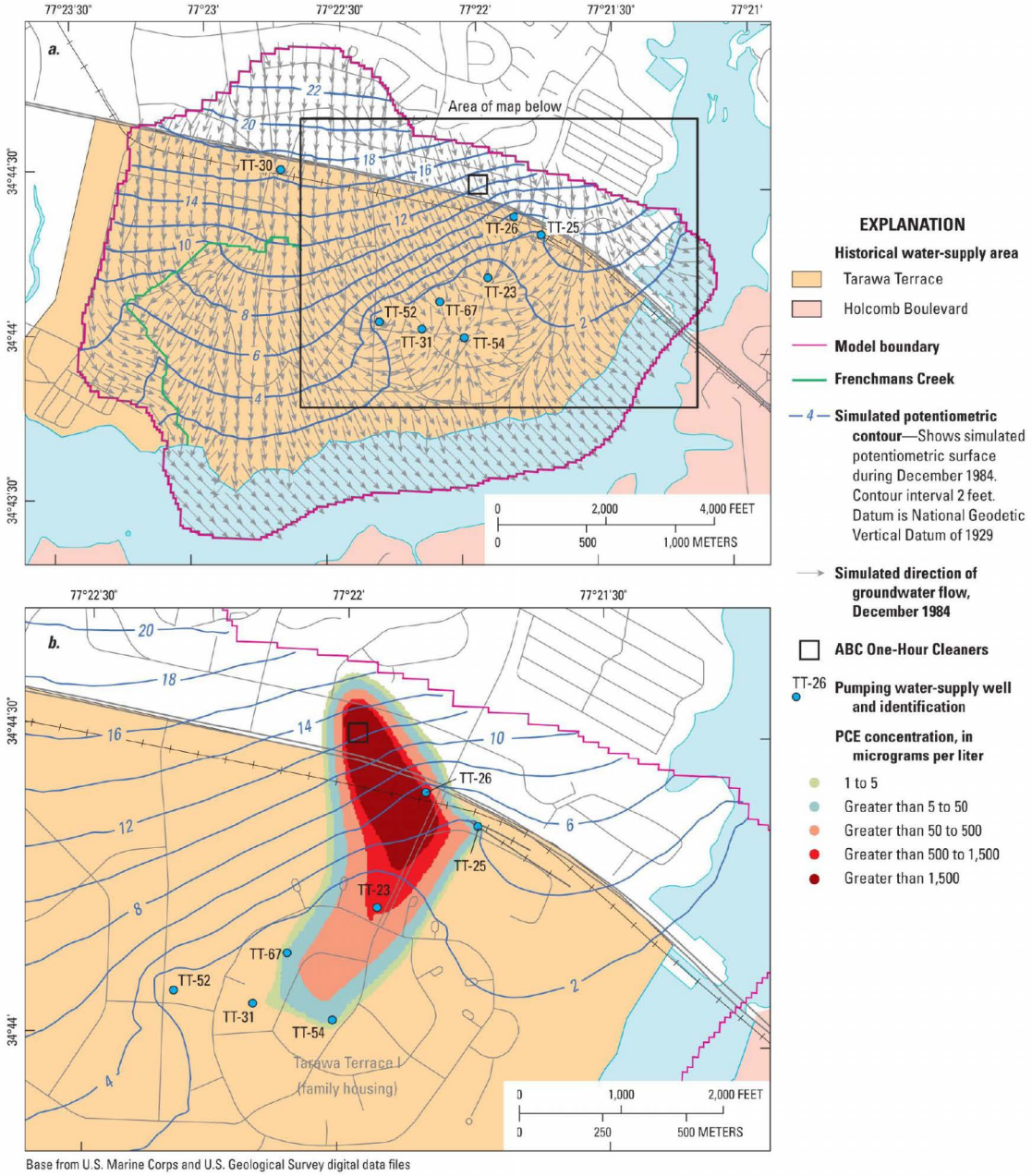

FIGURE 2-5 Simulated (*a*) water level and direction of groundwater flow, and (*b*) distribution of tetrachloroethylene (PCE), model layer 1, December 1984, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. Source: Maslia et al. 2007.

The modeling studies did not include any formal analysis to account for the temporal or spatial data-averaging effects. Instead, in the analysis presented by Faye (2008), the point measurements were used to set a "calibration target range" for constraining the model predictions; the range was arbitrarily set at about half the order of magnitude of the detected point measurements (Faye 2008); the actual target ranges used are shown in Table 2-8. For concentrations that are reported as nondetected, the lower target was set to 1 µg/L, and the upper limit was set at the analytic detection limit (Faye 2008).

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TABLE 2-8 Simulated and Observed PCE Concentrations at Water-Supply Wells and Calibration Target Range, Tarawa Terrace and Vicinity

Site	Date	PCE Concentration, µg/L		Calibrated Target Range, µg/L
		Observed	Simulated	
RW1	July 12, 1991	ND	0.0	0.0-2.0
RW2	July 12, 1991	760	1,804	240-2,403
RW3	July 12, 1991	ND	0.0	0.0-2.0
TT-23	Jan. 16, 1985	132	254	41.7-417
	Feb. 12, 1985	37.0	254	11.7-117
	Feb. 19, 1985	26.2	253	8.3-82.8
	Feb. 19, 1985	ND	253	0.0-10.0
	Mar. 11, 1985	14.9	253	4.7-47.1
	Mar. 11, 1985	16.0	253	5.2-52.5
	Mar. 12, 1985	40.6	253	12.8-128
	Mar. 12, 1985	48.0	253	15.4-154
	Apr. 9, 1985	ND	265	0.0-2.0
	Sept. 25, 1985	4.0	279	0.3-12.6
	July 11, 1991	ND	193	0.0-5.0
TT-25	Feb. 5, 1985	ND	6.2	0.0-10.0
	Apr. 9, 1985	ND	8.6	0.0-2.0
	Sept. 25, 1985	0.43[a]	18.1	0.14-1.4
	Oct. 29, 1985	ND	20.4	0.0-10.0
	Nov. 4, 1985	ND	20.4	0.0-10.0
	Nov. 13, 1985	ND	20.4	0.0-10.0
	Dec. 3, 1985	ND	22.8	0.0-10.0
	July 11, 1991	23.0	72.6	7.3-72.7
TT-26	Jan. 16, 1985	1,580	804	500-5,000
	Feb. 12, 1985	3.8	804	1.2-12
	Feb. 19, 1985	55.2	798	17.5-175
	Feb. 19, 1985	64.0	798	20.2-202
	Apr. 9, 1985	630	801	199-1,999
	June 24, 1985	1,160	732	367-3,668
	Sept. 25, 1985	1,100	788	348-3,478
	July 11, 1991	340	670	111-1,107
TT-30	Feb. 6, 1985	ND	0.0	0.0-10.0
TT-31	Feb. 6, 1985	ND	0.15	0.0-10.0
TT-52	Feb. 6, 1985	ND	0.0	0.0-10.0
TT-54	Feb. 6, 1985	ND	5.8	0.0-10.0
	July 11, 1991	ND	30.4	0.0-5.0
TT-67	Feb. 6, 1985	ND	3.9	0.0-10.0

[a]Estimated.
Abbreviation: ND = not detected.
Source: Faye 2008.

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ATSDR stated concerns about uncertainties in the pumping-schedule data used in the PCE modeling study discussed above and in the date when the MCL was predicted to be exceeded in water-supply wells and at the water-treatment plant (Faye 2008). ATSDR assumed that the major cause of uncertainty in the models was associated with pumping schedules. To address that issue, ATSDR applied PSOpS to evaluate the effect of variation in pumping schedules on the prediction of when the concentration of PCE would exceed EPA's MCL of 5.0 µg/L (Wang and Aral 2008). Analysis of PSOpS results indicated that the change in pumping schedules would change the date when the MCL was exceeded in well TT-26 from May 1956 to August 1959 and at the water-treatment plant from December 1956 to June 1960. Because insufficient historical pumping data were available to constrain the model predictions from 1953 to 1980, the ability of the advanced optimization models to estimate the dates accurately is questionable.

Biodegradation is one of the major processes by which PCE can be removed from groundwater. Under favorable natural conditions, PCE can degrade to toxic substances. ATSDR used the multiphase research tool TechFlowMP to simulate the fate and transport of PCE with three decay products: TCE, *trans*-1,2-DCE, and vinyl chloride (Jang and Aral 2008). The TechFlowMP model also predicted PCE vapor concentrations. PCE biodegradation is mediated by a series of coupled reactive transport processes, primarily under highly anaerobic conditions (Bradley 2003), and little is understood about the underlying biodegradation mechanisms. There are several controversies about the types of subsurface microorganisms that could facilitate the decay reactions (Major et al. 2003; Nyer et al. 2003). Although it is not stated explicitly in the modeling reports, ATSDR made the following assumptions for the TechFlowMP simulations: (1) the entire aquifer is anaerobic (the only known biochemical condition in which PCE can degrade); (2) the aquifer has the necessary microorganisms, which are uniformly distributed; (3) the aquifer has a carbon source sufficient to support microbial growth; (4) *trans*-1,2-DCE is the only DCE species in the decay chain; and (5) there is no spatial variation in the microbiologic or geochemical characteristics. ATSDR indirectly invoked all those conditions by assuming, for example, a constant, first-order PCE biotransformation rate coefficient of 0.0005 day^{-1} for all the layers in the aquifer. It is highly unlikely that that assumed biodegradation rate is applicable to the entire site. There are no microbiologic or geologic data are available to support the five assumptions. Therefore, the predicted concentrations of TCE, *trans*-1,2-DCE, and vinyl chloride in the Castle Haynes aquifer at the location of intake by Tarawa Terrace supply wells should be used with considerable caution.

Gaps in and Limitations of the Modeling

The committee reviewed the Tarawa Terrace modeling reports and found that ATSDR applied the public-domain codes for MODFLOW and MT3DMS and two cutting-edge research codes PsOps and TechFlowMP to model the complex groundwater-contamination scenario at Tarawa Terrace. However, there are some important limitations in ATSDR's modeling efforts because of the sparse set of water-quality measurements, the need to make unverifiable assumptions, and the complex nature of the PCE source contamination. The major gaps and limitations that the committee found with regard to the historical reconstruction and modeling work are summarized below. Future modeling efforts for the Hadnot Point water system should be designed in light of these limitations.

- The effects of the DNAPL in both unsaturated and saturated zones have not been included in the studies. As constructed, the DNAPL zone has no influence in any of the Tarawa Terrace groundwater models, because for each model ATSDR assumed that PCE was injected directly at a constant rate of 1.2 kg/day (that is, multiphase flow and dissolution reactions associated with DNAPL transport were ignored). PCE dissolution is a highly heterogeneous, rate-limited, mass-transfer process (Miller et al. 1990; Jackson 1998; Abriola 2005). Hence, the constant-mass injection approach used to model the complex PCE source zone may be prone to high uncertainty. Field data or other supporting evidence would be needed to justify the mass release rates. For example, Guilbeault et al. (2005) proposed some methods to characterize DNAPL source zones to estimate mass and contaminant release rates.

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- Constant values of dispersivity (longitudinal dispersivity of 25 ft and transverse 2.5 ft) were used in the transport model. There is insufficient information available on the nature and amount of heterogeneity to use these fixed values with a sufficient level of confidence in predictive simulations.
- The basis used for setting the values of the "calibration target range" was unclear. The repeated samples collected at some of the wells (multiple samples in 1 year) may provide some important information about the variability of observations caused by subsurface variations and possibly pumping variations. Perhaps these data could be used to determine observation variability that the computer model was not constructed to reproduce.
- The numerical codes TechFLowMP and PSOpS used in the modeling are research tools and are not widely accepted public-domain codes, such as MODFLOW and MT3DMS, so their validation is important. If data are not available, the results should be used with caution and should include appropriate uncertainty estimates.
- The PSOpS modeling study is based on the premise that an optimization model can be used to evaluate pumping stresses. Without site-specific pumping and water-quality data, the results will be non-unique and uncertain.
- Review of water-quality monitoring data indicates substantial temporal variability even at a single well. For example, the seven measurements taken on well TT-26 from January to September 1985 indicates that the concentrations at this well varied from 3.8 to 1,580 µg/L (see Table 2-8). The model predictions for the same timeframe ranged from 732 to 804 µg/L. The difference indicates that the real system is highly transient and that the model did not account for temporal and spatial averaging effects.
- The TechFlowMP model predicted very high vapor concentrations. For example, TechFlowMP predicted that the PCE vapor concentration in the top 10 ft of soil beneath the Tarawa Terrace elementary school should be 137 µg/L. Studies of PCE vapor concentrations in buildings that house or are near a dry-cleaning facility have reported measured concentrations around 55 µg/L (McDermott et al. 2005). The PCE vapor concentrations predicted by TechFlowMP should be treated with caution because they are theoretical estimates that have not been validated against field data from Camp Lejeune or compared with any measured vapor concentrations at other similar dry-cleaner sites.
- The biodegradation model used within the TechFlowMP code is based on an untested preliminary research model. Biodegradation of chlorinated solvent compounds will be influenced by several types of complex biogeochemical processes. The simple first-order modeling framework that also used a single decay coefficient for the entire modeling domain may not capture those biologic complexities. Therefore, the predicted concentrations of TCE, DCE, and vinyl chloride should be considered "crude" estimates, at best, unless validated with field measurements. In addition, biodegradation-model predictions are not supported by field data on biogeochemical indicators, which are commonly used to assess whether the assumed biodegradation pathways are active at a field site (EPA 1998a).
- The TechFlowMP simulations assumed that the biodegradation byproduct of TCE is *trans*-1,2-DCE. However, the scientific literature indicates that *cis*-1,2-DCE is the predominant product of TCE reduction under in situ groundwater conditions (Bradley 2003).
- Reporting absolute predicted concentrations of PCE and its biodegradation byproducts in finished water delivered by the Tarawa Terrace water-supply system with a precision up to five significant figures without any error bounds (for example, Jang and Aral [2008] report concentrations of PCE at 102.10 µg/L, TCE at 4.33 µg/L, DCE at 13.75 µg/L, and vinyl chloride at 7.50 µg/L) provides an unwarranted sense of certainty. Such reporting can contribute to misperceptions by the public and the epidemiology-research community that water-modeling efforts can produce a specific value for contaminant concentration. Posting such precise point estimates for PCE, TCE, DCE, and vinyl chloride concentrations on public Web pages (www.atsdr.cdc.gov/sites/lejeune) and encouraging former Camp Lejeune marines and their families to find the estimated exposure concentrations of these contaminants leads to a misleading perception that reactive transport models can make accurate predictions.
- In the absence of data, historical reconstruction efforts that use groundwater models can only provide a general conceptual framework for what happened at the site and why. At best, such models may

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be used only to estimate a range of possible concentrations. Without historical geochemical data, the uncertainly associated with many of the input parameters (such as the biodegradation parameters) could be very high. In addition, current understanding of subsurface reactive transport processes is inadequate, so transport models cannot be expected to provide definitive concentration estimates especially for biodegradation byproducts.

- The inherent and, in this case, profound limitations of historical modeling due to uncertainties in various model parameters and pumping stresses should be communicated along with modeling predictions.

ATSDR has completed a detailed groundwater-modeling study and have used the best possible techniques and tools. Several of the gaps and limitations mentioned above are due to the difficulty of reconstructing accurate groundwater-contamination scenarios. Without historical data, the natural processes that occurred several decades ago simply cannot be reconstructed. The committee understands this limitation and acknowledges that ATSDR has done its best under these difficult circumstances.

HADNOT POINT WATER SUPPLY

Approximately 100 wells have supplied water to the Hadnot Point system since it began operations in 1943, although not all were operational at the same time. ATSDR is currently determining the history of the individual well operations and capacities. Like the Tarawa Terrace system, water from the supply wells was pumped to the water-treatment plant and mixed and processed before distribution on the base. In July 1972, the Holcomb Boulevard water system took over supplying water to some areas originally served by the Hadnot Point system. The two systems were connected, such that on several occasions the Hadnot Point system temporarily served or supplemented the Holcomb Boulevard system. Specifically, water from the Hadnot Point system was used periodically during summer months and for 2 weeks in 1985 when the Holcomb Boulevard system was shutdown because of an emergency.

A comprehensive water-modeling analysis has not yet been conducted for Hadnot Point, so the committee sought to identify documents that provided some quantitative information on the contamination of the Hadnot Point water-distribution system. Relevant information was found in a 2007 GAO report, documents cited by ATSDR in its evaluation of Tarawa Terrace, remedial-investigation reports, and documents provided to the committee by the public. The selection of documents reviewed was not comprehensive but was informed by discussion with the Marine Corps, ATSDR, and the public. Primary sources of information for the committee's review included contaminant measurements taken while the contaminated wells were operating and data collected from monitoring wells, which were installed to conduct testing and monitoring for remediation purposes after the supply wells were closed.

The remedial investigations and the 2007 GAO report identify TCE and PCE as the primary contaminants of concern at Hadnot Point. After reviewing additional preliminary information, the committee decided also to investigate eight other contaminants: *trans*-1,2-DCE, *cis*-1,2-DCE, 1,1-DCE, 1,1,1-trichloroethane (TCA), vinyl chloride, methylene chloride, benzene, and toluene. The most useful information on those contaminants was a set of CLW documents, available on the CD accompanying Maslia et al. (2007). The set has 1,110 files made up of over 8,700 pages of material and includes laboratory reports, memorandums, field notes, and other written documents. The CLW documents were not organized or cataloged, so it was not possible to search readily for documents that contained water-quality measurements. The committee asked the Marine Corps for guidance on which CLW documents contained water-sample values from any location on the base during 1980-1986 (see Appendix C, Table C-2, for the list provided by the Marine Corps). The committee abstracted data from the subset of CLW documents that contained water-quality results from Hadnot Point potable-well and mixed water samples before March 1985.

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It was beyond the scope of the committee's task to conduct an exposure assessment or even a full-scale data abstraction for Hadnot Point. Such an undertaking would have required a systematic review of standard laboratory practices for the sampling and analytic methods for collecting, analyzing, and reporting on water samples at the contributing laboratories during the 1980s; review of the source documents for quality assurance; information on detection and quantitation limits; identification and elimination of duplicate measurements recorded in multiple documents; and information on sampling location and conditions. The committee's review of the available documents presented below constitutes an illustration of the information that is available and should help to inform future efforts for evaluating contamination of water supplies at Hadnot Point.

Potential Sources of Contamination of Hadnot Point Water Supply

Descriptions of the sources of contamination and results of sampling of monitoring wells were obtained from remedial-investigation reports (Baker Environmental, Inc 1993, 1994, 1999). The reports summarize results of analyses of samples of groundwater collected during the late 1980s and early 1990s, after the contaminated wells supplying the Hadnot Point water-distribution system were closed. They also provide information on the timing and characteristics of waste-disposal practices that resulted in contamination of environmental media in the vicinity of water-supply wells. Those locations eventually required official remedial action under U.S. environmental laws, a process that continues today. In general, the water samples from the monitoring wells were analyzed for the presence of a suite of contaminants (EPA priority pollutants) and yielded insight into the fate and transport of the contaminants from the source to the groundwater. The committee used data from the remedial-investigation reports to gain a better understanding of the nature and extent of contamination and to refine the list of contaminants of concern.

The Navy initially identified 13 sites as potential sources of contaminants of the Castle Hayne aquifer in the Hadnot Point area (Baker Environmental, Inc 1999). Each site was assigned a number (installation restoration [IR] site number), and they were grouped into operable units (OUs) to facilitate investigation and data management. Most of the sites were active in the 1940s to 1970s, before implementation of more rigorous requirements governing waste tracking, handling, and disposal. The contaminants detected in soil or groundwater samples in the course of remedial investigations are summarized in Table 2-9. Figure 2-6 is a map of the sites in relation to housing areas and water-supply wells in the Hadnot Point area.

IR site 78, the Hadnot Point industrial area, has been a center of industrial activities since the 1940s. The site included as many as 75 buildings that housed such operations as maintenance shops, refueling stations, administrative offices, printing shops, warehouses, painting shops, storage yards, a steam-generation plant, and other light industry (Baker Environmental, Inc 1994, 1999). The remedial investigation for site 78 was preceded by several investigations that confirmed the presence of VOCs related to fuels and solvents in the groundwater. Those investigations were followed by ones that set the stage for the systematic sampling conducted for the remedial investigation in 1992.

Sites 6 and 82 were used for open storage beginning in the 1940s. Many types of materials were stored on site, including pesticides and polychlorinated biphenyls. Groundwater in the vicinity of sites 6 and 82 was sampled as part of the Confirmation Study (1984-1988). Chlorinated solvents were detected in shallow and deep (Castle Hayne aquifer) monitoring wells during the remedial investigation study (Baker Environmental, Inc 1993).

OU 7 comprises sites 1, 28, and 30. The French Creek liquids disposal area (site 1) is 1 mile southeast of the Hadnot Point industrial area and was used by mechanized artillery units starting in the 1940s to dispose of waste petroleum, oil, and lubricants by ground spreading (dumping). Sporadic contamination of the upper aquifer with TCE and vinyl chloride was documented during the remedial investigation process (Baker Environmental, Inc 1995).

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TABLE 2-9 Installation Restoration Sites in the Hadnot Point Water-Supply Area

OU and IR Site	Site Description	Contaminants Identified During Remedial Investigation
OU 1, site 21	Transformer storage lot	Soil contaminated with pesticides, polychlorinated biphenyls
OU 1, site 24	Industrial area fly ash dump	Soil contaminated with metals, pesticides; shallow groundwater contaminated with pesticides
OU 1, site 78	Hadnot Point industrial area	Groundwater (shallow and deep) contaminated with chlorinated solvents, fuel compounds (benzene, toluene, ethylbenzene, xylenes) Soils contaminated with pesticides, metals
OU 2, site 6	Storage lots 201, 203; connected to site 82	Soil contaminated with pesticides, petroleum products, metals Groundwater (shallow and deep) contaminated with chlorinated solvents
OU 2, site 9	Firefighting training pit at Piney Green Road	Low concentrations of chlorinated solvents in shallow groundwater
OU 2, site 82	Piney Green Road VOC area; connected to site 6	Groundwater (shallow and deep) contaminated with chlorinated solvents
OU 7, site 1	French Creek liquids disposal area	Shallow groundwater contaminated with petroleum products, chlorinated solvents
OU 7, site 28	Hadnot Point burn dump	Surface soils contaminated with volatile, semivolatile compounds Shallow groundwater contaminated with metals
OU 7, site 30	Sneads Ferry Road fuel tank sludge area	Soil contaminated with VOCs
OU 15, site 88	Building 25, base dry cleaners	Soil, shallow groundwater contaminated with solvents
OU 18, site 94	Former PCX service station	Groundwater contaminated with petroleum hydrocarbons, chlorinated solvents
Pre-RI 10	Original base dump	No significant contamination of soil or groundwater identified
Pre-RI 12	Explosive ordnance disposal area	No significant contamination of soil or groundwater identified

Abbreviation: RI = remedial investigation.

Site 28 is a former 23-acre burn dump, operated from 1946 to 1971, south of the Hadnot Point industrial area (Baker Environmental, Inc 1995). Solid waste from industrial operations—including construction debris, industrial waste, trash, and oil-based paint—was burned on site (Baker Environmental, Inc 1995). The remedial investigation found frequent detection of semivolatile and inorganic compounds and sporadic detection of VOCs in soil samples (Baker Environmental, Inc 1995). Shallow aquifer samples from the same period revealed the presence of lead, which was detected sporadically in the deeper water (Baker Environmental, Inc 1995).

Site 30, the Snead's Ferry Road fuel-tank sludge area, was used by contractors to clean out fuel-storage tanks. A small amount of solvents was detected in soil samples collected in 1994, but there was no indication of groundwater contamination in samples from monitoring wells (Baker Environmental, Inc 1995).

Site 88 is the location of the former on-base dry cleaners. Underground storage tanks that were installed in the 1940s, which contained Varsol (a type of mineral spirits) and PCE, were removed in 1996. In 2005, it was determined that groundwater contamination extended 50 ft below ground surface, and the resulting plume of contaminants in the groundwater extended about 500 ft to the northwest. DNAPL was present in the groundwater, but aggressive treatment has reduced concentrations (CH2M Hill and Baker Environmental, Inc 2005).

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Contaminated Water Supplies at Camp Lejeune: Assessing Potential Health Effects

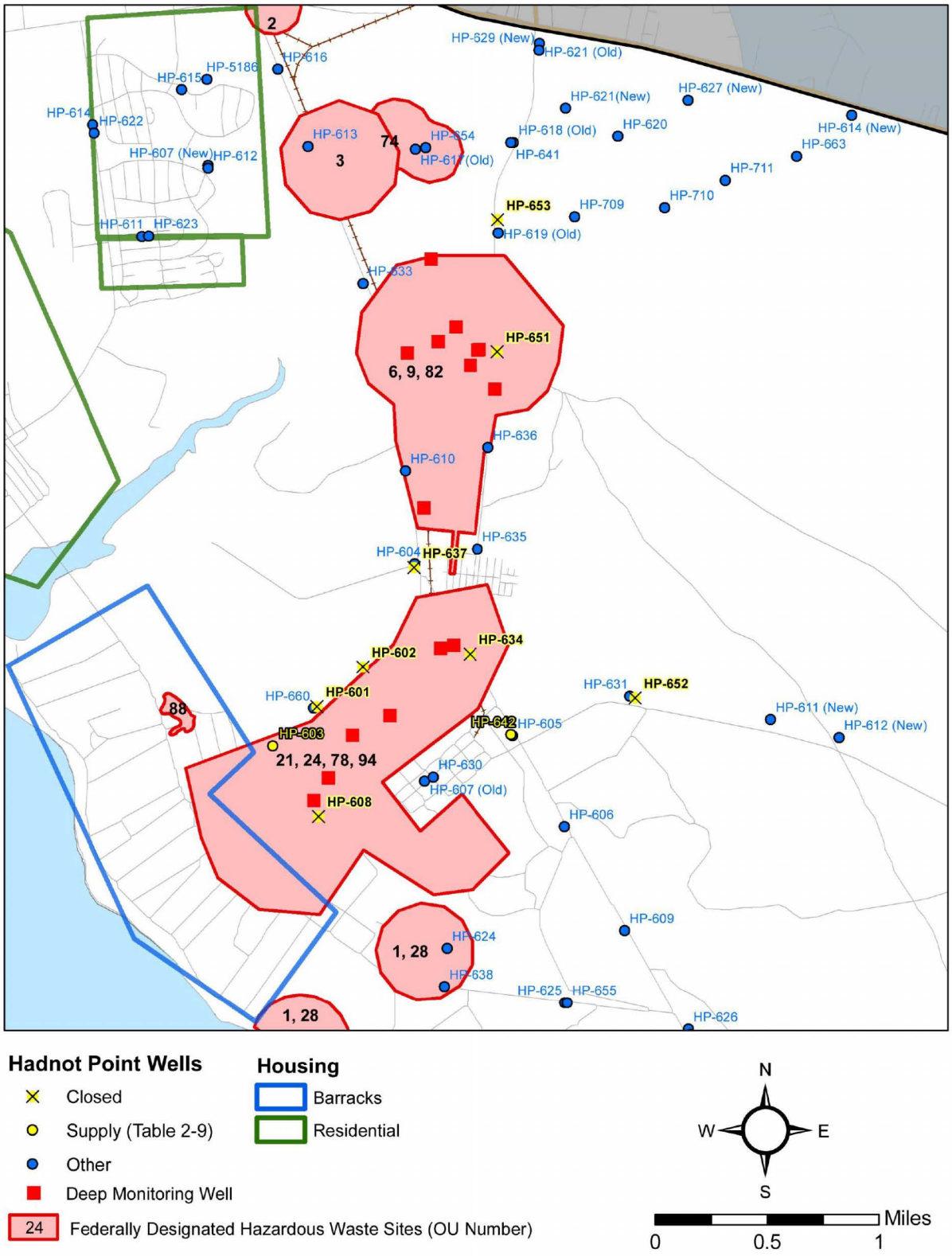

FIGURE 2-6 Designated hazardous-waste remedial investigation sites at Hadnot Point.

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Preremedial investigation (pre-RI) site 10, which was initially identified before the institution of the remedial investigation process, was the location of the original disposal area for Camp Lejeune waste. An investigation of the site in 1998 showed low concentrations of numerous organic and inorganic contaminants in the soil and in surface water and sediment from small ponds on site. Aluminum, arsenic, chromium, nickel, lead, and vanadium were detected at high concentrations in shallow groundwater samples (Baker Environmental, Inc 1999, 2001).

Pre-RI site 12 is a 10-acre former explosive-ordnance disposal area. No substantial residual contamination was detected during the remedial investigation process (Baker Environmental, Inc 1999, 2001).

Water-Quality Data on the Hadnot Point System

Published water-sampling data on Hadnot Point are sparse. One source (GAO 2007) reported on concentrations of contaminants detected in the Hadnot Point water-supply wells before they were removed from service in 1984 and 1985 (see Table 2-10). The highest concentrations of contaminants were reported for well 651, with TCE at 3,200 µg/L, PCE at 386 µg/L, and *trans*-1,2-DCE at 3,400 µg/L. The committee was also made aware of a water sample not included in the 2007 GAO report that was taken from well 651 on the day it was closed—February 4, 1985; the sample contained TCE at 18,900 µg/L (Ensminger 2007; CLW 3269).

Given that the water-quality data summarized in published reports were extremely sparse (for instance, see Table 2-10), the committee expanded its evaluation to assess additional data collected in the 1980s that were summarized in CLW documents. The committee reviewed a subset of the CLW documents that contained water-quality measurement data (see Appendix C, Tables C-3 and C-4, for data abstracted from the documents) for any samples connected to the Hadnot Point water supply that were collected through February 7, 1985. The subset includes 56 samples of supply-well water collected during the period November 30, 1984-February 4, 1985, and 52 samples of mixed water collected during October 21, 1980-February 7, 1985. It also includes samples collected at locations ordinarily served by the Holcomb Boulevard water-distribution system but temporarily served by the Hadnot Point water-distribution system after a fuel spill on January 27, 1985. Appendix C contains additional information about the abstraction process.

In Table 2-11, the committee presents a summary of the analytic results for the nine contaminants of concern that it identified for the Hadnot Point water system. Summary statistics of concentrations were computed only for the samples that had specific values recorded—samples listed as "non-detect," "detect," or "—" were excluded in these computations—and percentiles were reported only if at least five samples contained a given compound. Sample concentrations that are listed as not quantified were recorded in the source documents as D (detect) or ND (non-detect) or were not reported (shown as "—" in the data listing). Samples in which concentrations could not be quantified are summarized in Table 2-12.

Of the nine analytes, the most prevalent compounds in mixed water samples collected from various locations in the Hadnot Point water-treatment plant and distribution system with measurable concentrations were TCE (31 quantified samples had a mean of 399 µg/L and a range of 1-1,400 µg/L) and *trans*-1,2-DCE (21 quantified samples had a mean of 169 µg/L and a range of 2-407 µg/L). PCE was quantified in four (8%) of the 52 samples. Benzene, 1,1,1-TCA, 1,1-DCE, and toluene were not detected or quantified; methylene chloride and vinyl chloride were each detected in one sample. As in the mixed water, the most prevalent compounds in potable well-water samples were TCE (17 quantified samples had a mean of 2,596 µg/L and range of 5-18,900 µg/L) and *trans*-1,2-DCE (14 quantified samples had a mean of 1,519 µg/L and a range of 2-8,070 µg/L). There was at least one detection of all contaminants except 1,1,1-TCA. In particular, there were a few high concentrations of PCE (maximum, 400 µg/L), benzene (maximum, 720 µg/L), methylene chloride (maximum, 270 µg/L), and vinyl chloride (maximum, 655 µg/L) in the potable well samples.

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TABLE 2-10 Contaminant Concentrations in Supply Wells of Hadnot Point Water System

Well	Date Removed from Service	Concentration, µg/L[a]							
		TCE	PCE	Benzene	*Trans*-1,2-DCE	1,1-DCE	Methylene Chloride	Toluene	Vinyl Chloride
602	Nov. 30, 1984	1,600	24	120	630	2.4	—	5.4	18
601	Dec. 6, 1984	210	5	ND	88	ND	ND	ND	ND
608	Dec. 6, 1984	110	ND	3.7	5.4	ND	ND	ND	ND
634	Dec. 14, 1984	ND	ND	ND	2.3	—	130	—	ND
637	Dec. 14, 1984	ND	ND	ND	ND	—	270	—	—
651	Feb. 4, 1985	3,200	386	—	3,400	187	—	—	655
652	Feb. 8, 1985	9	ND	—	ND	ND	—	—	ND
653	Feb. 8, 1985	5.5	ND	—	ND	ND	—	—	ND

[a]Detection limit for each contaminants was 10 µg/L.
Abbreviation: ND = not detected.
Source: GAO 2007.

In Table 2-13, the committee provides a detailed summary of Hadnot Point area supply wells that had at least one nonzero value for at least one of the nine analytes. It shows the well number, IR sites near the well, well depth, screen interval, a summary of measured VOC concentrations, and dates of operation. Some of the water-supply samples were collected after individual wells were closed, and it is important to note that pumping can affect the degree of contamination in wells. Of the 10 wells summarized in Table 2-13, eight were closed from late 1984 through early 1985 (GAO 2007). Well 651 had the highest contamination, with detectable concentrations of TCE in all the reported samples. Well 651 also had relatively high readings of *trans*-1,2-DCE, PCE, and vinyl chloride. Wells 602 and 634 each had one sample with a TCE concentration above 1,000 µg/L (1,600 and 1,300 µg/L, respectively).

Hadnot Point Supply-Well Operation and Implications

The supply wells for the Camp Lejeune water system were on a cycled pumping schedule; that is, generally only some of the wells were pumping raw water to the water-treatment plant at any given time (GAO 2007). Typically, pumps at various wells are scheduled to cycle on or off at different times during the day, so a dynamic mixture of water from different wells flows into the water-treatment plant and into the distribution system serving residences and other facilities. Well cycling is important to consider if one wants to understand the presence of contaminants in the distribution system inasmuch as concentrations of contaminants might vary greatly from day to day or even over the course of a single day, depending on whether contaminated wells were pumping.

The committee is aware of one document (CLW 6950) that summarizes well-cycling information during a period assumed to be November 28, 1984-February 4, 1985 (Marine Corps, personal commun., February 26, 2008). The document lists Hadnot Point well numbers and some date information (calendar days without accompanying months or years) with an "X" whenever a well pumped on a given date. If the inferred dates are correct, the document shows that individual wells operated on the average for 38% of the days over the 69-day period, with a large range of operation frequency (individual wells pumped on 0-96% of the days). On the average, 16 wells pumped each day; the range was 9-27. In Table 2-14, the committee presents the well-cycling information in combination with water-sampling data from the same

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TABLE 2-11 Hadnot Point Water-Supply Quality Measurements (October 1980-February 1985)

Water Source	Contaminant	No. Samples[a]		% Samples Quantified	Individual Samples, µg/L	Summarized Data on Samples with Quantified Values, µg/L[b]					
		ND/NQ[c]	Quantified			Mean	Min	25th Percentile	Median	75th Percentile	Max
Supply wells	TCE	39	17	30		2,596	5	13	210	1,300	18,900
	PCE	48	8	14		153	2	5	17	392	400
	Benzene	50	6	11		180	2	4	62	230	720
	1,1,1-TCA	56	0	0							
	1,1-DCE	54	2	4	2; 187	95					
	trans-1,2-DCE	42	14	25		1,519	2	9	165	700	8,070
	MC	50	6	11		78	7	10	26	130	270
	Toluene	54	2	4	5; 12	9					
	VC	51	5	9		205	7	18	168	179	655
Mixed water	TCE	21[d]	31	60		399	1	19	200	849	1,400
	PCE	48[d]	4	8	1; 4; 8; 15	7					
	Benzene	52	0	0							
	1,1,1-TCA	52	0	0							
	1,1-DCE	52	0	0							
	trans-1,2-DCE	31	21	40		169	2	9	150	321	407
	MC	51	1	2	54	54					
	Toluene	52	0	0							
	VC	51	1	2	3	3					

[a]Samples in this table listed separately in Appendix C, Tables C-3 and C-4. Samples treated as distinct if reported on separate laboratory reports; in some cases, multiple samples reported from same location on same date, but it is not known whether these were duplicate samples.
[b]Sample concentrations presented as summary statistics if more than four samples were quantified. Quantified samples listed individually if four or fewer samples quantified.
[c]ND/NQ samples do not have reported concentrations for various possible reasons, including that they were not measured, were not detected, or were recorded merely as detected. See Table 2-12 for additional information about these samples.
[d] Concentrations measured in seven of 11 samples collected before 1984 were assumed to be detected on basis of notes on laboratory reports and inferences from later laboratory reports.
Abbreviations: DCE = dichloroethylene; MC = methylene chloride; ND = not detected; NQ = not quantified; TCA = trichloroethane; VC = vinyl chloride.

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TABLE 2-12 Summary of Data on Water Samples[a] from Hadnot Point Water System Recorded As Not Detected or Not Quantified in Table 2-11

Water Source	Contaminant	ND/NQ	ND/NQ Category			
			Reported as Detected	<2.0 or <1 µg/L	ND	No data
Supply wells	TCE	39			39	
	PCE	48			48	
	Benzene	50			50	
	1,1,1-TCA	56			56	
	1,1-DCE	54			54	
	*trans*1-2,DCE	42			42	
	MC	50			50	
	Toluene	54			54	
	VC	51			51	
Mixed water	TCE	21[b]	7	6	7	1
	PCE	48[b]	7	2	12	27
	Benzene	52			14	38
	1,1,1-TCA	52			14	38
	1,1-DCE	52			14	38
	*trans*1-2,DCE	31		7	10	14
	MC	51			13	38
	Toluene	52			14	38
	VC	51			13	38

[a]Data listed separately in Appendix C (Tables C-3 and C-4). Samples treated as distinct if reported on separate laboratory reports; in some cases, multiple samples reported from same location on same date, but it is not known whether these were duplicate samples.
[b]Concentrations measured in seven of 11 samples taken before 1984 assumed to be detected on basis of notes on laboratory reports and inferences from later laboratory reports.
Abbreviations: DCE = dichloroethylene; MC = methylene chloride; ND = not detected; NQ = not quantified; TCA = trichloroethane; VC = vinyl chloride.

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TABLE 2-13 Characteristics of the Hadnot Point Supply Wells With At Least One Contaminated Sample Taken Between October 1980 and February 1985

Well[a]	IR Site[b]	Well Depth, ft[c]	Screened Intervals, Number (Range, ft)[c]	No. Water Samples[d]	Contaminants, µg/L[d]								Year Well Started	Date Well Shut Down[e]
					TCE	PCE	*Trans*-1,2-DCE	1,1-DCE	MC	VC	Benzene	Toluene		
601	9, 78	195	4 (45-195)	3	26 210 230	ND 4 5	9 88 99		ND ND 10				1941	Dec. 6, 1984
602	9, 78	160	5 (70-160)	4	38 340 540 1,600	ND ND 2 24	74 230 380 630	ND ND ND 2		ND ND ND 18	ND 120 230 720	ND ND 5 12	1941	Nov. 30, 1984
603	78	195	5 (70-195)	3	ND ND 5				ND ND 7				1941	
608	78	161.5	4 (61.5-161.5)	3	9 13 110		ND 2 5		ND ND 14		2 4 4		1942	Dec. 6, 1984
634	9, 78	225	10 (63-225)	3	ND ND 1,300	ND ND 10	ND 2 700		ND ND 130	ND ND 7			1959	Dec. 14, 1984
637	6, 9, 78, 82	172	5 (90-172)	3					ND ND 270				1969	Dec. 14, 1984
642	9, 78	210	5 (112-196)	3					ND ND 38				1971	
651	9, 82	199	3 (125-194)	3[f]	3,200 17,600 18,900	386 397 400	3,400 7,580 8,070	ND ND 187		168 179 655			1971	Feb. 4, 1985
652				1	9								1972	Feb. 8, 1985
653	6, 82	270		1	6								1978	Feb. 8, 1985

[a]Wells installed before March 1, 1985. Many other wells were operating before March 1, 1985, but are not included in list because contaminants not detected.
[b]See Figure 2-6.
[c]Data abstracted from Baker Environmental, Inc (1993a,b).
[d]Samples listed in Appendix C, Table C-4. All readings are shown for individual compounds with at least one detection.
[e]Well-closing dates reported in GAO (2007).
[f]Includes two samples collected on same date and listed as "duplicates" on secondary source document.
Abbreviations: DCE = dichloroethylene; IR = installation restoration; MC, methylene chloride; ND = not detected; PCE = perchloroethylene; TCE = trichloroethylene; VC = vinyl chloride.

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TABLE 2-14 Concentrations of Contaminants in Mixed Water Samples Collected from Hadnot Point Water-Distribution System During Period of Documented Well Cycling[a]

Date	No. Water Samples[c]	Average Concentration, µg/L[b]				No. Wells Pumping	Wells[d]
		TCE	PCE	*trans*-1,2-DCE	MC		
Dec. 4, 1984	2	123	2	49	0	21	603, 608, 634, 637, 642, 652[e]
Dec. 10, 1984	1	2	0	2	0	10	637, 652
Dec. 13, 1984	1	0	0	0	54	18	652, 653
Dec. 14, 1984	1	0	0	0	0	18	652
Dec. 15, 1984	1	0	0	0	0	15	642, 652
Dec. 16, 1984	1	0	0	0	0	13	642, 652
Dec. 17, 1984	1	0	0	0	0	13	603, 642, 652
Dec. 18, 1984	1	0	0	0	0	13	603
Dec. 19, 1984	2	1	0	0	0	13	603
Jan. 29, 1985	3	463	[f]	[f]	[f]	18	603, 642, 651, 653
Jan. 31, 1985	14	618	[f]	225	[f]	19	603, 642, 651, 652, 653

[a]Dates estimated to be November 28, 1984, through February 4, 1985.
[b]All nondetected values treated as having concentrations of 0.
[c]The location from which the samples were taken are provided in Appendix C, Table C-3.
[d]Wells with at least one detected analyte that were pumping on same day or up to 2 days before date specified.
[e]Well 651 pumped 3 days before these samples were taken.
[f]Contaminant not measured or reported for mixed water samples collected on this date.
Abbreviations: DCE = dichloroethylene; MC = methylene chloride; PCE = perchloroethylene; TCE = trichloroethylene.

period to ascertain the potential effect of well cycling on measured contaminant concentrations. To illustrate the effect of well cycling on mixed-water contamination, the committee made the highly conservative assumption that all "non-detect" samples had zero concentrations of the listed contaminants. The table indicates that 10-21 wells delivered raw water to the water-treatment plant on days when at least one mixed-water sample was analyzed. At least one well with demonstrated contamination pumped on the same day or previous 2 days from the dates when water samples were collected, but contamination in the mixed water was not detected on all dates on which a sample was collected.

TCE, PCE, *trans*-1,2-DCE, and methylene chloride were detected in mixed-water samples taken during November 28, 1984-February 4, 1985. Benzene, 1,1-DCE, toluene, and vinyl chloride—all of which were reportedly detected in the Hadnot Point supply-well samples—either were not included in the laboratory analysis or were not detected in measurable concentrations in mixed-water samples during that period. The two dates with the highest average TCE concentrations (463 and 618 µg/L) were the dates when well 651 was supplying water to the system on the current and/or previous 2 days; this suggests that well 651 was an important source of contamination of the Hadnot Point water-supply system. In addition, the 14 mixed-water TCE measurements in samples from one of those days (January 31, 1985) had a range of 24-1,148 µg/L.

Hadnot Point Area Monitoring Wells

The committee focused its review on some of the earliest deep-groundwater monitoring data available from the remedial-investigation reports for waste sites 6, 9, 78, and 82 in the Hadnot Point area (Baker Environmental, Inc 1994). Monitoring wells were used to collect water samples from depths of about 148-153 ft below ground surface. Screens (elevations of water-intake portals in the well pipe) in

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most of the wells that supplied water to the Hadnot Point water system were installed at depths of 60-190 ft below ground surface. Each supply well had three to five screens. Thus, the analytic results on water samples taken from deep monitoring wells should be representative of contamination of the Castle Hayne aquifer at a depth consistent with water withdrawal from the water supply, albeit at least 7 years after the discovery of contaminants in the Hadnot Point supply wells.

The remedial investigation of site 78 was preceded by several investigations, including an initial assessment study (1983) that identified the groundwater contamination and a confirmation study (1984-1988) that documented the presence of VOCs related to fuels and solvents in the groundwater. A later supplemental characterization step study (1990-1991) and pre-investigation study (1992) set the stage for the systematic sampling effort for the remedial investigation in 1992 (Baker Environmental, Inc 1994).

Groundwater in the vicinity of sites 6 and 82 was also sampled as part of the confirmation study (1984-1988). The remedial investigation of sites 6 and 82 included three rounds of groundwater sampling, conducted in two phases: phase 1 in 1992 and phase 2 in 1993 (Baker Environmental, Inc 1993). The investigation at each site, including groundwater sampling and analyses, continued after the publication of the remedial-investigation reports. The committee judged that the focus on the remedial-investigation reports for Hadnot Point sites was justified because they provided a reasonable snapshot of contamination closest to the period of interest.

For the remedial investigation, groundwater samples were generally analyzed for two suites of common chemical contaminants known as the "target compound list" (TCL) and the "target analyte list" (TAL). The results of the detections are summarized below; a more complete discussion is presented in Appendix C (Table C-5).

The monitoring-well data identify TCE, phenol, benzene, *cis*- and *trans*-1,2-DCE, and 1,1-DCE as the most prevalent contaminants in groundwater at the locations and screened depths of the wells. Other contaminants with multiple detections were arsenic, cadmium, 1,2-dichloroethane, and PCE. TCE, phenol, and *cis*- and *trans*-1,2-DCE had the highest prevalence of concentrations measured above their limits of detection.

Concentrations reported in the remedial-investigation reports varied widely among the well sites. For example, the concentrations of TCE in 11 samples ranged from 1.3 to 58,000 µg/L. Similarly, detections of *trans*-1,2-DCE ranged from 1 to 26,000 µg/L, of phenol from 2 to 22,000 µg/L, and of benzene from 6.7 to 35 µg/L. The most contaminated locations were near supply well 651, next to sites 6 and 82.

At most locations, shallow groundwater (sampled at a depth of less than 25 ft) had the greatest number of contaminant detections, including such TCL chemicals as TCE (0.5-2,100 µg/L) and fuel constituents benzene (not detected to 9,200 µg/L), toluene (not detected to 18,000 µg/L), ethylbenzene (not detected to 3,000 µg/L), xylenes (not detected to 16,000 µg/L), and naphthalene (not detected to 260 µg/L) (Baker Environmental, Inc 1993, 1994). TAL metals that were commonly detected in shallow water, with some samples at exceedingly high concentrations relative to EPA's current MCLs, were arsenic (405 µg/L), barium (1,200 µg/L), chromium (858 µg/L), lead (126 µg/L), and manganese (714 µg/L) (Baker Environmental, Inc 1993, 1994). Only five wells of intermediate depth (about 50-75 ft) were sampled as part of the remedial investigation, and detected chemicals were generally measured at concentrations below risk-based criteria.

The results of groundwater sampling and analysis with monitoring wells provide additional information regarding the presence of contaminants in the aquifer. In many ways, the data are secondary to the analytic results on samples taken from the supply wells or the tap, at least for the purposes of understanding historical exposures. However, because the available information on such samples is sparse, it is important to consider all available data, including those from monitoring wells.

Contaminants of Concern in the Hadnot Point Water Supply

The paucity of water-quality measurements of the Hadnot Point water supply, both temporally and spatially, makes it difficult to characterize the contaminants of concern accurately. Multiple waste

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and operational sites have contributed to the groundwater contamination since the 1940s, so the nature of the contamination has probably varied. The few available measurements were taken during the 1980s and 1990s, decades after the contamination could have begun. The principal contaminants discovered in the wells that supplied Hadnot Point in the early 1980s were TCE and PCE. TCE, phenol, benzene, *cis*- and *trans*-1,2-DCE, and 1,1-DCE were the most prevalent contaminants in samples collected in 1992 and 1993 from deep monitoring wells. Other contaminants with multiple detections in monitoring wells were arsenic, cadmium, 1,2-dichloroethane, and PCE . The chemical 1,1,1-TCA, which was on the preliminary list of contaminants of concern compiled by the committee, is given only cursory attention in this report because it was not observed in any Hadnot Point water-quality samples collected before February 8, 1985. However, 1,1,2-trichloroethane was detected in one sample from a monitoring near well 651 at 5.8 µg/L (see Appendix C, Table C-5).

Groundwater Fate and Transport Model for Hadnot Point

ATSDR has proposed that the methods that were used for Tarawa Terrace be applied to reconstruct the historical contamination of water supplied by the Hadnot Point water-treatment plant (Maslia 2008). The proposed reconstruction will simulate the groundwater concentrations of TCE, PCE, and BTEX (benzene, toluene, ethylbenzene, and xylene). The preliminary data-screening efforts started in January 2008, and work is expected to be completed on October 2009. The study includes 10 technical tasks: analysis of data from16 sites; computation of mass of PCE, TCE, and BTEX at about six major sites; review of capacity histories of about 100 wells; statistical analysis of existing data; fate analysis; fate and transport model selection; grid design and data input; fate and transport analysis; water-distribution system analysis; and uncertainty analysis. ATSDR is also committed to providing updates on its progress by participating in external progress meetings and Community Assistance Panel meetings and by preparing and disseminating data analyses and model simulations. On the basis of work already carried out, ATSDR also indicated the following (Maslia 2008):

- Discovery of new or updated site information after the second quarter of FY 2008 that substantially alters baseline information may add time to the current timeline estimate.
- Because of the expanse of the area being modeled, computational time for fate and transport analyses may be longer than previously estimated. When model selection and grid design have been completed, a more refined estimate of required computational time will be made.

Earlier in this chapter, the committee identified several limitations in the Tarawa Terrace historical reconstruction and groundwater modeling. Because the contamination at Hadnot Point is more complex, the limitations and difficulties related to such modeling will be greater.

WATER USE PATTERNS AND BEHAVIORS

Place of residence is a key determinant of exposure to contaminants in water at Camp Lejeune, but individual behavior—including water consumption, showering or bathing patterns, and other water-related behaviors (such as dishwashing)—also would influence the degree of exposure. The committee is not aware of any historical information that documents individual water-use patterns and behaviors of residents of base housing. Some information on typical water use and other factors that affect individual exposure is available (EPA 1997, 2008). Some specific information on the Camp Lejeune population is being sought as part of ATSDR's case-control study focused on birth defects and childhood cancer outcomes (see Chapter 8). However, as in all retrospective epidemiologic studies of water-supply contamination, the validity of such information is open to question given that it requires retrospective recall of water-consumption habits and water-related behaviors that occurred decades earlier, increasing the like-

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lihood that error due to recall bias could be substantial. The contaminated water systems also supplied nonresidential areas of the base, including schools, workplaces, recreational areas, and a hospital. Water-use patterns and behaviors in those setting are expected to differ substantially from practices in residences. In addition, people could have been exposed to contaminated water at multiple locations, for instance, in both residential and nonresidential settings.

EXPOSURE PATHWAYS

Although most attention has focused on the ingestion of contaminated water, additional exposure pathways were possible, including the inhalation of chemicals that have volatilized from standing water in toilets or from faucet or shower water and dermal exposure from showering and washing. Although there are no contemporaneous data on the Camp Lejeune population, exposure via inhalation and dermal absorption of VOCs from water used for household purposes has been shown experimentally to account for as much exposure as that from drinking the water (see Chapter 3). The intrusion of vapor from shallow contaminated groundwater into homes and offices is yet another possible inhalation-exposure pathway. ATSDR's simulation efforts indicate a potential for vapors from plumes at Tarawa Terrace to have entered buildings, including an elementary school and family housing (Maslia et al. 2007). EPA recently examined the possibility of vapor intrusion at the Tarawa Terrace Elementary School and several housing units and did not find any current problems (EPA 2007a,b). Any estimates of past exposure to contaminated groundwater should consider all exposure pathways.

AFFECTED STUDY POPULATION

Residential history in housing areas served by the contaminated water supplies during the period of contamination is an important determinant of exposure. There are two major categories of housing at Camp Lejeune: family housing for personnel on assignment to Camp Lejeune and barracks for enlisted personnel rotating through the base for training. The committee was provided with an estimated number of residential houses on Camp Lejeune by water-supply system in any given year from 1941 to 2000 by the Marine Corps (Appendix C, Table C-6). The first year with substantial residential water service was 1943, in which an estimated 919 units were served by the Hadnot Point water system, the first to serve a residential development on the base other than a barracks. Large increases in the total number of family-housing units on the base occurred in 1952, with the construction of Tarawa Terrace housing (3,065 units); in 1958, with the construction of Marine Corp Air Station housing (3,500); in 1961, with the construction of Berkeley Manor and Paradise Point Capehart housing (4,177); and in 1978, with the construction of Watkins Village housing (4,550). Substantial shifts in the water-supply source for residential housing occurred in 1972 when about 1,886 housing units were transferred from the Hadnot Point water system to the Holcomb Boulevard system and in 1987 when about 1,955 housing units were transferred from the Tarawa Terrace system to the Holcomb Boulevard system. Translating the number of housing units into the size of the population that may have been exposed would require knowledge of the number of residents per household or at least the number of residents by housing area in each year. To translate that into potential years of residential exposure for a given person or household, the duration of residence on the base would need to be ascertained. To assess potential exposure of that person or household to specific contaminants in the water supply, more accurate information on the location and period of residence would need to be ascertained. Information on the population size or typical duration of residence of personnel assigned to barracks was not available.

Potential exposures in nonresidential settings should also be considered. Such exposures may occur in schools and job locations on the base. Table 2-15 presents potential sites of nonresidential exposure to contaminants from the Tarawa Terrace and Hadnot Point water systems in 1943-1985. No information was available on the number of persons in occupational, school, or day-care settings with potential exposure to contaminated water.

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EXPOSURE ASSESSMENT IN STUDIES OF HEALTH EFFECTS OF WATER-SUPPLY CONTAMINATION AT CAMP LEJEUNE

ATSDR has completed two epidemiologic studies of water-supply contamination at Camp Lejeune (ATSDR 1998; Sonnenfeld et al. 2001). They focused on prenatal outcomes, including mean birth weight, small for gestational age, and preterm birth. The studies were limited to singleton live-born infants (with estimated gestational ages of 20 weeks or more) whose mothers resided in base housing for at least 1 week before giving birth in January 1, 1968-December 31, 1985. The earlier study (ATSDR 1998) also included stillborn infants. The results of those studies are presented in Chapter 8, and this section briefly summarizes the exposure assessments that were used in each.

The 1998 ATSDR study evaluated residents of Tarawa Terrace and Hadnot Point, whereas the 2001 Sonnenfeld et al. study evaluated only residents of Tarawa Terrace. In both studies, exposure was defined by place of residence at delivery and ascertained by linking birth records to the base's family-housing records.

In the ATSDR study, residents of trailer parks were excluded because of the incompleteness of housing information and the inability to identify their water source. Infants whose mothers resided at Tarawa Terrace for at least 1 week before giving birth were classified as exposed. Also included in the exposed group were infants whose mothers received water from the Hadnot Point water system in the Hospital Point housing areas or resided in the service area of the Holcomb Boulevard water system and were pregnant for at least 1 week in a 12-day period in January 27-February 7, 1985. During that period, Hadnot Point water served or was present in the Holcomb Boulevard system for operational reasons. Infants whose mothers were residents in other base family housing (the Marine Corps Air Station, Rifle Range, and Courthouse Bay housing areas) were classified as unexposed, as were infants whose mothers lived in areas served by the Holcomb Boulevard water system (defined as Berkeley Manor, Midway Park, Paradise Point, and Watkins Village housing areas) during the study period other than the 2-week period in winter 1985 when the Holcomb Boulevard system received contaminated water from the Hadnot Point

TABLE 2-15 Potential Sites of Nonresidential Exposure to Contaminants in the Tarawa Terrace and Hadnot Point Water Systems, 1943-1985

Exposure Scenario	Years Contaminated
Employment at Hadnot industrial area or other workplace	Unknown-1985
Employment location served by Tarawa Terrace water system	1957-1985
Tarawa Terrace Elementary School	1957-1985
Tarawa Terrace day care	1957-1985
Hadnot Point-Holcomb Boulevard area schools • Russell School, 1943-1987 • Old high school/middle school, 1963-1987 • Berkeley Manor Elementary School, 1963-present • Stone Street Elementary School, 1959-present • Midway Park Elementary School, 1952-present	Until 1972; intermittent linkages with the Hadnot Point system; and during a 2-week period in 1985
Hadnot Point-Holcomb Boulevard area day-care services • New hospital, 1983-1987 • Building 712, 1966-1982 • Building LCH4025, 1960-1987 • Building 799, 1953-1987 • Building 2600, unknown-1987 • Building 899, 1985-1987 • Building 1200, 1942-1987	Until 1972; intermittent linkages with the Hadnot Point system after 1972; and during a 2-week period in 1985

Source: Marine Corps, personal commun., December 4, 2007.

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system. ATSDR also computed the number of weeks that a mother lived in the residence specified on the birth certificate on the basis of information about occupancy dates from the housing records, which were then categorized and used in analyses to explore the effects of duration of exposure on the adverse pregnancy outcomes that were under investigation. However, ATSDR discovered after the study was completed that the Holcomb Boulevard water-treatment plant had been in operation since 1968 (rather than 1972), so pregnant mothers receiving water from that system in 1968-1972 were incorrectly classified as "unexposed." A reanalysis to correct that error is planned; exposure estimates from the water-modeling study (http://www.atsdr.cdc.gov/HS/lejeune/erratum.htm) will be used.

In the Sonnenfeld et al. study, infants born to mothers living at Tarawa Terrace for at least 1 week before delivery were classified as exposed. With the exception of people who were excluded because they lived in base trailer parks or in areas served by distribution systems outside Tarawa Terrace that were also contaminated with TCE, all other infants whose mothers resided in base family housing were classified as unexposed. Misclassification of women as unexposed if they resided in areas served by the Holcomb Boulevard water system and were pregnant in 1968-1972 also affected this study. For each birth, length of maternal residence at Tarawa Terrace before delivery was computed by using dates of occupancy from the housing records and then categorized and used as another surrogate of exposure to explore effects on prenatal outcomes.

Given the nature of the contamination at Camp Lejeune, the committee found the application of broad classifications of exposure based on place and duration of residence to be an appropriate approach for assessing exposure in the studies described above. Historical reconstruction and groundwater modeling at Tarawa Terrace have provided additional characterization of potential exposure to PCE and an estimated timeframe for the contamination, but it is questionable whether the additional information improves the exposure assessment for epidemiologic studies. Retrospective data on time-activity patterns of water use and water-related behaviors could improve exposure assessment but will be of questionable accuracy because the assessment is for periods that extend 20 years or more into the past.

CONCLUSIONS

The Tarawa Terrace and Hadnot Point water supply systems were contaminated with VOCs—particularly TCE, PCE, and DCE—for decades ending in the middle 1980s. Most of the organic contaminants originated from DNAPLs, which have the potential to contaminate large volumes of groundwater over long periods. The hydrogeologic data indicate a high potential for contaminants from surface sources to migrate to water-supply wells in some areas of the base. The absence of a continuous impermeable barrier between the surface (source area) and the Castle Hayne aquifer (primary aquifer) supports the field observations that show contaminants in deep monitoring wells at the same depth as the water-supply wells.

The exact extent of the contamination at Camp Lejeune cannot be documented with certainty, but it is known that a few highly contaminated wells supplied water to the Tarawa Terrace and Hadnot Point systems and that the contaminated wells were in operation for multiple years. The contaminant concentrations in the water-supply system varied because well pumping was cycled (the contaminated wells were not operated continuously, so there were fluctuations in contaminant concentrations). The qualitative evidence suggests that the magnitude of groundwater contamination was much higher in the Hadnot Point system than in the Tarawa Terrace system. It is also known that the Hadnot Point system supplied water to the Holcomb Boulevard water-supply area before 1972 and periodically after 1972. Widespread water-supply contamination in other water systems on the base was not evident from available documentation, but the committee's review was too limited to be conclusive in this regard.

The fundamental problem in estimating exposure to contaminants in the water-supply systems of Tarawa Terrace and Hadnot Point quantitatively is the lack of information on water quality and treatment-system operation during the period of contamination. There are no water-quality data for the period before the 1980s, and this leaves a 40-year period for which the extent of water-supply contamination is un-

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documented. In addition, little documentation is available on water-treatment techniques, which would shed light on the efficiency of contaminant removal during treatment. Also lacking is information on well cycling, which is important for documenting when contaminated wells were pumping raw water into the system. For those reasons, any estimates of water-supply contamination must rely on unverifiable assumptions.

ATSDR applied best practices and cutting-edge modeling approaches to predict the complex groundwater-contamination scenario at Tarawa Terrace. The ultimate outcome of the modeling was averaged monthly predictions of the concentrations of contaminants in the water supply to which people could have been exposed. Although ATSDR recognized and tried to account for the limitations and uncertainties associated with developing its models, it is extremely difficult to obtain quantitative estimates of historical levels of exposure to PCE and its degradation products reliably on a monthly basis. Reporting such model predictions without clear error bounds gives the impression that the exposure of former residents and workers at Tarawa Terrace during specific periods within a given year can be accurately defined. It is the committee's judgment that ATSDR's model is suitable only for estimating long-term exposure qualitatively. From that perspective, a single exposure category of "exposed" appears to be applicable for persons residing or working at Tarawa Terrace at any time during 1957-1985.

Efforts at historical reconstruction of exposures at Hadnot Point will be even more problematic. The contamination scenario at Hadnot Point is so complex that the committee judges that only crude estimates of contaminant concentrations in the water supply can be obtained.

RECOMMENDATIONS

The history of water-supply contamination at Hadnot Point is much more complex than the history of that at Tarawa Terrace because of the multiplicity of sources and contaminants and the ill-defined period of contamination. Therefore, the committee recommends the use of simpler approaches (such as analytic models, average estimates based on monitoring data, mass-balance calculations, and conceptually simpler MODFLOW/MT3DMS models) that use available data to rapidly reconstruct and characterize the historical contamination of the Hadnot Point water-supply system. Simpler approaches may yield the same kind of uncertain results as complex models but are a better alternative because they can be performed more quickly and with relatively less resources, which would help to speed-up the decision-making process.

As needed, and if available, better field characterization and details (such as active supply wells and cycling schedules, geologic data, and source characteristics) may be added to the conceptual models to improve understanding of transport at selected locations where potential exposure was high. Detailed MT3DMS modeling studies should be performed only for selected sites (using locally-refined grids) and only after establishing a priori the clear need, objectives, and expected outcomes for such studies. On the basis of the results of the Tarawa Terrace models, application of cutting-edge research codes for groundwater modeling (such as PSOpS and TechFlow) is unlikely to reduce uncertainty in the Hadnot Point exposure scenarios, which are expected to be much more complex than at Tarawa Terrace.

Future modeling efforts should also be aided by additional field information about the physical and chemical characteristics of the sources and receptors (aquifers). Specifically, the hydrogeologic characterization of the recharge zones of the primary aquifer that was and is the source of water for the water-supply systems at Camp Lejeune should be determined. For example, the extent and characterization of the Castle Hayne confining unit are critical for understanding the potential for hydraulic connectivity between the waste sites identified and the source aquifer for the water-supply wells over the period of potential exposure (1943-present). It is well documented that the confining layer is neither continuous nor confining in all areas beneath the Camp Lejeune geographic boundary.

The committee's effort to evaluate potential exposures to contaminants in the Tarawa Terrace and Hadnot Point water systems was hampered by the fact that the available data on water quality of those systems was found in hundreds of documents. Most of the documents are publicly available on line, but

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they were not readily searchable or cataloged in an organized fashion for research. To facilitate future exposure-assessment efforts, the committee strongly recommends that a comprehensive, accessible database of water-quality measurements (including data from remedial investigations) be created and maintained. Such a database should include information on sample location, date, analytes measured, laboratory quality-control information (including limits of detection), and other information relevant to exposure assessment that relies on environmental samples collected in the course of investigating water, soil, and air quality at Camp Lejeune.

Because of the sparseness of water-quality data and the insufficient ability of water-quality modeling to make up for the absence of information, most exposure estimates in epidemiologic studies at Camp Lejeune will rely heavily on unverifiable assumptions and projections. Therefore, the most useful exposure assessment will likely be relatively crude and based for the most part on ascertaining the most likely time period and location (water supply system) of contamination, typical locations the study participant spent time on the base (for example, residence, school, daycare, workplace), and crude categorization of personal water-use activities during the exposure period.

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3

Systemic Exposures to Volatile Organic Compounds and Factors Influencing Susceptibility to Their Effects

When evaluating health effects of chemicals, it is important to understand how they enter and are distributed in the body (systemic exposure) and how the body handles them and their metabolites. This chapter reviews general issues related to evaluation of exposure to volatile organic compounds (VOCs) in that context. It considers characterization of differences between laboratory animals and humans and implications for the interpretation of the animal-toxicology literature that is presented in Chapter 4, identification of human populations that might be more susceptible than others to the effects of the primary contaminants of concern, and interactions that might result from exposure to mixtures of chemicals.

VOCs are the focus of this chapter because the primary water contaminants at Camp Lejeune and specified in the study charge are in this class of compounds. As noted in Chapter 2, other contaminants have been detected in the water supplies, so exposures were more complex than just VOC mixtures. However, for the purposes of this report, the review has been restricted to the primary VOC contaminants of concern.

ENVIRONMENTAL CONTAMINATION

The major drinking-water contaminants of interest at Camp Lejeune are volatile organic chemicals (VOCs), mainly trichloroethylene (TCE) and tetrachloroethylene (perchloroethylene, PCE) but also vinyl chloride, methylene chloride, benzene, toluene, *cis*- and *trans*-1,2-dichloroethylene (DCE), and 1,1-DCE (see Chapter 2). All those except benzene are halogenated, short-chain aliphatic hydrocarbons (halocarbons); benzene is an aromatic hydrocarbon. The water solubility of these compounds increases with decreasing numbers of carbon or halogen atoms. The maximum water solubilities of PCE and TCE at 25°C, for example, are 150 and 1,366 mg/L, respectively. Volatility increases with decreasing molecular weight, varying from 18.5 mm Hg for PCE to 74 mm Hg for TCE at 25°C (ATSDR 1997b,c).

Widespread use of TCE and other VOCs has resulted in their frequent escape into the environment (Wu and Schaum 2000). Figure 3-1 illustrates the pathways by which environmental media are contaminated and how people may be exposed. Most VOCs that enter the environment do so by evaporation during their use or discharge. Concentrations in air in the immediate vicinity of point sources may be high, but winds rapidly dilute and disperse the vapors (from nondetectable to nanograms per cubic meter of air). Migration of VOCs from subsurface soil or groundwater into the air in basements (vapor intrusion) also occurs. There does not appear to be a wide-scale assessment of the importance of the soil vapor intrusion pathway for human exposure to VOCs. The contribution of different variables to TCE permeation is described in a laboratory simulation by Fischer and Uchrin (1996), and another tracer gas was used to develop a mathematical model for the phenomenon (Olson and Corsi 2001).

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Contaminated Water Supplies at Camp Lejeune: Assessing Potential Health Effects

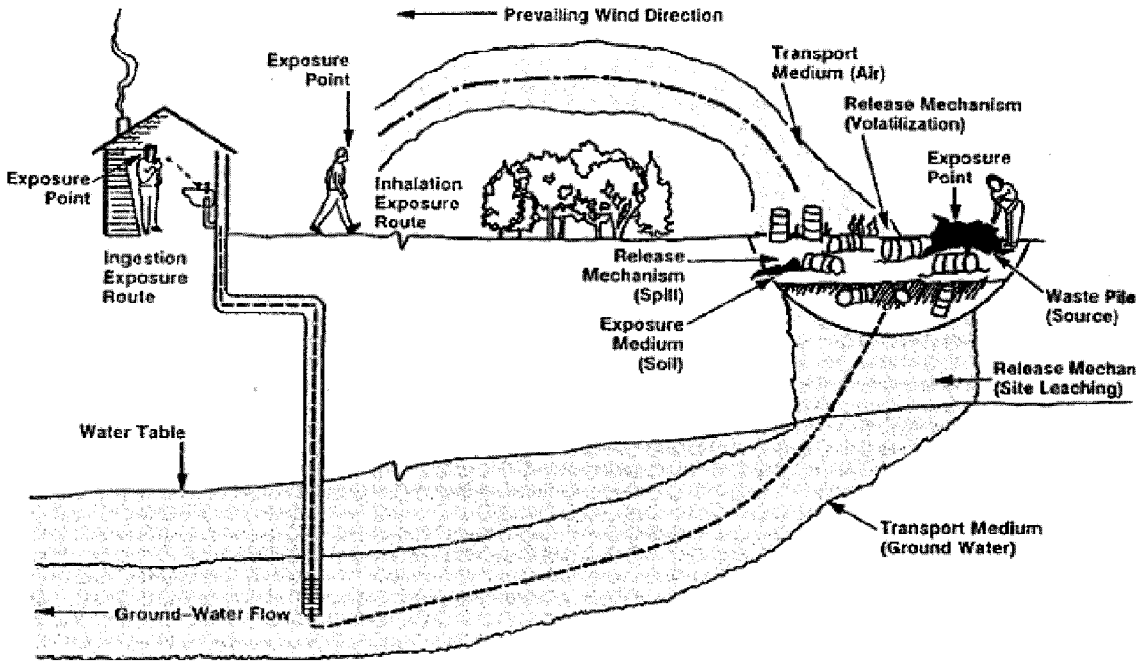

FIGURE 3-1 Environmental contamination from solvents and exposure pathways. Source: EPA 1989.

Contamination of drinking-water supplies is of greater health concern. In past years, halocarbons were generally regarded as water-insoluble. It is now recognized that they are soluble in water to a small extent. Maximum solubilities, for example, range from 150 mg/L (or parts per million) for PCE to 4,800 mg/L for methylene chloride. Concentrations typically found in finished drinking water in the United States range from parts per trillion to parts per billion (Moran et al. 2007).

VOCs are found as contaminants of surface water and groundwater. Concentrations diminish rapidly after VOCs enter bodies of water, primarily because of dilution and evaporation. Halocarbons rise to the surface or sink to the bottom, depending on their density. Halocarbons on the surface largely evaporate. The movement of halocarbons on the bottom depends on their solubilization in water and their mixing by currents or wave action; mixing causes them to reach the surface. Hydrocarbon solvents spilled onto the ground largely evaporate, although some can permeate soil and migrate through it until reaching groundwater or an impermeable layer. Migration of solvents through sandy soil of low organic content is most rapid and extensive (Munnecke and Van Gundy 1979). Solvents in groundwater tend to remain trapped until the water reaches the surface, although some are subject to microbial modification. PCE and TCE, for example, undergo reductive dehalogenation by microorganisms to a small extent to *cis*- and *trans*-1,2-DCE, vinyl chloride, and other products (Smith and Dragun 1984; McCarty 1993). Thus, halocarbon-contaminated groundwater usually contains a relatively high proportion of parent compounds and small amounts of microbial degradation products.

EXTERNAL EXPOSURE

People are exposed to halocarbons and other VOCs in water by three major routes: inhalation, skin contact, and ingestion. A number of studies have looked at the relative importance of those routes. Weisel and Jo (1996) based estimates of internal doses of TCE and chloroform received from showering on results of experiments with human subjects. They concluded that inhalation and dermal exposure resulted in an internal dose of each chemical comparable with the dose ingested in 2 L of water. Gordon et

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al. (2006) conducted a detailed investigation of the contribution of household water use to internal doses of chloroform and other trihalomethanes. Showering and bathing resulted in the highest blood and exhaled-breath concentrations of chloroform in human subjects in household settings; inhalation and percutaneous absorption were also found to be important routes of exposure. Giardino and Andelman (1996) reported that the temperature of water had a dominant effect on volatilization of TCE and chloroform during showering. Some 80% of TCE and 60% of chloroform were released from hot shower water. Haddad et al. (2006) used a physiologic model to assess different home exposure scenarios and concluded that ingestion contributed less than 50% of the total absorbed dose of TCE. Thus, systemic absorption from the lungs, skin, and gastrointestinal tract should all be taken into account in estimating internal doses that result from use of water supplies contaminated with VOCs.

INTERNAL EXPOSURE

The concept of dose has been refined during the last 15-20 years. The amount of a chemical to which a person is exposed is now termed the external exposure or administered dose. Absorption into the blood may be partial or complete, depending on the chemical and route of exposure. The amount of a chemical absorbed systemically from the lungs, gastrointestinal tract, and skin is termed the absorbed dose or internal dose. The amount of a chemical that reaches an organ or tissue where a toxic effect occurs is termed the target-organ dose. It is necessary here to specify the amount of the toxicologically active forms of the chemical. In the case of TCE, both the parent compound and trichloroethanol, a major metabolite, cause depression of the central nervous system (CNS) when present at sufficient concentrations. PCE can also produce CNS depression. Trichloroacetic acid, a major metabolite of both TCE and PCE, is believed to be primarily responsible for liver tumors in B6C3F$_1$ mice (Bull 2000; Lash et al. 2000a). Thus, it is important to know or to be able to estimate the quantity of the bioactive moiety and how long it remains in the target organ if one wants to predict the magnitude and duration of toxic action (Andersen 1987).

Pharmacokinetics, or toxicokinetics, and physiologically based toxicokinetic (PBTK) models are increasingly important in reducing uncertainties inherent in health risk assessments of TCE, PCE, methylene chloride, and other VOCs (Andersen et al. 1987; Andersen 2003; Clewell and Andersen 2004; Clewell et al. 2005; Krishnan and Johanson 2005). *Toxicokinetics* may be defined as the systemic uptake, distribution, metabolism, interaction with plasma and cellular components, and elimination of toxic chemicals and their metabolites. Kinetic processes determine how much of an external dose is absorbed into the blood; reaches the arterial circulation; binds to plasma proteins or other inactive sites; enters specific organs; is biotransformed to toxicologically active and inactive forms; interacts with target molecules, cells, and tissues; and is eliminated from the target tissue and the body (Bruckner et al. 2008). One or more of those processes can vary widely from one route of exposure to another, from high to low doses, from one species to another, and from one individual to another. Gaining an understanding of how kinetic processes differ can substantially reduce the number of assumptions made in assessing toxicity and cancer risks posed by VOCs.

Volatility and lipophilicity are two of the most important properties of VOCs that govern their toxicokinetics. The volatility of the compounds varies inversely with their molecular weight. TCE, for example, is of lower molecular weight and evaporates more readily than PCE. PCE is more lipid-soluble than TCE. Cell membranes are made up largely of lipids. Halocarbons pass freely through membranes from areas of high to low concentration by passive diffusion.

Absorption

Halocarbons and other VOCs are absorbed through intact human skin to a limited extent. The barrier to penetration is the stratum corneum, the skin's outermost layer. The stratum corneum is composed

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of very tightly adhering, keratinized epithelial cells, which present a much more substantial barrier to halocarbons than do living cell membranes. Important determinants of the rate and extent of percutaneous absorption of a chemical include the integrity and thickness of the stratum corneum, the surface area exposed and duration of contact, and the chemical's concentration, molecular size, and lipophilicity (Stewart and Dodd 1964; EPA 1992). Percutaneous absorption of VOCs is more extensive through rodent than through human skin, owing largely to the rodents' thinner stratum corneum and higher dermal blood flow rate (McDougal et al. 1990; Monteiro-Riviere et al. 1990). Poet et al. (2000) reported that the dermal permeability constant for absorption of 1,1,1,-trichloroethane from water into humans was one-fortieth that into rats. Those researchers concluded that people will not absorb substantial amounts of VOCs through their skin from contaminated water regardless of the duration of exposure. That conclusion conflicts with that of Weisel and Jo (1996) and Gordon et al. (2006), who found percutaneous absorption to be an important route of human exposure.

Halocarbons and most other VOCs are absorbed from the lungs rapidly and extensively. TCE and PCE, for example, appear in the arterial blood of rats within 1 min after initiation of inhalation exposure (Dallas et al. 1991, 1994). Most of the systemic absorption of inhaled VOCs occurs in the alveoli. The small lipophilic molecules readily diffuse bidirectionally through the thin capillary and alveolar type I cells. Such gases in the alveoli are believed to equilibrate almost instantaneously with blood in the pulmonary capillaries (Goldstein et al. 1974). The ratio of the concentration of a VOC in blood to its concentration in air at equilibrium is the blood:air partition coefficient. Partition coefficients have been measured in vitro with human and rat blood for a large number of VOCs (Gargas et al. 1989). Respiratory, or alveolar, ventilation rate and the ratio of cardiac output to pulmonary perfusion rate are two other important determinants of pulmonary uptake of VOCs. VOCs diffuse from areas of high to areas of low concentration, so increases in respiratory rate (to maintain a high alveolar concentration) and increases in pulmonary blood flow rate (to maintain a large concentration gradient by removing capillary blood that contains a VOC) enhance systemic absorption. The higher those factors are, the greater the systemic uptake. The TCE blood:air partition coefficient of the rat is 2.7 times greater than that of the human (Gargas et al. 1989). Resting alveolar ventilation rates of rats and mice are as much as 11 and 23 times higher, respectively, than that of humans. Cardiac outputs of rats and mice are about 6 and 10 times greater than that of humans (Brown et al. 1997). Thus, for equivalent inhalation exposures to TCE and other VOCs, internal doses are substantially higher in rodents than in humans (Bruckner et al. 2008).

Systemic absorption of VOCs during inhalation exposures depends on metabolism and tissue loading, in addition to the factors described above. The percentage uptake of inhaled TCE is initially high in experimental animals. Uptake progressively declines during exposure as a chemical accumulates in tissues, and its concentration in venous blood returning to the lungs increases, reducing the air:blood concentration gradient (Dallas et al. 1989). A near steady state, or equilibrium, in uptake and in blood concentrations is usually reached within an hour and maintained despite continued inhalation of a fixed air concentration of TCE. The same phenomenon was reported recently in human subjects inhaling TCE at 1 ppm for 6 h (Chiu et al. 2007). Blood concentrations of PCE, in contrast, slowly rose in the subjects during the last 4 h of a 6-h exposure to PCE at 1 ppm. That difference is due to PCE's higher lipid solubility, which results in its greater and more prolonged uptake into body fat. Persons using contaminated water at Hadnot Point and Tarawa Terrace probably had intermittent PCE or TCE exposures during the day when they drank water and used heated water. Day-to-day exposures were also intermittent because the individual water-supply wells operated on a cycle schedule (see Chapter 2).

Halocarbons and other VOCs are well absorbed after their ingestion. More than 90% of TCE given in water as an oral bolus (by gavage to rats that have been fasting) is absorbed systemically (D'Souza et al. 1985). Peak blood concentrations are observed within 5-10 min of dosing. The presence of food, particularly fatty foods, in the gut delays absorption of TCE and other organic solvents. Kim et al. (1990a) describe the time course of carbon tetrachloride in the venous blood of rats given an equivalent oral bolus dose of the halocarbon in water and in corn oil. The peak blood concentration of carbon tetrachloride is about 10 times higher in the water-vehicle group than in the oil-vehicle group, but the relationships between blood concentrations of carbon tetrachloride and time in the two groups are essen-

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tially the same. Liver injury is more pronounced in the group that ingested carbon tetrachloride in water, apparently because of the liver's markedly higher exposure to the hepatotoxin during the initial minutes after dosing.

Inhalation results in substantially higher arterial blood and target-organ concentrations of VOCs than does ingestion of comparable doses. A number of factors are responsible for that phenomenon. As described above, fatty foods serve as a reservoir in the gut to prolong the absorption of lipophilic chemicals. All the cardiac output passes through the pulmonary circulation compared with about 20% through the gastrointestinal tract. More rapid blood flow in the lungs creates a greater concentration gradient, which results in more rapid diffusion into the blood. The distance that VOCs must diffuse from their absorption surface to capillaries is considerably shorter in the alveoli than in the gastrointestinal mucosal epithelium. The most important route-dependent difference for well-metabolized VOCs is presystemic elimination after their ingestion (Bruckner et al. 2008).

Presystemic Elimination of Oral Volatile Organic Compounds

A substantial proportion of TCE and other well-metabolized VOCs that are ingested does not reach the arterial circulation or extrahepatic organs. It has not been established whether a significant proportion of low doses of VOCs undergo gastrointestinal metabolic clearance, though researchers have established the presence of several CYP3A isoforms in the small intestines of humans (Obach et al. 2001) and mice and rats (Martignoni et al. 2006). Chemicals absorbed into venous mesenteric blood vessels are conveyed via the portal vein through the liver before entering the mixed venous circulation. The liver contains the highest concentrations of CYP2E1 and other enzymes and is the major site of xenobiotic metabolism in the body. The efficiency of first-pass hepatic metabolism and clearance depends on the administered dose of the chemical, the rate at which it is ingested, and its propensity to be metabolized. White et al. (unpublished data) recently observed that bioavailability of 1,1,1,-trichloroethane, a poorly metabolized halocarbon, was markedly higher in orally dosed rats than was TCE, a well-metabolized halocarbon.[1] The bioavailability of TCE was substantially higher when it was given as a single oral bolus (that is, all at one time) than when it was given slowly over several hours. Administration of the quickly absorbed chemical as a bolus resulted in its rapid arrival in amounts that exceeded (or saturated) the liver's metabolic capacity. In contrast, neither the dose nor the rate of oral administration of 1,1,1,-trichloroethane affected its first-pass hepatic elimination or bioavailability, because it was poorly metabolized. The bioavailability of TCE, however, was significantly lower at lower doses because of its more efficient metabolic clearance. Lee et al. (1996) also found that hepatic first-pass elimination of oral TCE was inversely related to dose in rats. VOCs are exhaled during their first pass through the lungs. Lee et al. (1996) confirmed that pulmonary elimination of TCE was not dose-dependent. Andersen (NRC 1986) had proposed that pulmonary elimination of VOCs was governed instead by a VOC's blood:air partition coefficient. In summary, VOCs that are extensively metabolized and quite volatile are most efficiently eliminated before they reach the arterial circulation.

First-pass, or presystemic elimination, may have major implications for cancer and noncancer risks posed by ingestion of very low concentrations of VOCs in drinking water. Over 25 years ago, Andersen (1981) proposed that the liver was capable of removing "virtually all" of a well-metabolized VOC after its ingestion if the amount in the portal blood was not high enough to saturate hepatic metabolism. As described below, most of the VOCs of interest at Camp Lejeune are extensively metabolized. Metabolism is required for their conversion to potentially cytotoxic or mutagenic substances. The liver should bear the brunt of metabolizing ingested VOCs. However, first-pass hepatic metabolic clearance and exhalation will protect most extrahepatic organs by reducing the amount of parent compounds reaching them.

[1]White, C.A., S. Muralidhara, C. Hines, and J.V. Bruckner. Effect of oral dosage level and rate on the bioavailability and metabolism of trichloroethylene and 1,1,1-trichloroethane. Submitted to Toxicol. Sci. Manuscript being prepared for submission for publication.

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Parent halocarbons, as described previously, can depress CNS functions if they reach the brain in sufficient amounts. A number of extrahepatic tissues—including brain, lung, renal, testicular, and breast tissue and bone marrow—contain CYP2E1, other P-450s, and other enzymes that metabolize xenobiotics (de Waziers et al. 1990; Ding and Kaminsky 2003). The amounts of enzymes are usually considerably lower in those tissues than in the liver but can be high enough in some cell types to form quantities of reactive metabolites adequate to harm the cells. Hepatic halocarbon metabolites stable enough to be transported to other organs can potentially injure those organs. It is widely recognized, for example, that derivatives of glutathione conjugates of TCE and PCE formed in the liver are taken up and metabolized further by the kidneys to substabnces that may be nephrotoxic or carcinogenic (Lash et al. 2000b; Lash and Parker 2001; Lash et al. 2007). VOCs absorbed from the lungs and skin are not subject to presystemic elimination.

The efficiency of presystemic elimination of ingested halocarbons in humans remains to be established. Sufficiently sensitive analytic methods for quantifying VOCs in biologic specimens that allow direct testing of Andersen's (1981) aforementioned hypothesis have not been available until very recently. Lee et al. (1996) used a gas-chromatography-electron-capture headspace technique to measure blood concentrations in assessing presystemic elimination of TCE in rats. Their experimental approach required monitoring complete blood-TCE time courses. The lowest oral dose for which a complete time course could be delineated was 170 μg/kg. Some 60% of the dose was eliminated before reaching the rats' arterial circulation. More recently, a much more sensitive analytic method has been used; it involves VOC extraction and concentration on a solid fiber and measurement with gas chromatography-mass spectrometry. Using that technique, Blount et al. (2006) measured 31 VOCs in the blood of the general U.S. population. Liu et al. (2008) have also used the technique to obtain blood time-course data on rats given TCE orally at as low as 1 ng/kg. Bioavailability was about 10% at the lowest doses. The analytic method's limit of quantification was 25 pg/mL (ppt). Rats have a greater capacity to metabolize TCE and other VOCs than humans, so first-pass hepatic elimination should be somewhat less efficient in humans. Weisel and Jo (1996), however, were able to detect TCE in exhaled breath for only seconds to a few minutes after humans ingested water contaminated with TCE. Chloroform was undetectable in breath samples of persons who consumed chlorinated municipal water; this implies complete first-pass hepatic elimination. The efficiency of human presystemic elimination of TCE and other VOCs at environmental concentrations can be determined by extrapolation from animal data or by direct measurement. In summary, presystemic elimination should protect most extrahepatic tissues from harm after ingestion of TCE, PCE, and other VOCs at environmental concentrations.

Solvent or Vehicle Effects on VOC Toxicity

Oral and dermal administration of VOCs in toxicology studies usually require that the lipophilic chemicals be dissolved or diluted in a suitable solvent. Corn oil and other digestible oils have been the most commonly-used vehicles, though aqueous emulsions, suspensions, and gelatin-encapsulated preparations have been employed in toxicity and carcinogenicity investigations. Considerable effort has been devoted to assessing adverse health effects of VOCs in drinking water. A number of studies have been conducted to determine whether experiments in which VOCs were given to animals in corn oil were relevant to assessing risks from ingestion of VOCs in water. Kim et al. (1990a,b), for example, found that corn oil served as a reservoir in the gut to delay systemic absorption of carbon tetrachloride in rats. Although bioavailability of carbon tetrachloride given in corn oil and in an aqueous Emulphor emulsion was the same, peak blood concentrations of carbon tetrachloride and acute hepatotoxicity were much lower in the corn oil group. Raymond and Plaa (1997) found aqueous preparations of carbon tetrachloride were more acutely hepatotoxic to rats than when it was administered in corn oil, though the converse was true for nephrotoxicity of chloroform. Dissimilar findings have been reported in subacute studies. Condie et al. (1986), for example, observed that carbon tetrachloride was more hepatotoxic to mice after 90 days of oral dosing in corn oil than in an aqueous Tween emulsion. Koporec et al. (1995), however, found no dif-

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ference in rats when given carbon tetrachloride in either corn oil or aqueous solution for 13 weeks. As described below, chloroform and other VOCs have been found to be hepatocarcinogens in mice when given chronically by gavage in corn oil, but not when delivered in drinking water. Under these circumstances, interpretation requires consideration of the confounders introduced by both the vehicle and dose regimen.

There is concern that vehicles may not only affect the absorption of VOCs, but may influence VOC metabolism and disposition and may have biological actions of their own. Oils in the gastrointestinal tract largely retain VOCs until the oil is emulsified and digested (Kim et al. 1990b). The lipids thus delay VOC absorption into the blood and can carry some of the VOC along into the lymphatics. Common surfactants used as emulsifying agents are known to modify drug absorption by altering the physical properties of membranes, as well as certain transport mechanisms (Xia and Onyuksel 2000). Feeding rats a diet supplemented with corn oil enhanced the induction of hepatic cytochrome P4502B1 by phenobarbital (Kim et al. 1990c). This is one isozyme that metabolically activates high doses of TCE and several other VOCs in rats. Feeding animals a high-fat diet containing corn oil increases lipoperoxidation and susceptibility to oxidative stress by reducing antioxidant enzyme defenses (Domitrovic et al. 2006; Slim et al. 1996). A number of investigations have shown increased incidences of breast, colorectal, and prostate cancer in rodents maintained on high-fat diets, but recent human epidemiological studies have largely been inconclusive (Kushi and Giovannucci 2002; Thiebaut et al. 2007; Kobayashi et al. 2008).

Pattern of Water Ingestion

A person's pattern of consumption of VOC-contaminated water can have a marked effect on halogenated chemicals' toxicokinetics and toxic or carcinogenic potential. For convenience in chronic oral-carcinogenicity studies, TCE, PCE, methylene chloride, and chloroform have usually been given daily by gavage. In each instance, an increased incidence of liver tumors in $B6C3F_1$ mice was observed. No such increase was seen when the mice received tumorigenic doses of chloroform and other VOCs in drinking water (Jorgenson et al. 1985; Klaunig et al. 1986). Larson et al. (1994) saw marked necrosis and ensuing proliferation of hepatocytes in $B6C3F_1$ mice given chloroform by gavage, but no such effects in mice that consumed the same daily doses in their water. La et al. (1996) reported greater DNA-adduct formation and hepatocellular proliferation in mice given 1,2,3-trichloropropane by gavage than in those receiving the chemical in drinking water. Sanzgiri et al. (1995) administered the same doses of carbon tetrachloride to rats by gavage and over 2 h by constant gastric infusion. Arterial blood concentrations of carbon tetrachloride and the extent of acute hepatic damage were greater in the gavage groups. Carbon tetrachloride and other halocarbons are quickly absorbed from the gastrointestinal tract, and the rapid delivery of large quantities of carbon tetrachloride to the liver via the portal blood inhibited metabolism and killed hepatocytes. Both effects reduced hepatic metabolic clearance of the chemical. Such findings raise questions about the relevance of gavage toxicity and cancer-study results to real-life human exposures, in which people typically ingest contaminated water in divided doses over the course of the day.

Systemic Distribution

VOCs are transported by the arterial blood to tissues throughout the body. The lipophilic compounds do not bind appreciably to plasma proteins or hemoglobin but partition into their hydrophobic regions and into phospholipids, lipoproteins, and cholesterol present in the blood (Lam et al. 1990). Initial uptake into tissues depends primarily on their rate of blood flow and tissue:blood partition coefficient. The brain is a prime example of an organ with a high perfusion rate and high lipid content, hence a high brain:blood partition coefficient. Lipophilic VOCs quickly accumulate in the brain and can rapidly depress its functions on initiation of sufficiently high external exposures (Warren et al. 2000). Inhalation of a few hundred ppm of TCE and PCE can inhibit psychophysiological functions in humans, while inhala-

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tion of several thousand ppm will rapidly produce marked CNS depression. Then, redistribution to poorly perfused lipid-rich tissues (such as bone marrow, skin, and fat) with even higher tissue:blood partition coefficients occurs. Adipose tissue gradually accumulates large amounts of VOCs and slowly releases them back into the bloodstream because of its high tissue:blood partition coefficient and low blood perfusion rate. That prolongs exposure of other tissues to the chemicals (Bruckner et al. 2008).

Metabolic Activation and Inactivation of Trichloroethylene and Perchloroethylene

Metabolism, or biotransformation, plays a key role in modulating the toxicokinetics and the ensuing toxicity or carcinogenicity potential of the VOCs of interest at Camp Lejeune. As described previously, most VOC metabolism occurs in the liver. Biotransformation in other tissues is quantitatively insignificant but can be toxicologically significant if CYP2E1 and some other enzymes are present. Specific hepatic and extrahepatic enzymes convert the VOCs to relatively water-soluble metabolites that can be eliminated more readily in the largely aqueous urine and bile. Conversion of the parent compounds and their reactive metabolites to less active or inactive metabolites that are more water-soluble and therefore more efficiently eliminated is termed metabolic inactivation or detoxification. The relative extent of activation and inactivation of VOCs can vary substantially from one species to another and from one individual to another. It is well established that the metabolic activation of the VOCs of interest in Camp Lejeune water, in decreasing order of magnitude, is as follows: mice > rats > humans (Elfarra et al. 1998; Lipscomb et al. 1998; Volkel et al. 1998; Lash and Parker 2001). Mice express very low concentrations of epoxide hydrolase (Lorenz et al. 1984), the enzyme that catalyzes the hydrolytic degradation (detoxification) of highly reactive epoxide metabolites of TCE and PCE. Many other factors or variables may also influence the metabolism and toxicokinetics of VOCs (Lof and Johanson 1998).

The metabolic activation and inactivation of TCE has been described in detail elsewhere (ATSDR 1997b; Lash et al. 2000a; NRC 2006). TCE is metabolized primarily via an oxidative pathway involving sequential formation of a series of metabolites. The second, relatively minor pathway involves glutathione (GST) conjugation (Figure 3-2). The key metabolic pathways and metabolites of toxicologic interest are described briefly below.

The initial step in the oxidative pathway is catalyzed by microsomal cytochrome P-450s. CYP2E1, as noted previously, is the primary P-450 isozyme responsible for oxidation of low concentrations of TCE (Lipscomb et al. 1997; Ramdhan et al. 2008). P-450-catalyzed oxidation of TCE in rodents and humans, in decreasing order of magnitude, is as follows: mice>rats>humans (Lash et al. 2000a). Whether TCE is initially converted to TCE oxide is controversial. Cai and Guengerich (2001) were able to detect formation of trace amounts of the epoxide by phenobarbital-induced rat liver P-450s but not by human liver P-450s. The majority of TCE is apparently converted to an oxygenated TCE-P-450 intermediate, which rearranges to form chloral, a major metabolic intermediate. Chloral is oxidized to chloral hydrate, a sedative widely used in medical and dental procedures in infants and children (Vade et al. 1995; Keengwe et al. 1999). Chloral hydrate is both oxidized to trichloroacetic acid and reduced to trichloroethanol. Much trichloroethanol is conjugated with glucuronic acid and excreted in the urine. Trichloroethanol glucuronide that is excreted in the bile is hydrolyzed, reabsorbed, and oxidized in part to trichloroacetic acid. Chiu et al. (2007) recently observed that concentrations of trichloroacetic acid were significantly lower than trichlorethanol and trichloroethanol glucuronide concentrations in the blood of humans who had inhaled TCE at 1 ppm for 6 h. Modest amounts of dichloroacetic acid apparently are produced from trichloroacetic acid and trichloroethanol in mice, but relatively little dichloroacetic acid is formed in rats. Trace amounts of dichloroacetic acid were detected in one study of TCE-exposed humans (Fisher et al. 1998) but not in other studies (Lash et al. 2000b; Bloemen et al. 2001). Both trichloroacetic acid and dichloroacetic acid have been shown to be hepatic carcinogens in mice at high doses (Bull 2000). It is generally accepted that trichloroacetic acid is a nongenotoxic liver carcinogen in $B6C3F_1$ mice, although its ability to cause liver cancer in humans has been discounted by findings in a number of labo-

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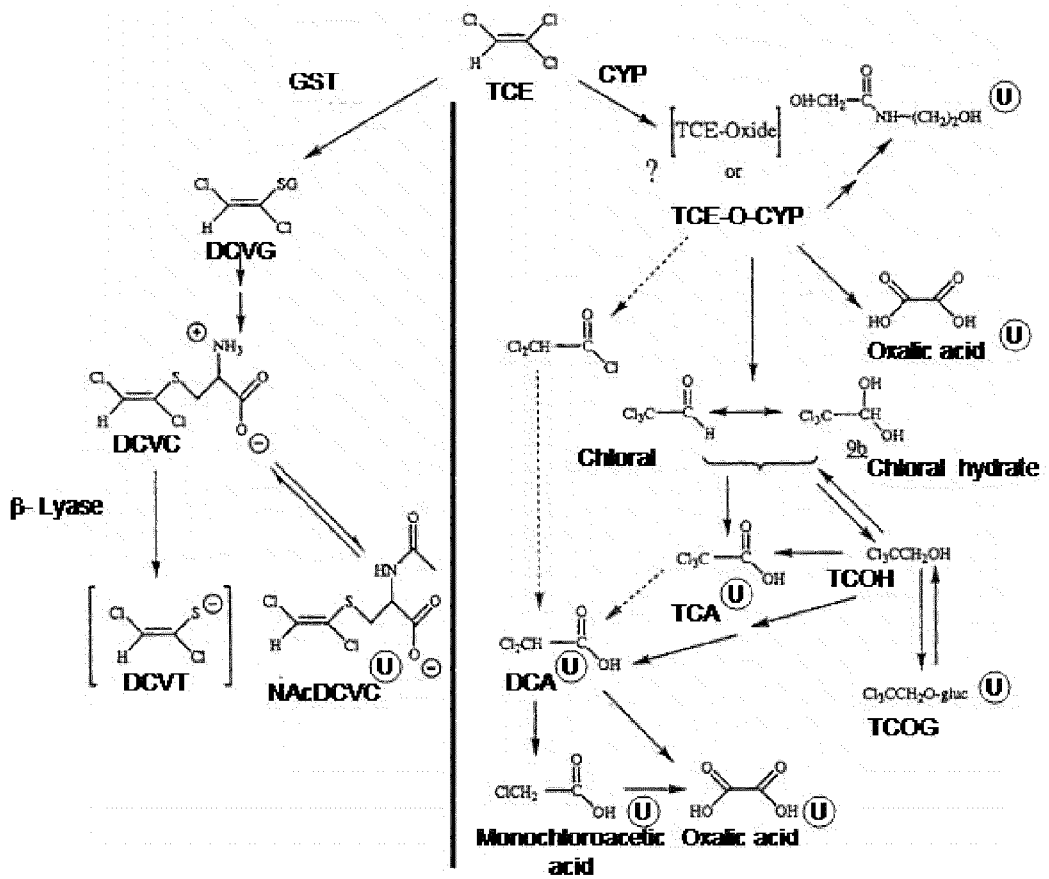

FIGURE 3-2 Metabolism of trichloroethylene. Metabolites marked with Ⓤ are known urinary metabolites. Arrows with broken lines indicate other possible steps in forming DCA. CYP, cytochrome P-450; DCA, dichloroacetic acid; DCVC, *S*-(1,2-dichlorovinyl)-L-cysteine; DCVG, *S*-(1,2-dichlorovinyl)glutathione; DCVT, *S*-(1,2-dichlorovinyl)thiol; GST, glutathione *S*-transferase; NAcDCVC, *N*-acetyl-*S*-(1,2-dichlorovinyl)-L-cysteine; TCA, trichloroacetic acid; TCE, trichloroethylene; TCE-O-CYP, trichloroethylene-oxide-cytochrome P-450 complex; TCOG, trichloroethanol glucuronide; TCOH, trichloroethanol. Source: NRC 2006.

ratory investigations (Bull 2000; Moore and Harrington-Brock 2000). The possible causative role of dichloroacetic acid in human liver cancer is even more controversial (Walgren et al. 2005; Caldwell and Keshava 2006; Keshava and Caldwell 2006; Klaunig et al. 2007).

The glutathione conjugation pathway is quite similar qualitatively, but not quantitatively, in rats and humans. The initial step in this second, minor pathway involves conjugation of TCE with glutathione to form *S*-(1,2-dichlorovinyl)glutathione (DCVG). DCVG formation occurs primarily in the liver at a rate about 10 times greater in rats than in humans (Green et al. 1997a). Much of the DCVG is excreted via the bile into the intestines and converted to *S*-(1,2-dichlorovinyl)-L-cysteine (DCVC). That metabolite is reabsorbed and taken up by the liver, where a portion is detoxified by *N*-acetylation. Bernauer et al. (1996) exposed rats and humans to TCE vapor at up to 160 ppm for 6 h. The rats excreted 8 times more *N*-acetyl-DCVC in their urine than did the human volunteers at each exposure level. Some DCVC is taken up by the kidneys and further metabolized by the enzyme β-lyase to *S*-(1,2-dichlorovinyl)thiol (DCVSH). DCVSH is then converted to unstable, highly reactive products, including chlorothioketene and thionoacylchloride (Lash et al. 2000a). Metabolic activation of DCVC to chlorothioketene was shown to occur 11 times more rapidly in rats than in humans (Green et al. 1997a). Lash et al. (2001b) also demonstrated that cultured rat renal cells are more sensitive to DCVC than are human renal cells. Chlorothioketene and

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similarly unstable congeners are capable of covalently binding to renal cellular proteins and DNA, and this results in genotoxicity and cytotoxicity with ensuing regenerative hyperplasia and potentially renal-cell carcinoma.

PCE, like TCE, is metabolized through cytochrome P-450-catalyzed oxidation and glutathione conjugation (Figures 3-3 and 3-4). CYP2E1 is not thought to play a major role. PCE is believed to be oxidized primarily by the CYP2B family in the rat (Hanioka et al. 1995). In humans, CYP2B6 is the primary isoform responsible for PCE metabolism, and there are minor contributions by CYP1A1 and CYP2C8 (White et al. 2001). The initial metabolite is the epoxide PCE-oxide. That metabolic intermediate can be biotransformed to several products (Lash and Parker 2001). The primary one is trichloroacetyl chloride, which reacts with water to form trichloroacetic acid, the predominant PCE metabolite found in the urine of rodents and humans (Birner et al. 1996; Volkel et al. 1998). Some trichloroacetic acid is converted to dichloroacetic acid. PCE is a much poorer substrate for CYPs than TCE (that is, PCE is much less

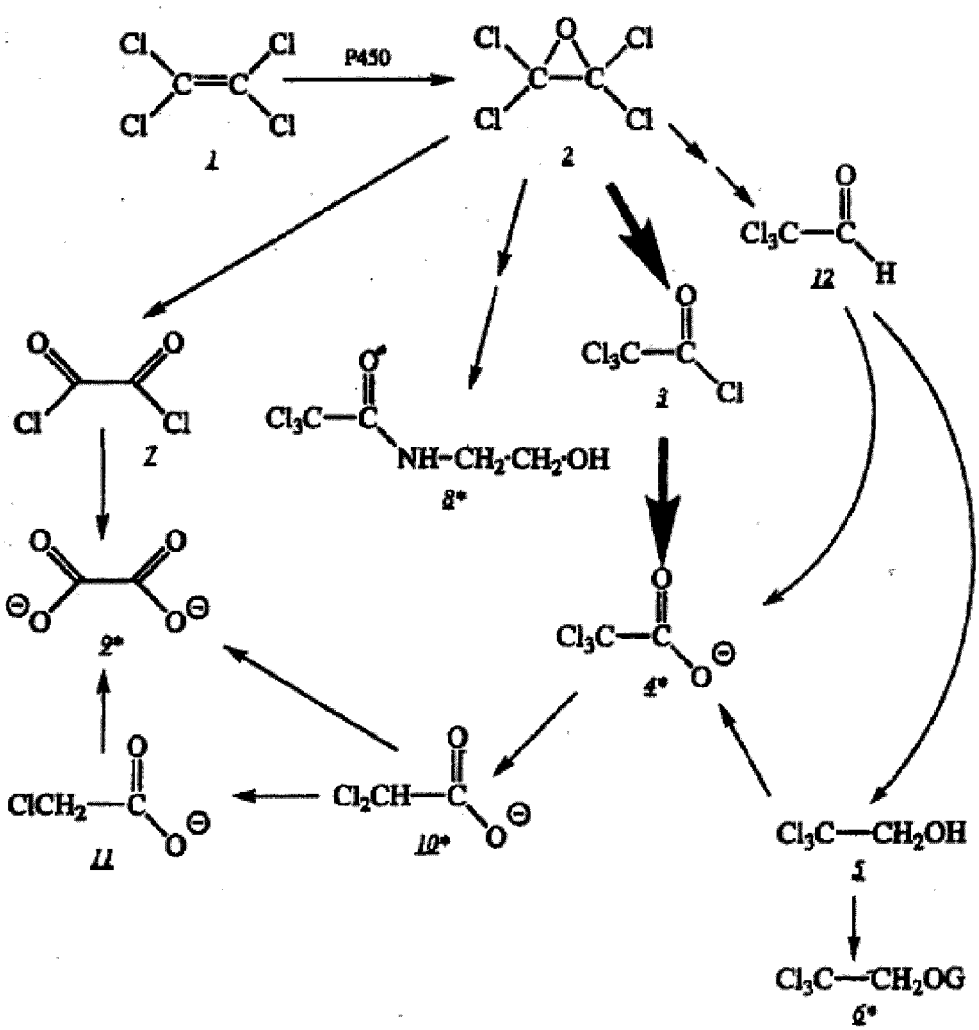

FIGURE 3-3 Metabolism of PCE by P-450 pathway. *Identified urinary metabolites: 1, PCE; 2, PCE epoxide; 3, trichloroacetyl chloride; 4, trichloroacetate; 5, trichloroethanol; 6, trichloethanol glucuronide; 7, oxalate dichloride; 8, trichloroacetyl aminoethanol; 9, oxalate; 10, dichloroacetate; 11, monochloroacetate; 12, chloral. Source: Lash and Parker 2001. Reprinted with permission; copyright 2001, *Pharmacological Reviews*.

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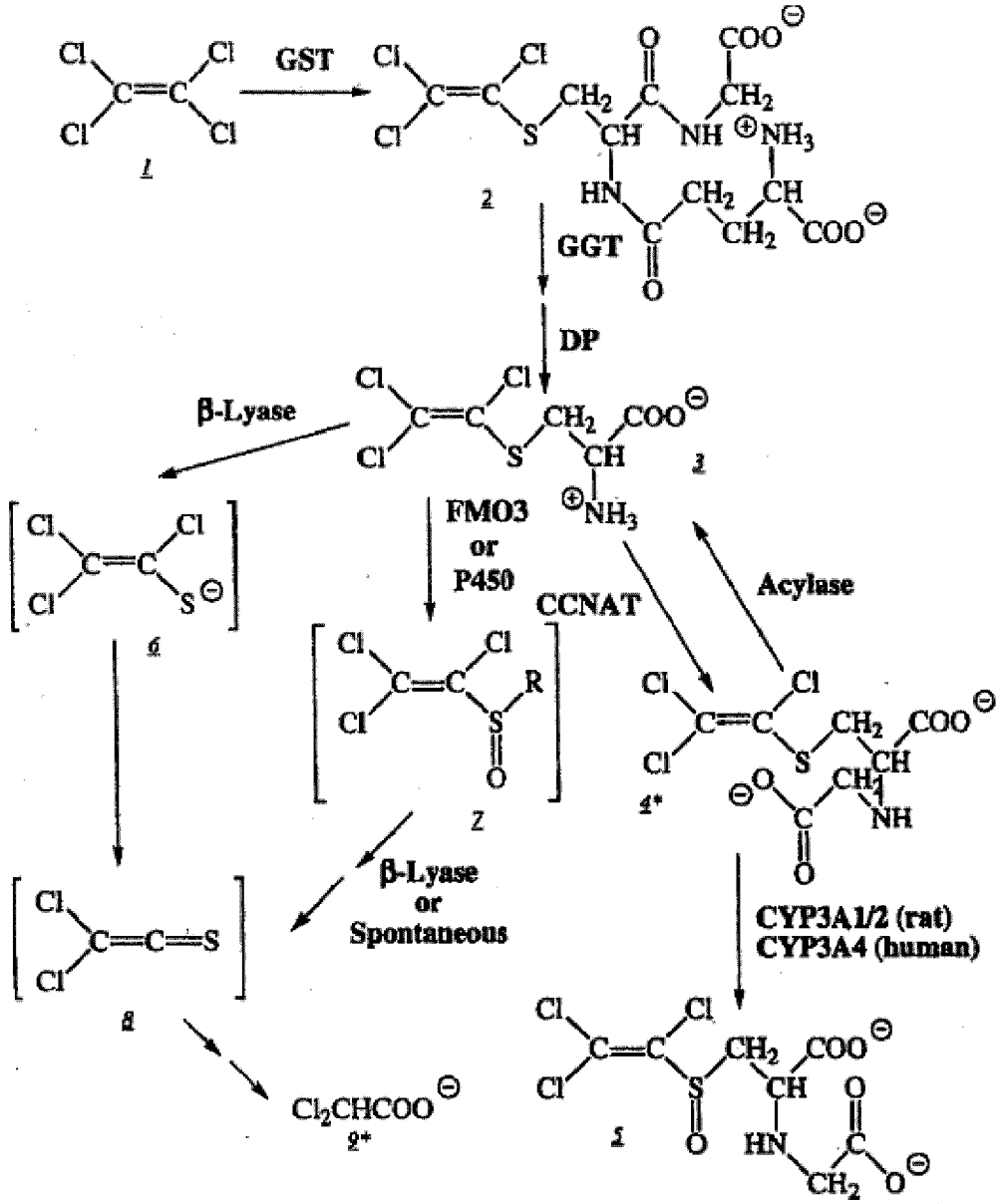

FIGURE 3-4 Metabolism of PCE by glutathione conjugation pathway. *Identified urinary metabolites: 1, PCE; 2, TCVG; 3, TCVC; 4, NAcTCVC; 5, NAcTCVC sulfoxide; 6, 1,2,2-trichlorovinylthiol; 7, TCVCSO; 8, 2,2-dichlorothioketene; 9, dichloroacetate. Enzymes: GST, GGT, dipeptidase (DP), β-lyase, FMO3, CCNAT, CYP3A1/2, and CYP3A4. Unstable, reactive metabolites are shown in brackets. Source: Lash and Parker 2001. Reprinted with permission; copyright 2001, *Pharmacological Reviews*.

extensively metabolized than TCE) (ATSDR 1997c; Chiu et al. 2007). Saturation of PCE oxidative metabolism occurs at a lower exposure concentration in humans than in rats. Rats metabolize substantially more PCE to trichloroacetic acid than do humans (Volkel et al. 1998). Only traces of dichloroacetic acid were detected in the urine of persons who inhaled PCE at 40 ppm for 6 h. Rats subjected to an equivalent exposure excreted relatively large amounts of dichloroacetic acid, a rodent hepatic carcinogen.

A small proportion of absorbed PCE undergoes conjugation with glutathione to form *S*-(1,2,2-trichlorovinyl) glutathione (TCVG). That initial metabolic step is catalyzed by glutathione *S*-transferases

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and occurs primarily in the liver. TCVG is converted to *S*-(1,2,2-trichlorovinyl)-L-cysteine (TCVC). TCVC, like the DCVC formed from TCE, is both detoxified in the liver by *N*-acetylation and metabolically activated by β-lyase in the kidneys to cytotoxic, mutagenic thioketenes (Lash and Parker 2001). TCVC is also oxidized by flavin-containing monooxygenase 3 (FMO3) to TCVC sulfoxide (Ripp et al. 1997), which can rearrange spontaneously to form 2,2-dichlorothioketene. Thus, potent alkylating agents are formed via two subpathways in the kidneys. 2,2-Dichlorothioketene can also decompose to dichloroacetic acid. Hence, dichloroacetic acid is derived from both glutathione- and CYP-dependent biotransformation of PCE. PCE is conjugated with glutathione more extensively by rats (1-2% of the dose) (Dekant et al. 1986) than is TCE (less than 0.005% of the dose) (Green et al. 1997a). The extent of glutathione conjugation of PCE increases when the oxidative pathways begin to become saturated at high PCE exposure concentrations. Metabolic products of glutathione conjugates of TCE and PCE are primary contributors to the halocarbons' nephrotoxicity (Lash et al. 2007).

Humans are likely to be less susceptible than rodents to the toxic or carcinogenic actions of PCE, as they are to those of TCE. Humans absorb less inhaled PCE and TCE, attain lower target-organ doses, and metabolically activate a smaller proportion of their internal dose. As noted above, rats exhibit a higher capacity for oxidation of PCE. Volkel et al. (1998) report finding substantially higher urinary excretion of trichloroacetic acid, *N*-acetyl TCVC, and dichloroacetic acid in the urine of rats than in the urine of humans subjected to identical PCE inhalation regimens. Lash et al. (1990) and Cooper (1994) report 10 times higher activity of cysteine conjugate β-lyase activity in rat than in human kidney. Green et al. (1990) report that β-lyase-dependent metabolism of TCVC in rat kidney cystosol is more rapid and efficient than in either mice or humans. TCVC metabolism is also greater in male than in female rats. The male rat is more susceptible to PCE-induced nephrotoxicity. A low incidence of kidney cancer is seen in male but not female rats in TCE and PCE cancer bioassays (ATSDR 1997b,c).

It is evident from the foregoing there is a great deal of information about the toxicokinetics, metabolism, and toxicology of TCE, PCE, and other VOCs in laboratory animals and humans. That knowledge allows scientists to judge the relevance of VOCs' adverse effects in animals to humans with a reasonable degree of certainty. Mice and rats absorb more inhaled TCE and PCE, metabolically activate more of their absorbed dose, and inactivate epoxide metabolites less efficiently than do humans. Such interspecies toxicokinetic differences contribute to the greater susceptibility of rodents than of humans to TCE- and PCE-induced hepatic, lung, and renal tumors. Toxicodynamic species differences that predispose $B6C3F_1$ mice to liver cancer are also recognized (see Chapter 4).

POTENTIALLY SENSITIVE POPULATIONS

Many factors or variables may alter the toxicokinetics of and the responses of a person to TCE, PCE, and other VOCs (Lof and Johanson 1998; Bruckner et al. 2008). Some variables that are characteristic of a particular group may increase susceptibility, others reduce it, and still others have no influence. The net effect of circumstances involving multiple variables can be difficult to predict. There are scenarios in which the toxicity or carcinogenicity of moderate exposure (for example, occupational exposure) or high exposure (for example, in animal cancer studies) to some VOCs may be significantly affected by variables like age, sex, genetics, physiologic condition, or lifestyle. As discussed below, that appears not to be the case for the concentrations of most of the VOC contaminants identified in water at Camp Lejeune.

Children

There is concern that infants and children may be more vulnerable than adults to some adverse effects of chemicals (Dourson et al. 2002; Daston et al. 2004). A National Research Council report (NRC 1993) emphasized that there were "windows of vulnerability" or short periods of early human develop-

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ment when chemical exposures may significantly alter organ function or structure. Potentially vulnerable targets in infants and young children include the endocrine, reproductive, immune, visual, and nervous systems. Little information is available on the effects of TCE, PCE, and other solvents on the development of those organ systems in laboratory animals or humans. There is considerably more knowledge of consequences of exposure of adults, as discussed in Chapter 4.

It is not clear whether organ-system development of young children or animals is influenced by exposure to VOCs. A number of chemicals—such as lead, mercury, thalidomide, chloramphenicol, and organophosphorus insecticides—are known to have more pronounced adverse effects in infants and young children than in adults (Bruckner 2000). Children are not necessarily more susceptible to toxicants. The most definitive human data on age-dependence available to the 1993 National Research Council committee were maximum tolerated doses of a variety of anticancer agents. Clinical trials in pediatric and adult patients revealed that children could tolerate higher doses of most of the antitumor drugs (Glaubiger et al. 1982; Marsoni et al. 1985). Susceptibility can vary markedly with a child's age. The youngest (premature and full-term newborns) are generally the most sensitive to drugs and other chemicals.

Toxicodynamic and toxicokinetic factors are responsible for age-dependent differences in the toxicity of VOCs and other chemicals. Toxicokinetic processes determine the amount of the active form of a chemical that reaches its target tissue or cell and how long it remains there. *Toxicodynamics* refers to the sequence of events that occur in a target tissue or cell on arrival of the bioactive form of a chemical. The events culminate in adverse effects that, in turn, dictate the magnitude and duration of toxic action. Major anatomic, biochemical, and physiologic changes occur during the neonatal period, infancy, childhood, and adolescence. Maturation can markedly affect the absorption, distribution, metabolism, and elimination of many chemicals (Bruckner and Weil 1999; Bruckner 2000; Ginsberg et al. 2004).

The systemic absorption of VOCs may be somewhat higher in infants in connection with some routes of exposure. Infants' and young children's respiratory rates and cardiac outputs are relatively high and favor uptake of inhaled VOCs. That is counteracted to some extent by their smaller alveolar surface area for absorption (Snodgrass 1992). The rate of dermal absorption is comparable in full-term newborns and adults, although the ratio of skin surface area to body weight is about 2.7 times greater in infants than in adults. TCE, PCE, and other solvents are well absorbed from the gastrointestinal tract of all age groups. The low plasma binding capacity of neonates should result in an increased rate of excretion of dichloroacetic acid and trichloroacetic acid, carcinogenic metabolites of TCE and PCE in mice, but it may be offset by neonates' larger extracellular water content, from which the metabolites have to be cleared. The net effect of immaturity on toxicokinetics can be quite difficult to predict (Bruckner 2000; Pastino et al. 2000).

Age-dependent changes in biotransformation have been reasonably well characterized in humans and may have the greatest impact on VOC toxicokinetics and health risks (Hines and McCarver 2002). Concentrations of metabolic enzymes are quite low in newborns and develop asynchronously during the initial months and years. Concentrations of CYP2E1, the P-450 isozyme primarily responsible for oxidation of low doses of TCE (Guengerich et al. 1991), are very low at birth and increase steadily during the first year of life (Johnsrud et al. 2003). Because infants lack the enzymes that convert TCE, PCE, and other VOCs to toxic or mutagenic metabolites, they should be less susceptible to the chemicals than adults. Concentrations of CYP2E1 and additional enzymes that catalyze other steps in VOC metabolic pathways generally attain adult values within 6 months to 3 years. Reimche et al. (1989) determined the half-lives of chloral hydrate, an obligate oxidative metabolite of TCE, in premature newborns, full-term newborns, and young children to be 39.8, 27.8, and 9.7 h, respectively. That finding shows how the ability to eliminate chloral hydrate metabolically increases with maturity. The greater metabolic clearance in children 1-6 years old is apparently due to their larger liver volume and higher blood flow (Murry et al. 2000) rather than higher CYP2E1 activity (Blanco et al. 2000). Greater metabolic capacity may result in increased formation of reactive metabolites of TCE and PCE, although they should also be more rapidly eliminated. Xenobiotic metabolism is similar in older children, adolescents, and adults (Alcorn and McNamara 2002).

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Age-related changes in one toxicokinetic process may be offset or augmented by concurrent changes in other processes. Validated PBTK models are useful for predicting target-organ doses of biologically active parent compounds or metabolites under such circumstances. Sarangapani et al. (2003) constructed a PBTK model that integrated age-specific respiratory measures so that the disposition of four VOCs (PCE, vinyl chloride, isopropanol, and styrene) could be predicted; blood concentrations of the parent compounds in infants and adults were comparable or differed by a factor of less than 2 during the first year of life. Nong et al. (2006) recently incorporated age-specific liver volumes and CYP2E1 content into a PBTK model for toluene; combined interindividual and interage variability in blood toluene concentrations over the periods of monitoring were within a factor of 2 except in neonates, whose concentrations were higher. Clewell et al. (2004) developed a "life-stage model" to simulate blood concentrations of VOCs (PCE, methylene chloride, vinyl chloride, and isopropanol); the predicted internal concentrations at different life stages were within a factor of 2 except during the neonatal period, when the largest differences were manifested. A recent model by Rodriguez et al. (2007) similarly yielded predictions of relatively high blood concentrations of TCE, PCE, methylene chloride, benzene, chloroform, and methyl ethyl ketone in neonatal rats; the increases were due largely to pronounced metabolic immaturity in neonates.

In summary, there is cause for concern that infants and young children will be more susceptible to adverse effects of chemicals. Anatomic and physiologic immaturity can predispose younger people to higher target-organ concentrations of some classes of chemicals. Heavy metals, such as lead and mercury, are known to be absorbed from the gastrointestinal tract and deposited in the brain in greater quantities in infants and young children. Cells in some developing organs (such as neurons in the brain) are more sensitive to injury because they must undergo highly ordered division, differentiation, and migration to function effectively in later life; relatively low concentrations of lead inhibit those processes and affect neurodevelopment and cognitive ability. Conversely, clinical experience has shown that children tolerate higher doses of a number of anticancer drugs than do adults before exhibiting toxicity. Thus, susceptibility is both chemical-dependent and age-dependent. The youngest (premature and newborn infants) are usually the most different from adults and the most likely to be more sensitive to chemical injury. The net effect of anatomic and physiologic immaturity on sensitivity is difficult to predict for chemicals on which there have been few or no studies or data. Although few data are available for TCE, PCE, and other VOCs, PBTK models predict a difference of no more than a factor of 2 in blood concentrations of VOCs after equivalent exposures of infants and adults. Newborns are predicted to have the highest blood concentrations and would be expected to be the most sensitive to any neurologic effects caused by high doses of the parent compounds. Newborns should be less susceptible to adverse effects caused by metabolites formed from lower doses of VOCs due to their immature xenobiotic metabolic systems.

The Elderly

The elderly, like infants and children, may be more or less susceptible than young adults to VOC toxicity. The net effect of pharmacodynamic and pharmacokinetic changes with aging determines the sensitivity of geriatric populations. The aging CNS, for example, undergoes pharmacodynamic changes (such as neuronal loss, alteration in neurotransmitter and receptor numbers, and reduction in adaptability to effects of toxicants) that may predispose to neurotoxicity (Ginsberg et al. 2005). Kiesswetter et al. (1997) observed more pronounced neurobehavioral effects of single or mixed solvents in occupational settings in older workers. Data are sorely lacking, however, on susceptibility to most other adverse effects.

Toxicokinetic changes during aging have been of interest primarily with respect to therapeutics, although the environmental-health arena is now also focusing attention on geriatric populations (Geller and Zenick 2005). Despite some reduction in pulmonary capacity, inhalation PBTK-model predictions of steady-state blood concentrations of PCE, vinyl chloride, styrene, and isopropanol differ little among 10-, 15-, 25-, 50-, and 75-year-old people (Sarangapani et al. 2003). Systemic clearance of many drugs is typically slower after the age of 60 years, particularly in those more than 80 years old (Ginsberg et al. 2005).

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Slowing of clearance is due largely to diminution in cardiac output, which in turn reduces hepatic blood flow and metabolism and renal blood flow and excretion (McLean and LeCouteur 2004). Clewell et al. (2004) predicted that, for a given magnitude of exposure, blood concentrations of PCE and trichloroacetic acid, its major metabolite, would progressively rise during old age. That was attributed to reduction in pulmonary and metabolic clearance of PCE coupled with its accumulation in relatively large amounts of adipose tissue. Much work remains to be done to refine geriatric PBTK models and to integrate them with age-dependent pharmacodynamic changes.

There are sources of variability other than pharmacodynamic and pharmacokinetic changes in responses of geriatric populations to chemicals. They include the common use of multiple medications, inadequate nutrition, and the prevalence of pre-existing disease states (Schmucker 1985). Compromised organ function can be exacerbated by toxicants in such a way that a modest degree of damage may result in marked dysfunction. In addition, normal aging processes can be accentuated by chemical stressors.

Sex Differences

It does not appear that women will differ substantially from men in most respects in their responses to TCE and most other VOCs. Uptake and disposition of these lipophilic chemicals, however, can differ because of the higher proportion of body fat in many females. Absorbed doses of inhaled VOCs are usually higher and internal exposure longer in females. Nomiyama and Nomiyama (1974), for example, measured lower TCE concentrations in the exhaled breath of women volunteers after controlled inhalation exposure. Clewell et al. (2004) used a PBTK model to simulate concentrations of PCE and trichloroacetic acid in men and women over a lifetime of daily ingestion of PCE at 1 μg/kg. The women were predicted to attain higher blood PCE and trichloroacetic acid concentrations. The major sex differences in cytochrome P-450-mediated hepatic metabolism and drug kinetics observed in rats have not been found in humans and other mammals (Schwartz 2003; Bebia et al. 2004). Sex-specific biotransformation data are lacking, however, on most VOCs. Activity of CYP2E1, the major catalyst of oxidation of low concentrations of many VOCs, does not differ significantly between men and women (Snawder and Lipscomb 2000). Nevertheless, a sex-specific PBTK model predicts that women will exhibit higher blood benzene concentrations and 23-26% higher benzene metabolism, which might place them at greater risk than men after equivalent exposures (Brown et al. 1998); higher female body fat content was the major factor in this instance. Another PBTK model's predictions of steady-state blood concentrations of PCE, vinyl chloride, and styrene were largely sex-independent (Sarangapani et al. 2003). Relatively little is known about potential influences of contraceptives or hormone-replacement therapy on the metabolism and disposition of chemicals.

Pregnancy

Relatively little is known about the potential influence of pregnancy on the absorption, distribution, metabolism, and elimination of VOCs. Physiologic changes that occur during pregnancy may protect against or enhance vulnerability to xenobiotic toxicity. Physiologic changes in gastrointestinal, cardiovascular, pulmonary, and renal systems may also affect xenobiotic absorption and elimination (Mattison et al. 1991). Fisher et al. (1989) developed a PBTK model for TCE and its primary metabolite, trichloroacetic acid, in the pregnant rat. Pregnant rats were exposed to TCE by inhalation, as a single oral bolus, or in drinking water. The PBTK model predicted that fetal exposure to TCE and TCA would be over 60% of the maternal exposure regardless of the exposure route. The results suggested that a developing fetus is at risk of TCE and TCA exposure, but such modeling has not been completed for humans.

Biochemical changes during pregnancy may also influence xenobiotic metabolism. Placental and fetal tissues, termed the fetoplacental unit, contain a variety of cytochrome P-450s, the enzyme superfamily responsible for much of phase I xenobiotic metabolism (Raucy and Carpenter 1993; Pasanen and

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Pelkonen 1994). Nakajima et al. (1992) found decreased cytochrome P-450 concentrations in the liver of pregnant Wistar rats. Pregnancy also decreased the metabolism of both TCE and toluene by maternal hepatic microsomes. Active CYP2E1 is believed to be present in human placenta at very low or negligible concentrations, although some evidence suggests that placental CYP2E1 may be induced by high exposure to ethanol (Rasheed et al. 1997; Hakkola et al. 1996; Botto et al. 1994). In general, those findings imply that the mother and fetus would be less exposed to the toxic metabolites formed via the oxidative metabolic pathway. Conversely, they would be more exposed to the parent compound. Because the placenta has little CYP2E1 activity, some amount of oxidative metabolites could be released into fetal circulation.

It is not clear whether CYP2E1 is present in the human fetus. Vieira et al. (1996) found no evidence of human fetal hepatic CYP2E1 before birth, although concentrations of the isozyme rapidly increase after birth. In contrast, Carpenter et al. (1996) detected CYP2E1 in human fetal liver during weeks 16-24 of gestation. In addition, CYP2E1 protein concentrations increased in human fetal hepatocytes exposed to ethanol or clofibrate.

There is no evidence of CYP2B6 mRNA expression or protein in the fetoplacental unit during any stage of pregnancy. Nonetheless, CYP2B6 is believed to be active in the oxidative metabolism of high doses of TCE, PCE, and other VOCs. Further study is needed to clarify those discrepancies in the presence and activity of fetoplacental CYP2E1 and CYP2B6.

A new subject of research is the effect of pregnancy on peroxisome-proliferator-activated receptors (PPAR). PPARs are transcription factors that belong to the nuclear hormone receptor superfamily. PPARs regulate genes involved in cell differentiation, development, and metabolism. The three identified and described PPAR isoforms are PPARα, PPARβ/δ, and PPARγ. Among the isoforms, PPARγ has the greatest influence on cellular homeostasis and carcinogenicity. However, all three PPAR isoforms play essential roles in physiologic change and development in the fetoplacental unit. Abnormalities in PPAR-regulated pathways may be implicated in reproductive and gestational disease (Toth et al. 2007; Borel et al. 2008). Two TCE metabolites, TCA and DCA, can induce PPARα activation in humans. The combined effect of pregnancy and TCE-metabolite-induced PPAR activation is unknown.

Genetics

A variety of genetic polymorphisms can affect the quantity and quality of enzymes and the outcomes of exposure to solvents (Raunio et al. 1995; Wormhoudt et al. 1999). Such polymorphisms occur with different frequencies in different ethnic groups. It is often difficult to disentangle the influence of genetic traits from those of lifestyle and socioeconomic status. Shimada et al. (1994) report that Caucasians have higher total cytochrome P-450 and CYP2E1 concentrations than Japanese. Stephens et al. (1994) describe ethnic differences in the CYP2E1 gene among American blacks, European-Americans, and Taiwanese. Pronounced interethnic differences in rates of ethanol metabolism are associated with alcohol dehydrogenase and aldehyde dehydrogenase polymorphisms. Alcohol dehydrogenase and aldehyde dehydrogenase catalyze secondary reactions in the TCE oxidative pathway. Inasmuch as CYP2E1 catalyzes the bioactivation of a number of VOCs to cytotoxic or mutagenic products (Guengerich et al. 1991), substantial differences in CYP2E1 concentrations in groups might be expected to result in different susceptibilities to injury. Lipscomb et al. (1997) found that hepatic CYP2E1 activity varied by a factor of about 10 in humans. PBTK model simulations of an 8-h inhalation exposure to TCE at 50 ppm and of consumption of 2 L of water containing TCE at 5 ppb revealed that the amount of VOC oxidized in the liver differed by only 2% in persons with the lowest and highest CYP2E1 content (Lipscomb et al. 2003). That blood delivery of TCE to the liver is much slower than CYP2E1-mediated bioactivation limits the influence of individual variability in CYP2E1. That phenomenon is addressed again below in connection with ethanol induction of TCE metabolism. Results of epidemiologic studies of possible relationships between CYP2E1 concentrations and cancer incidence in VOC-exposed groups have been contradictory, and studies of larger populations and having greater statistical power are needed.

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Other polymorphisms have been examined for their possible role in tumor induction in solvent-exposed populations. Bruning et al. (1997), for example, investigated the prevalence of glutathione *S*-transferase (GST) isozyme polymorphisms in TCE-exposed workers who had renal-cell carcinoma. The glutathione conjugation pathway appears to be responsible for formation of cytotoxic or genotoxic metabolites of TCE and PCE (see earlier section "Metabolic Activation and Inactivation of Trichloroethylene and Perchloroethylene"). Bruning et al. (1997) noted that workers who had renal-cell carcinoma were more likely to carry functional GST1 and GSTM1 genes. High percentages of Caucasians and other ethnic groups lack GSTM1 and GSTT1 (Bolt and Their 2006) and thus might be at reduced risk of renal cell carcinoma from TCE or PCE (Vermeulen and Bladeren 2001). Wiesenhutter et al. (2007), however, found no evidence that GSTM1, GSTP1, or NAT2 deletion polymorphisms affected development of renal cell carcinoma in persons with high occupational exposure to TCE.

In conclusion, genetic differences in metabolic activation of TCE by the oxidative pathway do not appear likely to influence toxic or carcinogenic risks posed by the chemical at the concentrations measured in mixed water supplies at Camp Lejeune. Polymorphisms that dictate the presence or absence of genes that code for isozymes that initiate metabolic activation of TCE via the glutathione conjugation pathway are more likely to influence susceptibility to TCE-induced kidney cancer.

Lifestyle

Dietary habits can influence the absorption, metabolism, and toxicity of VOCs in several ways. VOCs are rapidly absorbed by passive diffusion from all parts of the gastrointestinal tract. On ingestion with dietary fat, the chemicals partition into the lipids, and they remain there until they are emulsified and absorbed. That delays systemic uptake of VOCs, such as carbon tetrachloride, and results in reduced blood concentrations and reduced hepatic damage in rats (Kim et al. 1990a, b). Conversely, consumption of a high-fat diet increases hepatic CYP2E1 activity in rats, which can enhance the bioactivation of carbon tetrachloride and other VOCs (Raucy et al. 1991). Carbohydrate deficiency also enhances the metabolism of solvents. An increasing number of dietary supplements, fruit juices, and vegetable components are being identified as inducers or inhibitors of cytochrome P-450s (Huang and Lesko 2004). Flavonoids in grapefruit juice were one of the first documented classes of naturally occurring cytochrome P-450 inhibitors. Other potent inhibitors are bergamottin, echinacea, and some constituents of *Ginkgo biloba* (Chang et al. 2006).

Fasting for 1-3 days can significantly enhance the hepatotoxicity of medium to high doses of VOCs that undergo metabolic activation. Fasting results in decreased hepatic concentrations of glutathione because of cessation of intake of amino acids required for its synthesis. Glutathione plays a key role in detoxifying electrophilic metabolites of a number of VOCs, such as 1,1-DCE (Jaeger et al. 1974). Conversely, conjugation of glutathione with TCE or PCE can lead to limited formation of cytotoxic, mutagenic metabolites (see section "Metabolic Activation and Inactivation"). Withholding food for 12-24 h also results in induction of CYP2E1, the major catalyst of activation of many VOCs. Bruckner et al. (2002) found that lack of food intake during sleep results in lipolysis and formation of acetone, an effective CYP2E1 inducer, in rats. The animals were thus more susceptible to acute carbon tetrachloride hepatotoxicity during their initial waking hours. Long-term food deprivation (starvation), however, results in reduced synthesis of CYP2E1 and other cytochrome P-450s and decreased metabolic activation of VOCs.

Physical activity can significantly influence the toxicokinetics of solvents. Exercise increases two of the key determinants of uptake of inhaled VOCs: (1) respiratory and alveolar ventilation rate and (2) cardiac output and pulmonary blood flow. Exercise can double pulmonary uptake of VOCs (Astrand 1983), although this is often not considered in setting occupational exposure standards. Blood flow to the liver and kidneys is diminished with exercise, so biotransformation of well-metabolized solvents decreases. A PBTK model for methylene chloride predicted that light exercise would result in a doubling of blood concentrations of methylene chloride and of metabolite formation via cytochrome P-450- and glutathione-dependent pathways (Dankovic and Bailer 1994).

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Ethanol is an effective CYP2E1 inducer when ingested repeatedly in substantial amounts (Lieber 1997). There are numerous reports of marked potentiation of hepatic or renal damage by ethanol or other alcohols in persons occupationally exposed to potent hepatorenal toxicants, such as carbon tetrachloride (Folland et al. 1976; Manno et al. 1996). A group of moderate drinkers exposed to 1,1,1-trichloroethane vapor at 175 ppm showed a significant increase in metabolism and metabolic clearance of the chemical (Johns et al. 2006). 1,1,1-Trichloroethane is a relatively nontoxic solvent. Kaneko et al. (1994) exposed ethanol-pretreated rats by inhalation to TCE or 1,1,1-trichloroethane at 50-1,000 ppm. 1,1,1-Trichloroethane metabolism was enhanced at all vapor concentrations, but TCE metabolism was enhanced by ethanol only at the highest concentration (1,000 ppm). The researchers concluded that alterations in the rate of biotransformation of low doses of well-metabolized VOCs, such as TCE, are of little consequence toxicologically because their biotransformation is perfusion-limited (limited by hepatic blood flow); most of the TCE entering the liver is metabolized, even in nondrinkers who still have CYP2E1 in excess for the small amounts of TCE arriving in the blood. Kedderis (1997) used a PBTK model to predict that a 10-fold increase in CYP2E1 activity in humans inhaling TCE at 10 ppm would result in only a 2% increase in TCE metabolism by the liver. Thus, increased bioactivation capacity due to ethanol or other factors should not increase risks of toxicity or cancer in Camp Lejeune residents because of their low exposures to TCE, 1,1-DCE, methylene chloride, vinyl chloride, benzene, or other extensively metabolized VOCs. As previously described in this chapter, PCE is poorly metabolized, although some of its metabolites are cytotoxic or mutagenic. Kedderis (1997) predicted that a 10-fold increase in CYP2E1 activity in humans inhaling PCE, as opposed to TCE, at 10 ppm would result in a 3.8-fold increase in formation of PCE metabolites in the liver. Enzyme induction would result in increased health risks posed by PCE.

It should be recognized that the timing of ethanol consumption and VOC exposure is important. Prior repeated exposure to ethanol is necessary for substantial CYP2E1 synthesis to occur. Concurrent exposure to ethanol and a VOC, however, may sometimes be protective against both well-metabolized and poorly metabolized solvents. VOCs and ethanol are both metabolized by CYP2E1, so the two xenobiotics compete for the available isozyme. That situation is known as competitive metabolic inhibition. Muller et al. (1975) observed that concurrent intake of ethanol and inhalation of TCE at 50 ppm by human subjects resulted in a marked decrease in urinary excretion of TCE's major metabolites, trichloroacetic acid and trichloroethanol. In this instance, ethanol would afford protection against TCE's oxidative metabolites. Metabolism of ethanol produces an excess of nicotinamide adenine dinucleotide, a cofactor that favors formation of trichloroethanol from chloral hydrate, at the expense of trichloroacetic acid. Reduced formation of trichloroacetic acid would be protective against trichloroacetic acid-induced hepatic tumors. Larson and Bull (1989), however, observed that interaction in rats only with very high doses of TCE and ethanol.

Medications and drugs of abuse that induce or inhibit CYP2E1 and other enzymes involved in the metabolism of VOCs can potentially alter the chemicals' toxicity or carcinogenicity. Phenobarbital and other barbiturates were among the first recognized cytochrome P-450 inducers. Notable inducers of CYP2E1 include, in addition to alcohols and acetone (Gonzalez 2007), acetaminophen, salicylates, phenytoin, chlorpromazine, isoniazid, and diazepam. Nakajima et al. (1992) showed that pretreatment of rats with phenobarbital, ethanol, or 3-methylcholanthrene significantly increased TCE oxidation. The same would be expected to occur in humans at high TCE doses. Again, cytochrome P-450 induction will probably not be of consequence at the concentrations found in the water supplies at Camp Lejeune. Some drugs (such as cycloheximide, disulfiram, and chloramphenicol) and the aforementioned natural constituents of plants inhibit CYP2E1. Those compounds, in sufficient doses, would be protective against high doses of TCE and other VOCs that are bioactivated by CYP2E1.

Tobacco smoke contains a number of compounds that are strong cytochrome P-450 inducers. Polycyclic hydrocarbons, such as 3-methylcholanthrene, are potent inducing agents. The polycyclic hydrocarbons primarily stimulate synthesis of CYP1A1 and CYP1A2, cytochrome P-450 isozymes that play a modest role in catalyzing the biotransformation of TCE (Nakajima et al. 1992). Nicotine, however, is a

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strong CYP2E1 inducer in rats (Micu et al. 2003). Cigarette smoke is known to induce CYP2E1 in both rodents and humans.

Diseases

Illness can be a major source of variability in a person's response to VOCs. Impaired metabolism and systemic clearance of xenobiotics are commonly seen in persons with hepatitis or cirrhosis. Reduction in metabolic capacity results from decrease in liver mass, reduced enzymatic activity, or diminution in liver blood flow. Lower concentrations of CYP2E1, CYP1A2, and glutathione are found in cirrhotic livers (Murray 1992). Lower cytochrome P-450-mediated bioactivation of VOCs can be protective, but reduced capacity to conjugate their electrophilic metabolites would have the opposite effect.

Chronic renal disease has become more prevalent in the United States over the last decade (Coresh et al. 2007). Progressive loss of renal function will lead to impaired renal excretion of some potentially toxic or carcinogenic metabolites, such as trichloroacetic acid. Trichloroacetic acid is highly bound to albumin and other plasma proteins. Plasma-protein binding is reduced in patients with compromised renal function, apparently because of renal retention of substances that compete with trichloroacetic acid for protein-binding sites and because of reduced albumin synthesis. Thus, decreased formation of trichloroacetic acid from TCE and PCE and reduced plasma-protein binding would increase systemic clearance. That may be offset, however, by a decrease in renal excretion (Yuan and Venitz 2000). Impairment of renal bioactivation of glutathione metabolic intermediates of TCE and PCE by oxidation or β-lyase (see section "Metabolic Activation and Inactivation") would be protective (Bruckner et al. 2008).

Diabetes mellitus is a metabolic disease characterized by hyperglycemia as a result of insulin deficiency (type I) or insulin resistance (type II). Type II diabetes accounts for 90% of cases in the United States. Animal experiments show that type II diabetes increases susceptibility to the toxicity of certain solvents apparently because of inhibition of tissue repair (Sawant et al. 2004). The human relevance of these animal findings is uncertain. CYP2E1 induction is a prominent effect of type I diabetes in rats but not in humans. Type II diabetes results in CYP2E1 induction in humans (Lucas et al. 1998; Wang et al. 2003).

Obesity has been shown to result in induction of CYP2E1 in both rats and humans. Rats made obese by the feeding of an energy-rich diet were found to have higher hepatic catalytic activities for a number of CYP2E1 substrates (Raucy et al. 1991). The systemic clearance of chlorzoxazone, a CYP2E1 substrate, was recently shown to be more rapid in rats on a high-fat diet than in normal rats and more rapid in obese rats than in those on the high-fat diet (Khemawoot et al. 2007). CYP2E1 activity in hepatic and adipose-tissue microsomes of the animals followed the same order. Ketone bodies were increased in obese rats, as they were in diabetic animals that had fasted. Two ketone bodies, acetone and β-hydroxybutyrate, are CYP2E1 inducers. O'Shea et al. (1994) observed that ketone bodies were also increased in the blood of volunteers who had fasted. They found that obesity in people was associated with increased 6-hydroxylation of chlorzoxazone. Lucas et al. (1998) similarly observed higher CYP2E1-mediated hydroxylation of chlorzoxazone in 17 obese patients; such people may be at increased risk for cytotoxicity and tumorigenicity from moderate to high, but not very low, VOC exposure.

In summary, a number of factors may influence the toxicokinetics and, in turn, the adverse effects of TCE, PCE, and other VOCs. Much research has focused on factors that alter the metabolic activation or inactivation of those chemicals. Consumption of a high-fat diet and obesity can induce (increase the activity of) CYP2E1. Fasting, smoking, ethanol ingestion, acetone exposure, and several drugs induce CYP2E1 activity in the liver and other tissues. CYP2E1 induction can increase the toxic or carcinogenic potency of very high doses of some VOCs (such as TCE and PCE). That does not occur after low exposures to TCE and other well-metabolized VOCs (such as benzene, vinyl chloride, and methylene chloride). CYP2E1 induction, however, may increase the potency of slowly metabolized VOCs, such as PCE. Some drugs and the constituents of some foods inhibit CYP2E1 and would be protective against oxidative metabolites of most VOCs.

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INTERACTIONS

Many occupational and environmental exposures to VOCs involve multiple chemicals. That is particularly true of contaminated environmental media, in that widespread use of solvents leads to their volatilization and their entry into surface waters and groundwater. A major portion of VOCs spilled onto the ground evaporates. Some, however, leaches through soil into groundwater and remains trapped there. The groundwater at about 90% of 1,608 hazardous-waste sites on the U.S. National Priorities List contains VOCs. TCE is the most frequently found of all chemicals, followed by lead, PCE, and benzene (Fay and Mumtaz 1998). The most common four-component VOC mixture is TCE, PCE, 1,1,1-trichloroethene, and 1,1-dichloroethane. ATSDR (2004) published a toxicologic profile addressing potential health risks posed by that four-component mixture. Many U.S. cities' drinking-water supplies also contain complex mixtures of VOCs. Total concentrations range from parts per trillion to parts per billion (Moran et al. 2007). Trace amounts (less than 1 ppb) of a variety of VOCs are present in the blood of many nonoccupationally exposed members of the general population (Churchill et al. 2001; Blount et al. 2006).

Exposure to multiple VOCs and possibly other chemicals raises the question of the consequences of chemical interactions for human health. Most studies have involved experiments with binary or ternary mixtures. One chemical may have no effect on, potentiate (enhance), or antagonize (inhibit) adverse actions of a second or third chemical. Knowledge of mechanisms of VOC interactions involves largely the influence of one VOC on the metabolic activation or inactivation of another. Koizumi et al. (1982) published the results of one of the first such studies. They found that coexposure of rats to PCE and 1,1,1,-trichloroethane resulted in significant suppression of 1,1,1,-trichloroethane metabolism. Workers exposed to TCE and PCE were found to have lower urinary concentrations of TCE metabolites than workers exposed to TCE alone (Seiji et al. 1989). Such an interaction resulted from competitive metabolic inhibition, wherein the amounts of the combined chemicals exceeded the metabolic capacity of the study subjects. Such an interaction is protective against cytotoxicity and carcinogenicity in that the bioactivation of both TCE and PCE is reduced. Conversely, systemic concentrations of the parent compounds would be increased, and this might increase neurologic effects.

PBTK modeling has been used by several research groups to predict the metabolic and toxicologic consequences of exposure to VOC mixtures. Competitive metabolic inhibition was evident in a PBTK-model approach to studying TCE and 1,1-DCE (El-Masri et al. 1996) and TCE and vinyl chloride (Barton et al. 1995). Later PBTK modeling efforts predicted interaction thresholds below which competitive metabolic inhibition would not occur. Dobrev et al. (2001), for example, reported that the thresholds for interaction of TCE with PCE and 1,1,1,-trichloroethane vapor in rats were 25 and 135 ppm, respectively, when the TCE concentration was 50 ppm. Those findings imply that protection from adverse effects would occur in occupational settings when vapor concentrations were relatively high. An increase in blood TCE concentrations under these exposure conditions was predicted to result in a disproportionate increase in formation of nephrotoxic glutathione conjugation products in humans (Dobrev et al. 2002). Other PBTK modeling approaches are being developed to simulate the metabolic outcome of human exposures to up to four common VOC water pollutants (for example, TCE, PCE, chloroform, and 1,1,1-trichloroethane) (Mayeno et al. 2005). Competitive metabolic inhibition, with potentiation or protection from adverse effects of VOCs, would not occur at much lower exposure concentrations. Competitive metabolic inhibition and antagonism of (protection from) adverse effects of the VOCs would not occur at much lower exposures, such as those at Camp Lejeune.

Additivity of toxic effects of chemicals that act by similar mechanisms is typically assumed in the absence of experimental evidence to the contrary. There does not appear to be experimental evidence of greater than additive interactions of VOCs (ATSDR 2004). One possible mechanism of potentiation is induction of CYP2E1 by one or more members of a VOC mixture. Experiments in rats dosed with single VOCs have shown that most of the compounds are not effective inducers of CYP2E1 or other cytochrome P-450 isozymes. Competitive metabolic inhibition, as described above, would result in antagonism of (that is, less than additive) adverse effects if metabolites are the bioactive moieties. Goldsworthy and

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Popp (1987) found that the joint effect of TCE and PCE on peroxisome proliferation in the liver and kidneys of mice and rats was less than additive. Stacey (1989) studied the joint action of TCE and PCE on the liver and kidneys of rats. Combined administration of near-toxic-threshold doses of the two solvents produced modest hepatorenal toxicity. Jonker et al. (1996) provided evidence that TCE and PCE in combination with two other similarly acting solvents affected kidney weight in rats given subtoxic doses of each chemical by gavage for 32 days. Competitive metabolic inhibition at relatively high exposure levels of toluene, ethylbenzene, and xylene has been predicted by PBTK modeling to result in higher internal exposures (and CNS depressant effects) than would occur with simple additivity (Dennison et al. 2005). Although experimental data are limited, the assumption of additivity of potential risks posed by VOC water contaminants at Camp Lejeune seems to be a reasonable, prudent approach.

A few toxicity or carcinogenicity studies of complex chemical mixtures, including VOCs, have been conducted. The National Toxicology Program (NTP 1993) supplied F-344 rats and B6C3F_1 mice with drinking water containing 25 contaminants for up to 26 weeks. The mixture contained TCE, PCE, methylene chloride, 1,1,1-trichloroethane, 1,1-DCE, 1,1-dichloroacetic acid, other solvents, heavy metals, polychlorinated biphenyls, and a phthalate. The total no-observed-adverse-effect levels for histologic changes in organs were 11 ppm in rats and 378 ppm in mice. Suppression of immune function occurred in female mice that consumed the mixture at 756 ppm for 2 weeks or 378 ppm for 13 weeks. Constan et al. (1996) saw centrilobular hyperplasia and apoptosis in the livers of rats after 1 mo. A followup study in chemically tumor-initiated rats showed that the contaminant mixture did not promote preneoplastic foci in the liver (Benjamin et al. 1999). Wang et al. (2002) supplied ICR mice with water containing chloroform, 1,1-dichloroacetic acid, 1,1-DCE, 1,1,1-trichloroethane, TCE, and PCE for 16 and 18 mo. There was a trend of increasing frequency of hepatocellular neoplasms in the male mice and increasing incidence of mammary adenocarcinomas in the high-dose female mice. The total concentration of VOCs in the drinking water of females was about 1,555 ppb. Most of the mixture was TCE (471 ppb) and PCE (606 ppb). Those concentrations are far lower than have previously been reported to produce tumors. The results must be regarded as preliminary in that the study design had a number of limitations, and the results have not been replicated. In addition, male B6C3F_1 mice are particularly susceptible to hepatic tumors, and mice metabolically activate a substantially greater proportion of solvent doses than do humans.

Multiple VOCs and other chemicals are commonly present in trace amounts (parts per trillion to parts per billion) in water from contaminated wells in the United States. The Environmental Protection Agency, in the absence of information to the contrary, assumes that any adverse effects of chemicals that act by the same mechanism are additive. Several VOCs act on some organs by similar mechanisms. Animal experiments with high doses of combined VOCs have shown that one VOC inhibits the metabolic activation (that is, protects against adverse effects) of the other. That would not occur at the lower concentrations that were found in the water supplies at Camp Lejeune.

SUMMARY

Residents of homes supplied with contaminated water can be exposed orally by drinking the water, as well as by inhalation and dermal exposure when using heated water for bathing, showering, and washing clothes and dishes. Experiments with TCE and chloroform have shown that ingestion and inhalation make comparable contributions to systemically absorbed doses, and the contribution from skin absorption is minor.

The concept of dose has been refined to three components: administered, or external dose; systemically absorbed, or internal dose; and target organ and tissue dose. It is most important to specify the dose of the bioactive moiety, whether it is the parent compound or one or more metabolites. Concurrent pharmacokinetic processes, including absorption, tissue distribution, binding, metabolism, and elimination, determine tissue doses. One or more of these processes can vary significantly from one route of exposure to another, from one species to another, and from one person to another. Understanding how these processes differ can factor into predicting toxicity and cancer risks for various exposure scenarios.

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PCE, TCE, and other VOCs are quickly and extensively absorbed from the gastrointestinal tract. These small, uncharged, lipophilic molecules rapidly diffuse through membranes from areas of higher to lower concentration. It is typically assumed that 100% of doses of orally administered VOCs are absorbed. A portion of VOCs reaching the pulmonary blood are exhaled before reaching the arterial circulation. Pulmonary and hepatic first-pass elimination acting in concert are responsible for removing almost 90% of very low doses of TCE, thereby affording extrahepatic organs protection from noncancer and cancer effects from trace concentrations of such chemicals in drinking water. Less protection from poorly-metabolized VOCs (for example, PCE) is afforded. The pattern of consumption of contaminated water can substantially influence the toxicologic outcome. Differences in the type of controlled exposure used in animal studies compared with intermittent exposures in humans raises the question of the relevance of such cancer bioassay results to real-life human exposures.

TCE, PCE, and other VOC vapors are also very well absorbed from the lungs. Pulmonary absorption is largely determined by the chemical's blood:air partition coefficient, the animal's alveolar ventilation rate, and its cardiac output. The rats' TCE blood:air partition coefficient is almost three times that of humans. Resting alveolar ventilation rates and cardiac outputs are markedly higher in mice than in rats and significantly higher in rats than in humans.

Metabolism plays a key role in modulating the kinetics, and in turn the injury potential of VOCs. These chemicals can be biotransformed to more toxic or less toxic derivatives. The majority of metabolism occurs in the liver. TCE and PCE are metabolized by two primary metabolic pathways: cytochrome P-450s-catalyzed oxidation and glutathione *S*-transferase-mediated conjugation. The oxidation pathway accounts for the majority of metabolism of low-to-moderate doses of TCE and PCE. Oxidative metabolites are largely responsible for liver and lung toxicity and carcinogenicity. GSH conjugation becomes more prominent when high doses begin to saturate oxidation. TCE and PCE are metabolized quite similarly, although PCE is somewhat more potent because of formation of additional toxic products. Oxidative activation of TCE and PCE is much greater in mice and rats than in humans. Metabolic activation by the GSH pathway is substantially greater in rats than in humans. It is well-established that rodents absorb more inhaled TCE and PCE, metabolically activate a greater proportion, and detoxify epoxide metabolites less efficiently than humans.

It is not clear whether infants and children are more susceptible to adverse effects of VOCs. Age-dependent changes in pharmacokinetics and pharmacodynamics may make an immature human more or less sensitive, depending upon the individual's age, the chemical, and the organ system. Low concentrations of CYP2E1 in neonates and infants will result in increased TCE concentrations but low concentrations of oxidative metabolites. Conversely, children have a relatively large liver and high liver blood flow, placing them at greater risk than adults from effects of oxidative metabolites. Age-related changes in one toxicokinetic process may be augmented or offset by concurrent changes in other processes. Cells in developing organs (for example, neurons in the brain) are more sensitive to injury. Thus, toxicant exposure during such a "window of susceptibility" can have serious, long-lasting consequences. The net effect of anatomical and physiologic immaturities is difficult to predict, particularly for classes of chemicals (for example, VOCs) for which there is very little information from animal or human studies.

The net effect of toxicokinetic and toxicodynamic changes during aging is the major determinant of susceptibility of geriatric populations. It has been predicted with a PBTK model that PCE exposure will result in increased PCE concentrations in the elderly. Unfortunately, there are even fewer experimental data from geriatric humans or animals with which to verify outcomes than there are data from pediatric populations. Additional compounding factors in the elderly include use of multiple medications, poor nutrition, and preexisting disease states.

Women do not appear to differ substantially from men in their responses to TCE, PCE, and other VOCs. Metabolism of solvents is not sex-dependent, but higher female body-fat content results in accumulation of higher body burdens of the lipophilic chemicals and increased formation of their metabolites. Relatively little is known about the influence of pregnancy on maternal and fetal disposition of VOCs and their metabolites. Animal models, however, show lower maternal TCE metabolism during pregnancy and limited fetal exposure to oxidative metabolites.

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A variety of genetic polymorphisms in human populations can affect the quantity and quality of CYP450 and glutathione *S*-transferase enzymes and, in turn, the outcomes of exposure to solvents. There are marked interindividual differences in activity of hepatic CYP2E1, the primary isozyme responsible for metabolic oxidation of TCE. This interindividual difference is not believed to be toxicologically significant, however, for persons exposed to very low concentrations of TCE and other well-metabolized VOCs. The interindividual difference in oxidative capacity may be important, however, in the extent of metabolic activation and response to poorly-metabolized VOCs, such as PCE.

Lifestyle can potentially influence an individual's responses to VOCs in a number of ways. Dietary habits and components, physical activity, ethanol intake, and certain drugs can affect metabolism and deposition of solvents. Serious illness, impaired metabolism and systemic clearance of parent compounds, and obesity are some additional factors that can affect the way the body handles exposure to TCE and PCE.

Many occupational and environmental exposures to VOCs involve multiple chemicals. Knowledge of mechanisms of chemical interactions largely involves the effect of one VOC on the metabolic activation of a second. Concurrent exposures to sufficiently high doses typically involve competitive metabolic inhibition, which results in increased concentrations of parent compounds and lower production of metabolites. Such interactions will not occur at very low exposure concentrations.

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4

Review of Toxicologic Studies

This chapter summarizes findings of animal studies of trichloroethylene (TCE) and tetrachloroethyle (perchloroethylene, PCE) toxicity and relevant end points. The review was based in part on previously published comprehensive reviews on the two chemicals of interest, but numerous published studies were reviewed individually in greater detail. Studies were examined according to criteria that reflected robustness of study design related to the hypothesis being tested and that included such characteristics as number of animals tested, measurement methods used, appropriateness of statistical methods, and concordance of conclusions with data presented. Studies substantially lacking in some of or all those and other measures of study quality and studies whose outcomes were not able to be repeated in later studies or in other laboratories were given less weight in the evaluation. Salient findings on principal health end points are summarized by chemical and organ system. The administered doses or the doses associated with the no-observed-adverse-effect levels (NOAELs) or the lowest-observed-adverse-effect levels (LOAELs) are reported when possible. At the conclusion of this toxicologic review, a hazard evaluation of TCE and PCE exposure at Camp Lejeune was conducted for selected health end points. A hazard evaluation is conducted to provide information on the intrinsic toxic potential of an exposure and is not meant to provide a quantitative risk assessment.

As noted in Chapter 2, the committee identified nine volatile organic compounds (VOCs) of concern. To manage the vast amount of information on each, we provide different degrees of review according to the findings from the exposure assessment regarding the frequency and concentrations of the contaminants in the affected drinking-water systems. This chapter presents detailed toxicologic evaluations of the two chemicals of greatest concern, TCE and PCE. Information on the metabolism of TCE and PCE and factors that influence their toxicity was presented in Chapter 3 and is drawn upon in this chapter. Chapter 7 provides an integrated discussion of the toxicologic evidence in context with the epidemiologic evidence on TCE and PCE. For completeness of the literature review, Appendix D provides brief reviews of the toxicologic data on the seven other chemicals.

TRICHLOROETHYLENE

Data on the toxicity of TCE were summarized in a report by the National Research Council (NRC 2006). In some cases, more recent literature reviews on particular subjects were available (e.g., Lamb and Hentz 2006; Watson et al. 2006), and they were relied on for defining the body of literature available up to the time of publication. In addition, a literature search of Medline was done to determine whether any relevant new publications were available. Conclusions drawn for the present report were based on a review of the body of available peer-reviewed literature. Because TCE and PCE have some of the same metabolites and effects, salient finding of studies of PCE are discussed in relevant sections of the TCE review. More detailed review of the PCE literature is provided later in the chapter. To facilitate a comparison of the toxicologic data with the epidemiologic data in Chapter 7, the toxicologic data are pre-

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sented below according to organ system and in some sections divided to consider toxic effects separately from carcinogenic effects.

Hepatic Effects

Toxicity

TCE, even in high doses, produces only a modest degree of injury of hepatocytes in laboratory animals. Klaassen and Plaa (1966) compared the acute hepatotoxicity of TCE with that of other common halogenated aliphatic hydrocarbons (halocarbons) in male mice dosed by intraperitoneal injection. The dose of TCE required to produce an increase in serum alanine-aminotransferase activity, 1.6 mL/kg, was almost as high as the dose that was lethal in 50% of test animals, 2.2 mL/kg. Oxidative stress was assessed by measuring thiobarbituric-acid-reactive substances in the livers of male Fischer rats that received one intraperitoneal injection of TCE at 0, 100, 500, or 1,000 mg/kg (Toraason et al. 1999). Thiobarbituric-acid-reactive substances were increased in the 500- and 1,000-mg/kg groups. Hepatic concentrations of 8-hydroxy-2′-deoxyguanosine adducts, induced in DNA by oxygen-based radicals, were also increased at 500 mg/kg and presumably at 1,000 mg/kg. It should be recognized that the 500- and 1,000-mg/kg doses produced stage II and stage III-IV anesthesia, respectively. Channel et al. (1998) gave male B6C3F$_1$ mice TCE at 0, 400, 800, or 1,200 mg/kg in corn oil by gavage 5 days/week for 8 weeks. Transient increases in cell and peroxisome proliferation, centered around day 10, were observed only at the highest dose. There were no differences from controls in the incidences of hepatocellular apoptosis or necrosis. Thiobarbituric-acid-reactive substances were significantly increased in the groups treated with TCE at 800 and 1,200 mg/kg on days 6-14. 8-Hydroxy-2′-deoxyguanosine adducts in liver DNA were significantly increased throughout much of the study with TCE at 1,200 mg/kg. Buben and O'Flaherty (1985) saw a modest increase in serum alanine aminotransferase and decrease in hepatic glucose-6-phosphatase activity in mice given TCE at 500 mg/kg or greater in corn oil by gavage five times a week for 6 weeks. Mice receiving as little as 100 mg/kg per day had an increase in relative liver weight. It is clear that TCE, even when given repeatedly to mice and rats at narcotic doses, has little ability to damage hepatocytes.

Adverse effects of TCE on the liver are usually attributed to metabolites of the cytochrome P-450-mediated oxidative pathway (Bull 2000). Buben and O'Flaherty (1985) reported that plots of their mouse subchronic-hepatotoxicity data against urinary-metabolite excretion values indicated that TCE's effects are directly related to the extent of its metabolism. As described in Chapter 3, TCE is oxidized by cytochrome P-450s (notably CYP2E1 at low to moderate TCE doses) to chloral, which is converted to chloral hydrate. That intermediate has a short half-life; it is rapidly oxidized to trichloroacetic acid, which is reduced to trichloroethanol (Lash et al. 2000a). Relatively small amounts of dichloroacetic acid may arise from trichloroacetic acid or other metabolites. Induction of CYP2E1 in rats with pyridine increases the toxicity of TCE to isolated rat hepatocytes (Lash et al. 2007). High concentrations of trichloroacetic acid and dichloroacetic acid are not toxic to hepatocytes freshly isolated from B6C3F$_1$ mice (Bruschi and Bull 1993); the researchers proposed that trichloroacetic acid and dichloroacetic acid cause peroxisome proliferation and the ensuing generation of reactive moieties that deplete glutathione and can cause oxidative injury. Dichloroacetic acid does not induce peroxisome proliferation in male B6C3F$_1$ mice in the same dose range at which it produces hepatic tumors (DeAngelo et al. 1999). Laughter et al. (2004) found that high oral doses of TCE increased liver weight, peroxisome proliferation, and hepatocellular proliferation in male mice. Those effects appeared to be due primarily to trichloroacetic acid's activating a nuclear protein known as the peroxisome-proliferator-activated receptor alpha (PPARα). PPARα-dependent changes seen in gene expression may contribute to the carcinogenicity of TCE in mouse liver.

TCE-induced hepatic injury is not a common finding in humans and was rarely reported in patients when TCE was used as an anesthetic (Lock and Reed 2006). Clearfield (1970) described hepatocellular degeneration in two men who intentionally inhaled extremely high vapor concentrations of TCE for their intoxicating effects. In contrast, James (1963) saw only small foci of fatty accumulation in the liver

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(steatosis) of a man who died after 10 years of TCE abuse. Bruning et al. (1997) found renal injury but no evidence of hepatotoxicity in a man rendered unconscious for 5 days by drinking about 70 mL of TCE in a suicide attempt. Pembleton (1974) reported a transient postoperative rise in serum aspartate aminotransferase activity in four of 100 patients anesthetized with TCE for surgical procedures. A study of 289 British workers who experienced central nervous system (CNS) symptoms from TCE inhalation and dermal exposure in the workplace revealed no clear diagnoses of hepatotoxicity (McCarthy and Jones 1983). Such findings over the last 50 years indicate that acute or repeated high-dose exposures to TCE will produce a modest degree of hepatic injury in some people but not in most people (ATSDR 1997a).

Cancer

The carcinogenic effects of TCE and its metabolites have been assessed in a number of lifetime studies of several strains of mice and rats (NCI 1976; Fukuda et al. 1983; Henschler et al. 1984; Maltoni et al. 1986; NTP 1988, 1990a). Results of studies of TCE induction of hepatic tumors in rodents are summarized here on the basis of the extensive National Research Council review (NRC 2006).

It has been well established that TCE, when administered chronically in very high doses by gavage, can produce an increased incidence of hepatocellular cancer in $B6C3F_1$ mice. In the original bioassay (NCI 1976), technical grade TCE (containing epichlorohydrin and 1,2-epoxybutane as stabilizers) had this effect. Concern that these stabilizers are well-established mutagens and contributed to TCE's apparent carcinogenicity led scientists to utilize TCE without these stabilizers in future bioassays. Henschler et al. (1984) saw no increase in liver tumors in either sex of Swiss ICR/HA mice, rats, or Syrian hamsters that inhaled highly-purified TCE (stabilized with 0.0015% triethanolamine) for 18 months. Exposure of male and female $B6C3F_1$ mice to epichlorohydrin-free TCE by corn oil gavage at 1,000 mg/kg/day for 2 years caused increases in hepatocellular carcinoma. No such increase in liver tumor incidence was manifest in F344/N rats (NTP 1990a). Another study of four additional strains of rats of both sexes ingesting epichlorohydrin-free TCE at 125-1,000 mg/kg also showed no increase in liver tumors (NTP 1988). Thus, it has been demonstrated that TCE itself, when administered chronically in very high oral doses, results in an increased incidence of liver cancer limited to male and female $B6C3F_1$ mice.

The major oxidative metabolites of TCE—trichloroacetic acid, dichloroacetic acid, and chloral hydrate—have also been extensively studied in rodents (Herren-Freund et al. 1987; Bull et al. 1990; DeAngelo et al. 1991, 1996, 1997, 1999; Daniel et al. 1992, 1993; Pereira 1996; George et al. 2000; NTP 2002a,b,c; Leakey et al 2003). Trichloroacetic acid is a species-specific carcinogen that induces peroxisome proliferation and hepatocellular carcinomas when administered in drinking water to male and female $B6C3F_1$ mice ($B6C3F_1$ mice are particularly susceptible) (Herren-Fruend et al. 1987; Bull et al. 1990; DeAngelo et al. 1991). The blood concentration of trichloroacetic acid required to induce hepatic tumors in mice is in the millimolar range. Effects have been observed with drinking-water concentrations of trichloroacetic acid of 0.05-5 g/L. TCA did not induce hepatic tumors in male F344 rats under similar treatment conditions (Daniel et al. 1993; DeAngelo et al. 1997). $B6C3F_1$ mice produce a large amount of trichloroacetic acid after exposure to TCE relative to unresponsive mouse strains (see Chapter 3). Trichloroacetic acid increases the rate of hepatocellular proliferation, production of reactive oxygen species, hepatocellular hyperplasia, and hepatomegaly (see Chapter 3). Marked species differences in susceptibility to peroxisome proliferation associated with liver cancer after increased fatty-acid beta oxidation and modulation of hepatocellular replication related to activation of the PPARα nuclear receptor by TCE and its metabolites have been investigated and reviewed in detail (Klaunig et al. 2003; Cattley 2004; Laughter et al. 2004). Rats exhibit saturation of TCE oxidative metabolism that results in amounts of trichloroacetic acid that are probably insufficient to induce hepatic peroxisome proliferation. It is thought that humans, like rats, have lower rates of oxidative metabolism and higher rates of conjugation than do mice.

Trichloroacetic acid produces hepatic tumors only in $B6C3F_1$ mice, but dichloroacetic acid induces them in mice and in F344 rats at exposures up to 5 g/L in drinking water for 104 weeks (Herren-Freund et al. 1987; Bull et al. 1990; Daniel et al. 1992; DeAngelo et al. 1996, 1999; Pereira 1996; NRC

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2006). Dichloroacetic acid is a major metabolite of TCE in $B6C3F_1$ mice but a minor metabolite in Sprague-Dawley rats (Larson and Bull 1992). Marked liver enlargement and cytomegaly in dichloroacetic acid-treated mice also indicate that induction of hepatic tumors depends on stimulation of increased cell division secondary to hepatoxoic damage (Bull et al. 1990). Inhibition of dichloroacetic acid metabolism by the parent compound at less than 1 to 500 μM (Kato-Weinstein et al. 1998) is thought to contribute to the variation in mouse hepatic tumors observed at this dose range (Bull et al. 2002).

Choral hydrate induces hepatic tumors in male $B6C3F_1$ mice but not in female mice or F344 male rats (George et al. 2000; NTP 2002a,b; Leakey et al. 2003). Female $B6C3F_1$ mice given choral hydrate in water by oral gavage for 104 weeks at up to 100 mg/kg per day had no increase in hepatic tumors (NTP 2002a), whereas exposure at the same doses in two groups of male mice fed ad libitum (NTP 2002a,b) or fed a calorie-controlled diet (Leakey et al. 2003) had increased incidences of hepatocellular adenoma or carcinoma (combined). Dietary control of caloric intake in the latter study was thought to improve survival and to decrease interassay variation. Choral hydrate is metabolically converted to trichloroacetic acid or dichloroacetic acid, and this contributes to its weak carcinogenicity. Overall, choral hydrate is an ineffective hepatic carcinogen that induces tumors only in male mice.

An epidemiologic study was conducted of short-term clinical exposure to choral hydrate used as a hypnosedative and possible cancer risk in humans (Haselkorn et al. 2006). An increasing risk of prostatic cancer with chloral hydrate was found, but the trend wat not statistically significant. Thus, the authors concluded that there was no persuasive evidence of a causal relationship between choral hydrate exposure and cancer in humans, but they were unable to rule out a causal relationship because statistical power was low. Trichloroacetic acid elicits hepatic tumors in mice with a phenotype typical of peroxisome proliferators, whereas dichloroacetic acid produces hepatic tumors with a distinctly different phenotype and also increases tumor growth (Bull 2000; Thai et al. 2003).

The relevance of TCE- and PCE-induced hepatic tumors to humans has been the subject of a great deal of research. Oral and inhalation carcinogenicity bioassays of TCE in rodents have shown that adenocarcinomas are strain- and species-specific (that is, are limited to the $B6C3F_1$ mouse). Haseman et al. (1998) reported a spontaneous hepatic-tumor incidence of 42.2% in male control $B6C3F_1$ mice used in National Toxicology Program (NTP) studies. The NTP recently held a series of workshops to determine whether another mouse strain and a rat strain should be adopted. In light of the high background hepatic-tumor incidence, it was recommended that the NTP explore the use of multiple mouse strains (King-Herbert and Thayer 2006).

It has been clearly established that the toxicokinetics (target-organ dosimetry) of TCE and PCE of the mouse and the human are different (see Chapter 3). Mice absorbed substantially more TCE and PCE because of their greater respiratory and alveolar ventilation rate, cardiac output and pulmonary blood flow rate, and blood:air partition coefficient. Mice also metabolically activate substantially more of their absorbed doses to bioactive substances (Lipscomb et al. 1998). On an equivalent inhalation exposure to PCE, rats exhibited markedly higher blood and urinary concentrations of trichloroacetic acid and dichloroacetic acid than humans (Volkel et al. 1998). The rats' blood also contained much higher concentrations of protein adducts (Pahler et al. 1999). Physiologically based toxicokinetic models similarly predict that mice will produce higher target-organ (liver) doses of trichloroacetic acid than humans after exposure to PCE (Clewell et al. 2005) and TCE (Clewell and Andersen 2004).

The primary mode of action of trichloroacetic acid, and to a smaller extent dichloroacetic acid, is activation of PPARα. Stimulation of PPARα can enhance DNA replication, resulting in expansion of some clones of hepatocytes and suppression of apoptosis, so initiated and precancerous cells will be spared. Male wild-type mice dosed orally with TCE exhibit hepatocyte proliferation and changes in expression of genes involved in cell growth (Laughter et al. 2004). PPARα-null mice are refractory to those effects, which are associated with carcinogenesis. Mice expressing human PPARα fail to show increases in markers of cell proliferation and are resistant to liver cancer if treated with PPARα agonists (Morimura et al. 2006; Yang et al. 2008). The concentration of PPARα in human cells is about 10% of that in the livers of rodents (Palmer et al. 1998; Klaunig et al. 2003; Lai 2004). The interpretation of mouse hepatic-tumor induction in 2-year bioassays relative to the inducing compound's mode of action, including induc-

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tion of peroxisome proliferation, has been assessed in a human-relevance framework (Cohen et al. 2003, 2004; Meek et al. 2003; Holsapple et al. 2006; Meek 2008). The relevance of $B6C3F_1$ mouse hepatic tumors to humans is also weakened by the observations that the background incidence of hepatic tumors in unexposed $B6C3F_1$ mice is about 60% and that large numbers of chlorinated compounds induce such tumors in mice (Gold and Slone 1995). The human is likely to be much less responsive toxicodynamically than the mouse to the cellular effects of trichloroacetic acid and dichloroacetic acid.

Many toxicologists have judged that the mode of action for hepatic carcinogenesis observed in mice after administration of peroxisome-proliferation-inducing drugs and other chemicals (such as TCE and PCE) makes it unlikely that such chemicals pose a hepatic-cancer risk in humans (Cattley et al. 1998; NTP 2000; Clewell and Andersen 2004; NRC 2006; Klaunig et al. 2007). It was concluded by the National Research Council that the PPARα mode of action for liver cancer in mice is not relevant to humans (NRC 2006). However, others have raised questions about the interpretation of PPARα actions and whether it is the only relevant mode of action for such chemicals (Keshava and Caldwell 2006), and this continues to be a subject of active debate (Peters et al. 2005; Klaunig et al. 2007; NRC 2008).

Toxicodynamic mechanisms of hepatic carcinogenicity other than peroxisome proliferation have been explored. Both trichloroacetic acid and dichloroacetic acid apparently contribute to hepatic tumorigenesis in mice (Bull et al. 2002; Caldwell and Keshava 2006). High, repeated doses of those TCE and PCE metabolites initially stimulate and then depress the growth of normal liver cells (Bull 2000). That may confer a growth advantage on initiated cells. Dichloroacetic acid at high concentrations also appears to act by increasing the clonal expansion and decreasing apoptosis of such precancerous cells. Moderate amounts of dichloroacetic acid are apparently produced from trichloroacetic acid and trichloroethanol in mice, but only trace amounts were found in one of three studies of TCE-exposed humans (see Chapter 3). It is important to recognize that stimulation or inhibition of cell growth through PPARα activation ceases when the metabolites are eliminated (Miller et al. 2000). Thus, such alteration of cell signaling is not a genotoxic mechanism of action. Very high concentrations of dichloroacetic acid and chloral hydrate have a weak genotoxic action in vitro. Bull (2000) and Moore and Harrington Brock (2000), however, conclude that it is unlikely that those metabolites would cause tumors in any organ through genotoxocity or mutagenicity at exposure concentrations relevant to humans.

Renal Effects

Toxicity

TCE has limited capacity to produce renal injury in rodents that are subjected to high oral exposures for extended periods. Jonker et al. (1996), for example, gave female Wistar rats TCE at 500 mg/kg by corn-oil gavage for 32 consecutive days. Urinalyses showed only slight increases in *N*-acetyl-β-glucosaminidase and alkaline phosphatase activities. A comparable exposure to PCE produced somewhat larger increases. Kidney weights were modestly increased by both chemicals. Microscopic examination revealed multifocal areas of vacuolation and karyomegaly in the animals' renal tubules. Male Eker rats received TCE at 50, 100, 250, 500, or 1,000 mg/kg by corn-oil gavage 5 times a week for 13 weeks (Mally et al. 2006). There were no changes in γ-glutamyltransferase activity or other urinary indexes of renal cytotoxicity. There was tubular-cell proliferation at 250 mg/kg or greater and karyomegaly at 500 mg/kg or greater. Overt nephropathy was restricted to the 1,000-mg/kg group. Nephropathy has been a common finding in rats and mice in chronic, high-dose cancer bioassays of TCE (NCI 1976; NTP 1986a, 1988, 1990a). Nephrosis and cytomegaly were more severe in the rats than in the mice, and male rats were generally affected more severely than females. Cytomegaly was manifested as frank enlargement of the cytoplasm and the nucleus of scattered tubular cells in the inner cortex and outer stripe of the medulla. Karyomegaly was later observed in the proximal tubular epithelial cells of the pars recta. The affected tubules were dilated, and the cells were flattened and elongated and contained enlarged, hyperchromatic

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nuclei with irregular shapes. A low incidence of renal tumors was seen consistently in several strains of male rats in the bioassays.

TCE has also been found to have some adverse renal effects when inhaled acutely or repeatedly at high concentrations for long periods. Proximal tubular damage was reported in male F344 rats exposed for 6 h to TCE vapor at 1,000 or 2,000 ppm (Chakrabarti and Tuchweber 1988). Mensing et al. (2002) subjected male F344 rats to TCE at 500 ppm for 6 h/day 5 days/week for 6 months. Glomerulonephritis was seen on histopathologic examination, but urinary biomarkers of glomerular damage were not found. Increases in urinary *N*-acetyl-β-glucosaminidase and low-molecular-weight proteins reflected mild proximal tubular damage.

Adverse effects of TCE on the kidneys are due largely to metabolites formed via the glutathione conjugation pathway (Lash et al. 2000b). As described in Chapter 3, conjugation of TCE with glutathione to form *S*-(1,2-dichlorovinyl)glutathione (DCVG) occurs primarily in the liver. DCVG is secreted into bile and blood. That in the bile is converted to *S*-(1,2-dichlorovinyl)-L-cysteine (DCVC), which is reabsorbed into the bloodstream. As noted in Chapter 3, humans have a lower capacity than rats to metabolize TCE by the glutathione pathway. Lash et al. (1999) were able to detect DCVG in the blood of humans who had inhaled TCE at 50 or 100 ppm for 4 h, but Bloemen et al. (2001) could not find DCVG or DCVC in the urine of similarly exposed subjects. DCVG in the blood is taken up by the kidneys and metabolized to DCVC by γ-glutamyltransferase and a dipeptidase. Lash et al. (2001b) observed the following decreasing order of toxic potency in freshly isolated rat cortical cells: DCVC > DCVG >> TCE. DCVC can be detoxified by acetylation and activated further by two pathways: (1) cleavage by renal cytosolic and mitochondrial β-lyases to dichlorothioketene, which in turn can lose a chloride ion to yield chlorothioketene or tautomerize to form chlorothionacyl chloride (the latter two moieties are very reactive and acylate proteins and DNA), and (2) oxidation by renal cytochrome P-450s or flavin-containing monoxygenases to the epoxide, DCVC sulfoxide (DCVCS). Lash et al. (1994) reported that DCVCS was a more potent nephrotoxin than DCVC in vitro and in vivo in rats. Apoptosis was observed after as little as 1 h of incubation of cultured human renal proximal tubular cells with DCVC and DCVCS (Lash et al. 2003, 2005). Cellular proliferation accompanied by increased expression of proteins associated with cellular growth, differentiation, stress, and apoptosis was also an early response to low doses. Necrosis, however, was a late, high-dose phenomenon in this cell system. Exposure of human renal proximal tubular cells to DCVC at lower concentrations for 10 days also resulted in expression of genes associated with cell proliferation, apoptosis, and stress (Lash et al. 2005) and repair and DCVC metabolism (Lash et al. 2006).

Proximal tubular-cell damage, as discussed above, appears to be a prerequisite for renal-cell cancer. Bruning et al. (1996) observed urinary protein-excretion patterns indicative of tubular damage in all of a group of 17 workers exposed for years to peak TCE vapor concentrations that caused CNS depression. They later reported small increases in urinary excretion of glutathione *S*-transferase α and α_1-microglobulin in a group of 39 cardboard workers without renal-cell cancer who had been heavily exposed to TCE for about 16 years (Bruning et al. 1999). Both indexes are markers of proximal tubular injury. Higher α_1-microglobulin excretion was reported in renal-cell cancer patients with TCE exposure than in renal-cell cancer patients without TCE exposure in an updated study (Bolt et al. 2004). Green et al. (2004) described similar findings in 70 electronics workers who inhaled TCE at an average concentration of 32 ppm for about 4 years. A battery of tests for nephrotoxicity was assessed after 4 days of exposure. Urinary albumin and *N*-acetyl-β-glucosaminidase were higher than in controls, although there was no correlation with the magnitude or duration of TCE exposure. There was also a suggested increase in urinary glutathione *S*-transferase α activity that correlated with the intensity but not with the years of exposure. Finally, Bruning et al. (1998) evaluated renal damage in a man who ingested about 70 mL of TCE in a suicide attempt. He was rendered unconscious for 5 days. His urinary glucose and protein concentrations were normal, but α_1- and β_2-microglobulin, *N*-acetyl-β-glucosaminidase, and several low-molecular-weight protein concentrations were increased. Such modest, reversible signs of renal injury demonstrate that TCE, even in extreme exposure conditions, has quite small nephrotoxic potential in humans.

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Cancer

TCE was given in corn oil to F344/N rats and B6C3F$_1$ mice of both sexes by oral gavage at doses up to 1,000 mg/kg in rats and 6,000 mg/kg in mice in a 13-week study and up to 1,000 mg/kg in both species and sexes in a 103-week study (NTP 1990a). Two-year oral-gavage studies in four additional rat strains were also conducted (NTP 1988). Nonneoplastic renal lesions were found in all animals dosed for 2 years. In all strains of rats tested, cytomegaly and karyomegaly of tubular cells in the renal corticomedullary region were observed. Frank toxic nephropathy was observed with higher frequency beginning at 52 weeks of exposure. A statistically significant increase in renal-tumor incidence was observed only in male F344/N rats exposed to TCE at 1,000 mg/kg for 2 years (this was the LOAEL). TCE has been shown to cause toxicity in proximal renal tubules in vivo; results of in vitro studies have also indicated toxicity of TCE and its metabolite DCVC in primary cultures of rat tubular cells (Cummings et al. 2000).

Nephrotoxicity was reported in Long-Evans rats after 6 months of inhalation exposure to TCE at 500 ppm (Mensing et al. 2002). The urinary-protein profile reported is consistent with impairment of tubular reabsorption of filtered protein. Inhalation studies were conducted in both sexes of Sprague-Dawley rats with TCE at 100, 300, and 600 ppm for 2 years and in Swiss mice at 100 and 600 ppm for 78 weeks (Maltoni et al. 1988a). Renal adenocarcinomas were reported in male rats at 600 ppm (the LOAEL), but no renal effects were observed in mice. Cytokaryomegaly or megalonucleocytosis was observed at the end of 2 years of exposure in male rats (77% of the 600-ppm group and 17% of the 300-ppm group) with no indication of pathologic conditions earlier.

Inconclusive evidence of induction of $\alpha_{2\mu}$-globulin by TCE, formic acid formation, or peroxisome proliferation as a mechanism or mode of action of TCE as a renal carcinogen was found (Goldsworthy et al. 1988; Green et al. 2003).

Results of animal studies indicate that kidney cancer occurs at high doses (for example, 1,000 mg/kg and 600 ppm) in male rats and is preceded by nephrotoxicity affecting the proximal tubule. An analysis by the U.S. Environmental Protection Agency with pooling across strains indicated a modest tumor effect in female rats (EPA 2001). Renal-cell cancers observed in German workers who were highly exposed to TCE have generally been assumed to be due to an initiating genotoxic effect of DCVC or DCVC coupled with the promoting effects of recurring cytotoxicity and compensatory hyperplasia (Bruning and Bolt 2000). The complete TCE glutathione conjugation pathway and assumed penultimate nephrotoxic metabolites are described in Chapter 3. It has been proposed that exposures below nephrotoxic concentrations or some threshold of exposure probably pose no risk of cancer in that nephrotoxicity is deemed to be a prerequisite for development of kidney cancer (Bruning and Bolt 2000; Harth et al. 2005). TCE oxidative metabolizing enzymes (such as CYP2E1 and CYP3A5 isoforms) have polymorphic forms. Known human population diversity in bioactivation and detoxification capabilities is an additional consideration in determining the exposure concentration below which nephrotoxicity is unlikely. For TCE inhalation exposure in the occupational setting, the suggested practical threshold below which nephrotoxicity is unlikely to occur is 250 ppm as an 8-h time-weighted average (Harth et al. 2005).

In humans, inactivation of the von Hippel-Landau (*VHL)* tumor-suppressor gene is responsible for the hereditary *VHL* cancer syndrome. Affected people are predisposed to a variety of tumors; more than 80% of sporadic renal-cell carcinomas are associated with inactivation of this gene. Brauch et al. (2004) noted that renal-cell cancer patients unexposed to TCE did not have the somatic *VHL* gene mutational characteristics of TCE-exposed renal-cell cancer patients. According to Moore and Harrington-Brock (2000), TCE itself has little if any mutagenic potential, and it is unlikely that any TCE-induced tumors would be mediated by its major oxidative metabolites. TCE recently also yielded negative results when tested in a *Salmonella typhimurium* strain (Ames test) that contained DNA coding for cytochrome P-450 reductase, cytochrome b5, and cytochrome P-450 2E1 (Emmert et al. 2006). TCE glutathione-conjugated metabolites DCVG and DCVC have, however, been shown to have genotoxic effects in in vitro test systems.

A recent study provides insight into a TCE renal-carcinogenesis threshold proposal. A strain of rats (Eker) uniquely susceptible to renal carcinogens was exposed to TCE at an administered dose of 100,

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250, 500, and 1,000 mg/kg by gavage 5 days/week for 13 weeks (Mally et al. 2006). The Eker rat is a unique animal model for renal-cell carcinoma, carrying a germ-line alteration of the *Tsc-2* tumor-suppressor gene. Results showed a significant increase in cell proliferation in renal tubular cells but no increased preneoplastic renal lesions or tumor incidence. In vitro studies were conducted on primary Eker rat renal epithelial cells by exposing them to the TCE metabolite DCVC dissolved in water at 10-50 μM for 8, 24, and 72 h. Concentrations of DCVC that reduced rat renal-cell survival to 50% also resulted in cell transformation. No carcinogen-specific mutations were identified in the *VHL* or *Tsc-2* tumor-suppressor genes in the transformed cells. Renal-cell carcinomas in the Eker rat have substantial similarities to human renal-cell carcinomas. It is not entirely clear that this or any contemporary experimental animal model adequately mirrors humans with regard to the effects of TCE-induced mutations in the *VHL* gene, but the authors firmly suggest that TCE-mediated renal carcinogenicity may occur only secondarily to nephrotoxicity and sustained regenerative cell proliferation. The latter findings, coupled with the aforementioned data of Lash et al. (2005, 2006), suggest that renal-cell cancer may result from prolonged, high-dose cytotoxicity and sustained cell proliferation but that TCE's metabolites may lack initiating activity.

Both DCVC and its mercapturic acid metabolite *N*-acetyl-*S*-(1,2-dichlorovinyl)-L-cysteine have been found in urine of humans exposed to TCE, and illustrates that the glutathione conjugation pathway is active (Bernauer et al. 1996). Exposure of volunteers to TCE at 50 or 100 ppm showed that DCVG concentrations were 3.4 times higher in males than in females (Lash et al. 1999). Genes associated with stress, apoptosis, cell proliferation, repair, and DCVC metabolism were up-regulated almost double in cultured human renal tubular cells exposed to subcytotoxic doses of DCVC for 10 days (Lock et al. 2006). Male rats display higher reduced glutathione conjugation, γ-glutamyl transpeptidase, and cysteine conjugate β-lyase activity than female rats. Taken together, results in the cited studies indicate that male humans and male rats both possess significant glutathione conjugation capacity and can produce the critical TCE metabolite DCVC; renal carcinoma has been observed in male rats and male workers when both have been exposed to high TCE concentrations for prolonged periods of time. These observations show data congruence, indicating that the conjugation pathway plays a central role in induction of renal carcinoma in males of both species. As discussed in Chapter 3, rats have greater capacity to metabolically activate TCE by this pathway than humans.

Evaluation of potential risks to human health related to contaminants in water supplies is a central concern of this project. Given the foregoing, it is sensible to begin to apply recent toxicologic information to contemporary maximum environmental values. In summary, exposure to high TCE concentrations appears to lead to saturation of the oxidative metabolic pathway with an attendant pronounced increase in metabolism via the glutathione-dependent pathway and likely increased production of penultimate toxic metabolites, such as DCVC sulfoxide, chlorothioketene, and thionoacylchloride from DCVC (Dobrev et al. 2002). As previously described, substantially larger quantities of these toxic moieties are produced from TCE by rat kidney than by human kidney. In addition, cultured rat cortical cells have been shown to be more susceptible to DCVC-induced necrosis than cultured human proximal tubular cells (Lash et al. 2001a). Human kidney cells have the capacity to metabolically activate and to respond adversely to low concentrations of DCVC, but not to the extent exhibited by male rat kidneys.

Pulmonary Effects

Toxicity

The pulmonary-toxicity potential of TCE has been studied extensively in mice and rats; there appear to be no reports of TCE-induced lung injury in humans. Forkert et al. (1985) were among the first scientists to describe lung toxicity in mice. Intraperitoneal injection of very high doses of TCE (2,000 and 2,500 mg/kg) into male CD mice rapidly caused damage of bronchiolar Clara cells and alveolar type II cells, anesthesia, and a marked reduction in pulmonary cytochrome P-450 content. Female CD-1 mice

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inhaling TCE at 20-2,000 ppm 6 h/day for up to 5 days exhibited dose-dependent vacuolation of Clara cells (Odum et al. 1992). Pyknosis of the bronchiolar epithelium also occurred at the higher concentrations. No morphologic changes were seen in the lungs of rats that were exposed to TCE vapor at 500 or 1,000 ppm. Isolated mouse Clara cells metabolized TCE to chloral, trichloroacetate, and trichloroethanol, but no trichloroethanol glucuronide was detected. It was proposed that the inability of these cells to conjugate trichloroethanol with glucuronic acid led to accumulation of chloral to cytotoxic concentrations (Odum et al. 1992; Green 2000). Forkert et al. (2005) found that oxidation of TCE to chloral was catalyzed in murine lung microsomes by cytchrome P-450s 2E1, 2F2, and 2B1. Forkert et al. (2006) later demonstrated that bioactivation of TCE by CYP2E1 and CYP2F2 occurred in Clara cells. Dichloroacetyl lysine adducts were localized in Clara cells in the TCE-treated CD-1 mice, and CYP2E1 and CYP2F2 are highly concentrated there (Forkert 1995). It is generally accepted that the cytotoxicity and possibly the weak mutagenicity of chloral and diacetyl chloride contribute to the development of lung tumors in mice.

The mouse appears to be uniquely sensitive to TCE-induced pulmonary toxicity and cancer. Mice, but not rats, developed lung tumors in the inhalation bioassays conducted by Fukuda et al. (1983) and Maltoni et al. (1988a). Clara cells are numerous and present throughout the airways of mice. They are found much less frequently in rats and are rare in humans (Green 2000). Mouse Clara cells contain considerable amounts of smooth endoplasmic reticulum, a membrane network in which cytochrome P-450s are bound. Human Clara cells are largely devoid of this organelle. Accordingly, metabolic activation of TCE to chloral is high in mouse, much lower in rat, and undetectable in human microsomes (Green et al. 1997b). Green et al. measured high CYP2E1 concentrations in mouse lung microsomes; concentrations of CYP2E1 were lower in rats and undetectable in humans. Mace et al. (1998), however, were able to detect very low concentrations of CYP2E1 mRNA and protein in human peripheral lung tissue. Forkert et al. (2005) found that male CD-1 mouse lung microsomes efficiently metabolize TCE to chloral hydrate, whereas the reaction was observed—at low rates—in samples from only three of eight human donors. Those findings suggest that TCE poses only a minimal risk of pulmonary toxicity in humans.

Cancer

TCE inhalation exposure caused an increased incidence of pulmonary tumors in ICR, Swiss, and B6C3F$_1$ mice but not in rats or hamsters. When female ICR mice were exposed to TCE at 150 and 450 ppm 7 h/day 5 days/week for 104 weeks followed by an observation period of 3 weeks, lung-tumor incidence increased by a factor of 3 (Fukuda et al. 1983); epichlorohydrin was used as a TCE stabilizer in this experiment. Female Sprague-Dawley rats exposed at the same concentrations for the same period had no increase in lung tumors. Male Sprague-Dawley rats had no increase in lung tumors but did have an increase in testicular and renal tumors after exposure to TCE at 600 ppm for 104 weeks but not at 100 or 300 ppm (Maltoni et al. 1986). Excess lung tumors were observed in Swiss mice and B6C3F$_1$ mice exposed to TCE at up to 600 ppm for 78 weeks (Maltoni et al. 1988a). Five gavage studies were also reviewed for induction of lung tumors in several strains of rats and mice; no excess lung tumors were found (NRC 2006). These results, the information presented in the preceding section on pulmonary toxicity, and the lack of reports of pulmonary injury and cancer in workers suggest that the risk of lung cancer in TCE-exposed human populations is minimal.

Genotoxicity

TCE is a weak genotoxicant in a number of test systems (Bruning and Bolt 2000; Moore and Harrington-Brock 2000; NRC 2006). Genotoxicity generally includes mutational end points, cytogeneticity, and primary DNA damage, whereas mutagenicity refers to the ability to induce heritable mutations. TCE oxidative metabolites trichloroacetic acid, dichloroacetic acid, and chloral hydrate generally have shown weak or no reactivity in mutagenicity tests; the weight of evidence in both in vitro and in vivo test sys-

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tems indicates that mutations are probably not key events in induction of cancer by these compounds (Moore and Harrington-Brock 2000). TCE was negative in a *Salmonella typhimurium* test strain that had cytochrome P-450 2E1 metabolizing capacity (Emmert et al. 2006).

Neonatal B6C3F$_1$ mice were given chloral hydrate, trichloroacetic acid, and TCE by intraperitoneal injection at the ages of 8 and 15 days; their livers were examined for 8-hydroxy-2′-deoxyguanosine 24 and 48 h and 7 days after the final dose (Von Tungeln et al. 2002). Mice treated with trichloroacetic acid or chloral hydrate showed significantly higher DNA-8-hydroxy-2′-deoxyguanosine adduct formation related to lipid peroxidation or oxidative stress; the authors concluded that male neonatal B6C3F$_1$ mice are not sensitive to induction of liver cancer by these compounds.

Significant increases in DNA migration in the Comet assay and micronuclei formation were reported in human HepG2 cells after treatment with TCE at 0.5-4 mM (Hu et al. 2008). Increases in both 8-hydroxy-2′-deoxyguanosine-DNA adducts and thiobarbituric acid-reactive substances were observed; depletion of glutathione increased susceptibility to TCE-induced effects, whereas cotreatment with *N*-acetylcysteine prevented the effects. That indicated that oxidative stress probably played a role in TCE-induced genotoxic damage in those cells. Hypomethylated DNA was found in both dichloroacetic acid-promoted and trichloroacetic acid-promoted mouse hepatic tumors in an initiation-promotion experiment (Tao et al. 2004). Gene expression controlling cell growth, tissue remodeling, and xenobiotic metabolism was altered in in dichloroacetic acid-induced mouse hepatic tumors (Thai et al. 2003). Overall evidence indicates that TCE and the oxidative metabolites trichloroacetic acid, dichloroacetic acid, and chloral hydrate are unlikely to act primarily by a mutational or genotoxic mechanism as hepatic carcinogens.

The TCE glutathione conjugate DCVC has been shown to have genotoxic effects, including increased reverse mutations in *S. typhimurium* tester strains, unscheduled DNA synthesis, and formation of DNA adducts in vitro (Bruning and Bolt 2000; Moore and Harrington-Brock 2000). Genotoxicity measures in rodent kidneys and primary cultures of human renal cells showed significant dose-dependent increases in results of the Comet assay (DNA single-strand breaks and alkali-labile sites) and in micronuclei frequency with subtoxic concentrations of TCE (Robbiano et al. 2004). Among the six rodent renal carcinogens tested, TCE was among the ones that exhibited the lowest potency for these end points; nonetheless, the results indicated that TCE is genotoxic in renal cells isolated from rats and humans. In another experiment, rats were exposed to TCE by inhalation or to DCVC by oral gavage. Proximal tubules isolated from kidneys of treated rats were assessed for DNA damage with the Comet assay (Clay 2008). Positive controls were included to demonstrate the sensitivity of the assay. Test results with TCE indicated a negative response in this assay. DCVC showed slight effects in a few animals 2 h after treatment and at the highest dose tested (10 mg/kg), but the effects were not strong enough to be considered positive. On the basis of those findings and other published data, the authors concluded that renal tumors seen in bioassays are nongenotoxic in origin.

Reproductive Effects

Toxicity

Studies in Males

Several studies of the reproductive effects of TCE have been conducted, and many of these were reviewed by the National Research Council (NRC 2006). Zenick et al. (1984) found reduced copulatory behavior in male rats after an oral dose of 1,000 mg/kg per day 5 days/week for 6 weeks but indicated that the changes may have been related to the narcotic effects of TCE. Mice exposed to TCE by inhalation 4 h/day for 5 days (Land et al. 1981) showed an increased percentage of abnormal sperm at 2,000 ppm, the highest dose tested (about 3,000 mg/kg per day) and no increase at 200 ppm (about 300 mg/kg per day). Kumar et al. (2000a,b) exposed male Wistar rats by inhalation to 376 ppm for 12 or 24 weeks (4 h/day 5 days/week) and reported decreased epididymal sperm count and motility, reduced testosterone concentra-

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tions, and lower fertility when the treated rats were mated with untreated females. There were also significant reductions in body weight, testicular weight, total cauda epididymal sperm count, and percentage of motile sperm; the effects were greater after 24 weeks than after 12 weeks of exposure. By 24 weeks, the testes were atrophied and had smaller seminiferous tubules. Sertoli cells were present, but tubules contained no spermatocytes, and spermatids and Leydig cells were hypoplastic (Kumar et al. 2001). Xu et al. (2004) exposed male mice by inhalation to TCE at 1,000 ppm 6 h/day 5 days/week for 1-6 weeks and found no effects except for a significant reduction in the fertilizing ability of sperm from the TCE-exposed males when they were combined in vitro with eggs from superovulated control females or when the males were mated with superovulated control females. A study in male rabbits (Veeramachaneni et al. 2001) reported that a mixture of several agents, including TCE, caused alterations in mating desire and ability, sperm quality, and Leydig-cell function. The effects were assessed subjectively, and it is difficult to determine the contribution of TCE to the changes seen.

Forkert et al. (2002) demonstrated that CYP2E1 is involved in the metabolism of TCE to chloral in Leydig cells and epididymides. Greater sensitivity of the mouse epididymis to high TCE vapor exposures correlated with greater chloral formation and higher concentrations of CYP2E1 in the epididymis than in the testis. Forkert et al. (2003) later found CYP2E1 in human epididymal epithelium and Leydig cells. Seminal-fluid samples from eight TCE-exposed mechanics who had diagnoses of clinical infertility contained TCE and some of its oxidative metabolites. More recently, Kan et al. (2007) evaluated epididymal damage by TCE at the light-microscopic and electron-microscopic levels in mice after inhalation at 1,000 ppm for 1 day or for 1, 2, 3, or 4 weeks. The study showed epithelial sloughing and degeneration with separation of the seminal tubules from the basement membrane after exposure for 1 week or more. Epididymal damage became more severe with increasing duration of exposure. DuTeaux et al. (2003) found CYP2E1 and dichloroacetyl adducts in the epididymis and afferent ducts, which were indicative of the formation of reactive cytotoxic metabolites in the cells that were damaged. The absence of mitochondrial β-lyase and the lack of formation of protein adducts in the epididymis and afferent ducts of rats dosed with DCVC suggest that TCE metabolites formed via the glutathione conjugation pathway do not participate in male reproductive toxicity. DuTeaux et al. (2004a,b) investigated the bioactivation of TCE and adduct formation in the testis and epididymis. In male rats ingesting TCE at estimated doses of 1.6-2.0 and 3.4-3.7 mg/kg per day in drinking water for 14 days, there was a dose-dependent reduction in capacity for in vitro fertilization of ova from untreated females. That effect occurred in the absence of any apparent alteration in the sperm other than a dose-dependent increase in oxidized proteins. The increase in lipid peroxidation implicates CYP2E1-mediated formation of reactive metabolites as a mechanism of toxicity.

Studies in Females

Manson et al. (1984) exposed female rats orally by gavage to TCE at 10, 100, or 1,000 mg/kg per day for 2 weeks before mating, 1 week during mating, and throughout gestation. Although high concentrations of TCE were measured in fat, adrenal glands, and ovaries, and uterine tissue contained high concentrations of trichloroacetic acid, female fertility was not affected. However, 17% of females in the high-dose group died, and weight gain was significantly reduced. Neonatal survival was also significantly reduced at the high dose, particularly in female offspring.

Cosby and Dukelow (1992) conducted a study of oral exposure of pregnant mice to TCE at 24 or 240 mg/kg per day during gestation and in vitro fertilization studies with TCE, trichloroacetic acid, dichloroacetic acid, and trichloroethanol. No effects were noted in the in vivo study; in the in vitro studies, there was a dose-related decrease in the percentage of fertilized embryos with trichloroacetic acid, dichloroacetic acid, and trichloroethanol but not with TCE.

Female rats were exposed to several male reproductive toxicants, including TCE, at 0.45% in drinking water for 2 weeks (Berger and Horner 2003). Oocytes collected after induced ovulation were incubated with sperm from unexposed males. The percentage of oocytes fertilized, the number of pene-

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trating sperm per oocyte, and the ability of oocytes to bind sperm plasma membrane proteins were all significantly reduced.

Studies in Mating Pairs

The NTP (1986b,c) conducted fertility-assessment-by-continuous-breeding studies of TCE dietary exposure in mice and rats. The feed for both studies contained microencapsulated TCE at 0.15%, 0.30%, and 0.60%. In mice, the body weights of male F_1 pups and the combined body weights of male and female F_1 pups were significantly reduced in the 0.60% group. Sperm motility was reduced in the F_0 parental males at the highest dose, but no other reproductive effects were seen. There were changes in testis and epididymis weight, increased liver weight, and increased combined kidney and adrenal weight. F_0 females showed no reproductive effects but had increased liver weight. Treatment-related lesions were seen in the livers and kidneys of both males and females. Increased perinatal mortality was seen in the F_1 pups at the highest dose level (NTP 1986b). In rats, there was a statistically significant trend toward reduced numbers of litters per pair, and crossover mating was reduced if either of the parents was treated. General signs of toxicity included reduced body-weight gain, altered testis and epididymis weight, and increased relative liver weight and kidney and adrenal weight at all doses (NTP 1986c).

Cancer

The majority of chronic carcinogenicity bioassays of TCE in rodents have failed to reveal an increased incidence of testicular tumors. Maltoni et al. (1988a) did, however, report a dose-related increase in Leydig-cell tumors in male Sprague-Dawley rats exposed to TCE vapor at 100, 300, or 600 ppm for 104 weeks. The biologic significance of findings in that investigation has been discounted because of methodologic and statistical deficiencies (ATSDR 1997b). The NTP (1986a, 1988) reported the findings of a 2-year bioassay in which four strains of rats were gavaged with TCE at 0, 500, or 1,000 mg/kg 5 days/week. Only Marshall rats exhibited a dose-related increase in Leydig-cell tumors. Leydig-cell adenoma is the most frequently encountered testicular tumor in mice and rats (Cook et al. 1999). The incidence varies from 1-5 % in control Sprague-Dawley rats to nearly 100% in F344 rats. Almost all those neoplasms are benign and occur in older rats. Most human testicular tumors are of germ-cell or Sertoli-cell origin and occur in young or middle-aged men. Leydig-cell tumors are rare in men (Cook et al. 1999). Thus, spontaneous or TCE-induced Leydig-cell tumors in rats are of questionable relevance to humans.

In summary, the 2006 National Research Council report concluded that TCE is toxic to spermatogenesis and the fertilizing ability of sperm. A detailed review by Lamb and Hentz (2006) concluded that male reproductive effects were generally seen at high concentrations that cause systemic toxicity and are more frequent in mice than in rats. The LOAEL for male reproductive effects after inhalation exposure is 376 ppm for 12 weeks (4 h/day 5 days/week) in rats, and there is general toxicity at that exposure. A NOAEL of 200 ppm for 5 days (4 h/day) was reported in mice in the Land et al. (1981) study, but no data for determining general toxicity were available. The LOAEL in rats for oral exposure is 1.6 mg/kg per day for 14 days in drinking water, but the relevance to humans of effects on in vitro fertilizing capacity is unclear. At 1,000 mg/kg, there were effects on copulatory behavior but with concomitant narcosis. No oral NOAEL was identified.

The oral NOAEL for female fertility in mice was 240 mg/kg per day in in vitro fertilization studies and in rats was 1,000 mg/kg per day with exposure before and during mating and during gestation. The LOAEL for impaired fertility in studies in which both males and females were exposed was about 145 mg/kg per day in rats and 875 mg/kg per day in mice. There was an indication of systemic toxicity at those doses. The NOAEL was about 70 mg/kg per day in rats and 405 mg/kg per day in mice.

Additional studies of the reproductive toxicity of TCE are needed to permit better identification of LOAELs and NOAELs in both male and female rats and mice. In addition, more work on the mechanisms of action and potency of the various metabolites is needed.

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Developmental Effects

Pregnancy Outcomes

Several studies of TCE and metabolic products in rodents and avian species were reviewed in the 2006 National Research Council report. Early rodent studies using inhalation exposure (Schwetz et al. 1975; Dorfmueller et al. 1979) indicated little or no developmental toxicity as a result of exposure, whereas later studies by Dawson et al. (1990, 1993) and Johnson et al. (1998a,b, 2003) reported an increase in cardiovascular malformations at concentrations as low as 0.25 ppm. However, the latter studies used direct delivery of TCE to the gravid uterus or in drinking water and a novel examination process for examining the heart and great vessels. Fisher et al. (2001), using the same examination process as the Dawson and Johnson groups and in collaboration with them, reported no increase in cardiac or vascular defects. Warren et al. (2006) examined fetuses from the Fisher et al. (2001) study and found no ocular defects after TCE exposure. More recently, Carney et al. (2006), using a standard test protocol (inhalation exposure to TCE at 0, 50, 150, or 600 ppm for 6 h/day on gestation days 6-20), reported no effect of TCE on development in rats at up to 600 ppm, a concentration that produced minimal maternal toxicity.

Collier et al. (2003) showed changes in gene expression during cardiac development after TCE exposure, and Klaunig et al. (1989) reported that TCE inhibited in vitro gap-junction-mediated intercellular communication. Coberly et al. (1992) used the chimera assay and showed no effects of TCE in mouse preimplantation embryos. There is evidence from one laboratory that direct administration of the metabolites trichloroacetic acid and dichloroacetic acid to pregnant rats increased congenital cardiac defects in their offspring (Smith et al. 1989, 1992; Epstein et al. 1992); effects were observed at doses of 330 mg/kg per day and greater over multiple days and at single doses of 1,900-3,500 mg/kg.

Several in vitro rodent and avian studies have shown effects of TCE on embryonic development, and these models have been used to investigate potential mechanisms for TCE and metabolite effects. For example, Saillenfait et al. (1995) reported concentration-dependent decreases in growth and differentiation indexes and increases in morphologic abnormalities in rat whole-embryo cultures, and Boyer et al. (2000), Hoffman et al. (2004), and Drake et al. (2006a,b) reported on TCE effects in a chick model. Changes in eye, pharyngeal arches, and cardiovascular development could be seen at high exposure concentrations (such as 80-250 ppm). In most cases, the TCE metabolites trichloroacetic acid and dichloroacetic acid were also studied and found to be at least as effective as TCE. Drake et al. (2006a,b) studied the effects of timing of TCE yolk-sac injection on chick heart development and found a greater effect if exposure occurred during endocardial cushion formation (Hamburger Hamilton [HH] stages 13-20) than if exposure occurred at earlier stages of development (HH stages 3+-17). Those authors also reported hypercellularity and increased proliferation in the outflow tract and atrioventricular canal of the heart. However, Mishima et al. (2006), using chick whole-embryo organ culture and TCE at low concentrations (10-80 ppm) in medium, reported reduction in mesenchymal cells in endocardial cushions. Ou et al. (2003), using an in vitro bovine organ culture, showed that TCE reduced heat-shock protein interactions with endothelial nitric oxide synthase, causing the synthase to shift to superoxide-anion generation, and inhibited vascular endothelial-cell proliferation stimulated by endothelial growth factor. Those effects on endothelial function are important in the development of cardiac defects. Although the in vitro studies are important in understanding the mechanism of TCE effects on development, their relevance for hazard characterization is unknown.

The recent studies by Carney et al. (2006) address some of the recommendations of the 2006 National Research Council report that additional studies are needed to evaluate a LOAEL. The Carney study clearly shows no effects on heart or other organ development in the rat at exposure concentrations up to a minimal maternally toxic concentration. Several studies have been published to address mode of action but have not made clear which species is most appropriate for human modeling. Otherwise, the more recent data reviewed here do not change the conclusions of the 2006 National Research Council report on the prenatal toxicity of TCE. An in-depth review of the animal and human data on cardiovascular defects by Watson et al. (2006) concluded that there is no indication of a causal link between TCE and cardiovas-

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cular defects at environmentally relevant concentrations. On the basis of that review and the Carney et al. (2006) study results, the conclusion is appropriate.

In summary, the database on the prenatal developmental effects of TCE is robust and indicates a lack of pregnancy outcomes up to concentrations that are minimally toxic in adults. The in vitro and whole-embryo studies are intriguing, but effects reported in them are probably due to the degree of exposure. On the basis of the Carney et al. (2006) study, the LOAEL of inhalation exposure during prenatal development in rats is greater than 600 ppm, and the NOAEL is also 600 ppm. The LOAEL for maternal or adult toxicity is 600 ppm, and the NOAEL is 150 ppm.

Growth and Development

A few studies have examined the neurologic effects of TCE after developmental exposure. For example, rat pups from dams exposed during gestation and lactation to TCE in drinking water at 312 mg/L (about 30 mg/kg per day) showed a reduction in 2-deoxyglucose uptake in the brain, indicating a reduction in glucose uptake or brain metabolism (Noland-Gerbec et al. 1986). Taylor et al (1985) showed an increase in activity of 60- and 90-day-old rats whose dams were exposed to TCE at 312 mg/L and above during gestation and lactation. In a followup study, Isaacson and Taylor (1989) reported that TCE at similar doses in rats reduced the amount of myelin in the dorsal hippocampus and proposed that the change might account for the behavioral effects of TCE. Another study by Isaacson et al. (1990) involved dosing young rats beginning at weaning with TCE in drinking water (312 mg/L) for 4 weeks, then with distilled water for 4 weeks. A second group was treated with TCE in drinking water for 4 weeks, distilled water for 2 weeks, then TCE for 2 weeks (as adults). Animals in the second group, but not the first group, showed reduced latency and improved learning in a Morris water maze. Both groups showed reduced hippocampal myelin. All those studies used small numbers of animals, and the dose was unclear, but they suggest neurologic effects of developmental exposure to TCE (see further discussion in the next section).

A study by Peden-Adams et al. (2006) reported immunotoxicity after developmental exposure of mice to TCE at 0, 1,400, or 14,000 ppb in drinking water from gestational day 0 through the age of 3 weeks or 8 weeks. There was a decreased plaque-forming-cell response in males at both ages and doses and a decreased plaque-forming-cell response in females exposed to TCE at 1,400 ppb at the age of 8 weeks and at 14,000 ppb at both ages. Reduced numbers of splenic B220 cells were seen in 3-week-old pups exposed at 14,000 ppb. There was an increase in all thymic T-cell types ($CD4^+$, $CD8^+$, $CD4^+/CD8^+$, and $CD4^-/CD8^-$) at 8 weeks and increased delayed-type hypersensitivity in females at both concentrations and in males at only the high dose. This was the first study to report developmental immunologic effects at lower concentrations than in adults. The authors indicate the need to replicate and expand the examination of critical windows for exposure (see section "Immunologic Effects" below).

In summary, except for the studies described above, there are no studies on growth and development of animals after developmental exposure to TCE either prenatally or postnatally. The above studies indicate neurologic and immunologic effects of TCE exposure during development. However, they have limitations in design and interpretation. Further study of TCE is required to determine the types of effects, the lowest effect levels, and critical windows of development.

Neurologic Effects

TCE, like many other VOCs, inhibits functions of the CNS and possibly the peripheral nervous system. Acute effects in humans range from slight dizziness, fatigue, and headache to incoordination, anesthesia, and death. TCE was commonly used for decades in vapor concentrations of about 2,000 ppm as a surgical, dental, and obstetrical anesthetic (Pembleton 1974). Such use was discontinued in the late 1970s. Chloral hydrate, an obligate intermediate of TCE's oxidative metabolic pathway, remains one of the most widely used sedatives for dental, emergency medical, and imaging procedures for young chil-

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dren (Keengwe et al. 1999). The magnitude of CNS depression induced by chloral hydrate and TCE depends on the administered dose and on the target organ (brain) dose. CNS inhibitory effects diminish and disappear as TCE is metabolized and it and its metabolites are eliminated from the body. It should be recognized that trichloroethanol, an end metabolite of the oxidation pathway, depresses the CNS. TCE's narcotic effects are generally considered to be reversible. Irreversible (neurotoxic) effects, however, have been reported in human populations exposed for years to concentrations of TCE and other organic solvents high enough to produce clinically significant CNS symptoms (Evans and Balster 1991; ATSDR 1997b; Bruckner et al. 2008). There is concern that exposures to lower concentrations may also pose a risk of residual neurotoxic effects (EPA 2001; NRC 2006).

TCE and other VOCs are intentionally inhaled for their euphoric and intoxicating effects. TCE and other solvents may be abused for years and result in malnutrition, cachexia, and residual damage of the brain and other organs; chronic neurologic and neuropsychologic sequelae have long been recognized. Rosenberg et al. (2002), for example, reported that a group of solvent abusers did significantly worse on tests of working memory and executive cognitive function than did alcoholics and cocaine addicts. A much higher percentage of solvent users had structural abnormalities in subcortical regions of the brain, as visualized by magnetic resonance imaging. They also exhibited moderate to severe diffuse abnormalities of cerebral white matter, a condition termed white-matter dementia. Inhalant abuse is the extreme form of TCE exposure, in that participants repeatedly subject themselves to vapor concentrations high enough to produce narcosis.

Occupational exposures to TCE often involve inhalation of relatively high concentrations for years. Usual exposure concentrations are much lower than those experienced by solvent abusers but substantially higher than encountered environmentally. Several studies of human subjects have been conducted to establish thresholds below which inhalation of TCE in the workplace will not impair motor or cognitive functions (ATSDR 1997b). Those studies have yielded surprisingly similar quantitative findings. Vernon and Ferguson (1969) exposed eight men to TCE at 0, 100, 300, and 1,000 ppm for 2 h. The highest concentration adversely affected performance on three of six standardized visual-motor tests; no significant decrements were found in response to the lower exposures. Stewart et al. (1970) measured a number of indexes of motor function in humans who inhaled TCE at 100 or 200 ppm for up to 7 h on 5 consecutive days. No decrements in performance were found, but some subjects described mild fatigue and sleepiness during their 4th and 5th days of inhaling TCE at 200 ppm. There were no significant differences in standardized achievement-test scores and self-reporting scales between controls and subjects who inhaled 100 ppm 6 h/day on 5 consecutive days (Triebig et al. 1977). Results of such studies served as the primary basis for the current occupational threshold limit value of 10 ppm and the short-term exposure limit of 25 ppm for TCE (ACGIH 2008). Those values were adopted in recognition that exercise enhances VOCs' systemic uptake and CNS effects.

There have been a number of reports of different neurophysiologic and neuropsychologic effects of TCE in workers after short-term and long-term exposure (ATSDR 1997b; NRC 2006). Acute exposures to vapor at 500 ppm and higher result in dose-dependent signs of intoxication. Those effects are usually reversible, although there have been occasional cases of residual nerve dysfunction in persons overcome by a single high exposure (Feldman et al. 1985; Leandri et al. 1995). The patient described by Leandri et al. exhibited trigeminal nerve damage up to 4 months after exposure. Effects of repeated long-term exposure include memory loss, mood swings, impairment of cognitive function, and olfactory and trigeminal neuropathy. In most instances, TCE concentrations were not known, and many of the study subjects were exposed to solvent mixtures. A few investigations measured vapor concentrations in the workplace. Workers chronically exposed at 38-172 ppm described symptoms of dizziness, headache, nausea, and sleepiness, but trigeminal nerve dysfunction was not apparent (El Ghawabi et al. 1973). Albee et al. (2006) recently found no change in trigeminal nerve evoked potentials in rats inhaling TCE at up to 2,400 ppm over 13 weeks. Ruijten et al. (1991) found a change in one of two indexes of trigeminal nerve impairment in 31 printing workers exposed to TCE at 35-80 ppm for an average of 16 years. No impairment of motor or autonomic nerves was found.

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Feldman et al. (1992) measured prolonged latency in the blink reflex, which is indicative of trigeminal nerve impairment, in two metal degreasers heavily exposed to TCE for 7 and 16 years. Ruijten et al. (1991) found slight reductions in sensory nerve conduction velocity consistent with subclinical impairment of the peripheral nervous system. Rasmussen et al. (1993) found no disturbance of the trigeminal nerve but observed altered function of the olfactory nerve in 99 metal degreasers exposed to "high" concentrations of solvents (primarily TCE) for an average of 11 years; they also described dose-dependent increases in motor dyscoordination in the degreasers.

A substantial number of neurotoxicity studies of TCE of acute and intermediate duration have been conducted in rats. CNS-depressant effects in the animals appear to be similar to those in humans and generally occur at higher exposure concentrations (ATSDR 1997b). That may be attributable in part to the availability of less sensitive measures of CNS depression in rodents. Bushnell and Oshiro (2000) found that inhalation of TCE at 2,000 or 2,400 ppm for 9 days reduced performance of rats on a sustained-attention task. Performance progressively improved (tolerance developed) during the protocol. Oshiro et al. (2004) then reported that inhalation of TCE at 1,600 or 2,400 ppm 6 h/day on 20 consecutive days did not impair later learning of a sustained-attention task. Inhalation at up to 1,500 ppm 16 h/day 5 days/week for 18 weeks increased latency in a visual-discrimination task but had no influence on spontaneous activity, grip strength, coordinated movement, or peripheral-nerve conduction time (Kulig 1987). Latency in a visual-discrimination task improved progressively in the 500-ppm and 1,500-ppm groups.

Auditory deficits in the midfrequency tone range have been observed in several strains of rats in response to inhalation of high concentrations of TCE (NRC 2006). Crofton and Zhao (1993), for example, described the onset of hearing loss after the fifth daily 6-h exposure at 4,000 ppm. It persisted for up to 14 weeks after exposure. The LOAEL in the study was 2,400 ppm. Histopathologic examination of rats that inhaled 4,000 ppm 6 h/day for 5 days revealed a loss of spiral ganglion cells in the middle turn of the cochlea and an inconsistent loss of hair cells (Fletcher et al. 1998). Recently, Albee et al. (2006) found focal loss of hair cells in the upper basal turn of the cochlea of rats that inhaled TCE at 2,500 ppm but not 800 ppm for 6 h/day 5 days/week for up to 13 weeks. Occupational exposures to such solvents as toluene and styrene have resulted in evidence of some hearing loss (Hodgkinson and Prasher 2006). That outcome has apparently not been assessed in groups exposed to TCE vapor at high concentrations. Kilburn (1999) reported an effect on the vestibulo-oculomotor system (balance) in a study of 150 jet-engine repairmen subjected to metal dusts and solvents, including TCE.

There have been some accounts of neurologic effects in animals caused by relatively low doses of TCE. Changes in visual evoked potentials were described in rabbits exposed repeatedly to TCE at 350 ppm over 12 weeks (Blain et al. 1992). Reduced exploratory and social behavior was seen in rats after weeks of daily 6- to 7-h exposures to TCE vapor concentrations as low as 100 ppm. Silverman and Williams (1975) did not use objective measurement techniques in their early study but merely observed the animals. Rats inhaling TCE at 50, 100, or 300 ppm for 8 h/day 5 days/week for 6 weeks exhibited altered sleep patterns; the effects were not dose-dependent (Arito et al. 1994). Decreased wakefulness during and after exposure was observed in the 50- and 100-ppm groups, respectively. The biologic or toxicologic significance of that effect is not apparent, but the Agency for Toxic Substances and Disease Registry (ATSDR) and the U.S. Environmental Protection Agency (EPA) each chose to use 50 ppm as the LOAEL with which to determine human exposure guidelines. ATSDR used an interspecies uncertainty factor of 3; EPA did not account for interspecies kinetic differences in its calculations. As described in Chapter 3, systemic uptake of inhaled VOCs is significantly greater in rodents than in humans. Physiologically based pharmacokinetic modeling has shown that higher blood concentrations are attained in rats during the initial hours of an 8-h exposure to TCE at 10 and 100 ppm (Bruckner et al. 2004).

Some investigations of potential cognitive effects of relatively low concentrations of TCE in rodents showed few adverse effects. Grandjean (1963) observed that inhalation of TCE at 800 ppm reduced swimming time in rats but produced no change in shuttle box or maze performance. Bushnell (1997) assessed the influence of a series of vapor concentrations on rats' response times to obtain a food reward; the NOAEL was 800 ppm. Albee et al. (1997) did not find alteration of flash-evoked potentials in rats inhaling 250 ppm. Waseem et al. (2001) stated that daily inhalation by rats of TCE at 376 ppm over 180

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days or consumption of TCE at 350, 700, or 1,400 ppm in water did not alter acquisition of a conditioned shock-avoidance response (cognition) but did enhance spontaneous motor activity. Similar findings in rats were described by Grandjean (1960) after acute 11- to 14-h inhalation exposures at 200 and 800 ppm. Those activity increases reflect the initial stimulant phase of action of CNS depressants.

A few studies of TCE exposure in drinking water at about 30 mg/kg per day during pregnancy and lactation reported increased activity, reduced 2-deoxyglucose uptake in brain, and reduced hippocampal myelin (Taylor et al. 1985; Noland-Gerbec et al. 1986; Isaacson and Taylor 1989). An additional study (Isaacson et al. 1990) reported learning deficits and reduced hippocampal myelin in rats exposed as weanlings and adults. All those studies were from the same group, involved small numbers of animals, and require confirmation (see section "Growth and Development" above).

Cancer

Standard practice in 2-year bioassays is to perform gross and often microscopic pathologic investigations of all organ systems in animals, including animals that die early. In general, an animal model is deemed relevant to establish the relative importance of the types of cancer, if any, that exposure to a given chemical at specific doses over a lifetime would be likely to elicit. In that context, animal TCE cancer bioassays cited previously did not show causality for brain cancer or other neurologic cancers.

Immunologic Effects

TCE has been reported to produce several forms of immunotoxicity, including the ability to act as a skin sensitizer, to exacerbate respiratory hypersensitivity (allergic asthma), to produce immunosuppression, and to influence autoimmune diseases. Autoimmunity has been by far the most studied, and will be given the most attention here.

Allergic Sensitization

There have been many reports that workers exposed to TCE often show a severe irritating contact dermatitis manifested by a rash on the extremities, face, neck, or trunk with or without fever (Kamijima et al. 2007). It is sometimes referred to as severe generalized dermatitis, but it is unclear whether it has an immunologic etiology. Recently, a study conducted in workers at an electronic-element and metal-plating production plant in Guangdong Province, China, suggested an association with TCE-induced severe generalized dermatitis and the HLA-B*1301 allele (Li et al. 2007). HLA alleles, known to be involved in governing immune recognition, are often reported to be associated with immune diseases. The evidence that TCE causes allergic contact dermatitis (skin allergy) comes primarily from a study by Tang et al. (2002) that used a modified guinea pig maximization test. TCE molecules themselves are too small to be antigenic and would need to bind covalently with skin proteins to elicit an immune response.

There is no evidence that TCE can directly induce asthma, but data suggest that it can modulate asthma. Acute intraperitoneal administration of TCE to rats at 0.1mL/kg enhanced the production of several regulatory cytokines, including interleukin-4 (IL-4), and induced histamine release from basophils in animals previously immunized with a protein allergen (Seo et al. 2008). IL-4 and histamine are involved in the development of allergic asthma. The authors showed similar effects by treating cells in vitro with TCE from animals immunized with a protein allergen. Thus, unlike the Tang et al. (2002) study, which suggested that TCE directly causes allergic contact dermatitis, the studies by Seo et al. (2008) suggest that TCE may act as an adjuvant in enhancing allergic respiratory disease. Other studies have shown that VOCs may modulate immune cell types to favor induction of allergic responses in young children (Lehmann et al. 2001). It is worth noting that a number of indoor and outdoor air pollutants are believed to

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exacerbate asthma, particularly in children (Selgrade et al. 2006). Further studies are needed to clarify those observations and determine whether TCE can induce or modulate allergic diseases.

Immunosuppression

That TCE can cause immunosuppression was first suggested on the basis of experimental-animal studies. Sanders et al. (1982) showed that mice exposed to TCE in drinking water for 4 or 6 months had deficiencies in their ability to mount normal immune responses. At a concentration as low as 100 mg/L (about 22 mg/kg per day), cell-mediated immunity and bone-marrow stem-cell colonization were inhibited. Wright et al. (1991) were able to confirm many of those findings in mice and rats treated with TCE by intraperitoneal injection. Peden-Adams et al. (2006) recently reported that mice exposed prenatally and postnatally to TCE are immunosuppressed at concentrations as low as 1.4 ppm in drinking water from gestation day 0 through the age of 3 or 8 weeks. Developmental immunotoxicity was manifested by suppression of antibody responses and decreases in B-cell numbers with a concomitant increase in delayed hypersensitivity responses and T-cell numbers. The shift in immune function would favor the development of infections from extracellular bacteria, such as streptococci and klebsiellae. The authors indicated that their data were preliminary and needed to be replicated (see section "Growth and Development").

Kaneko et al. (2000) reported that TCE suppressed immune functions in MRL-*lpr/lpr* mice after inhalation exposure to vapor at 1,000 or 2,000 ppm for 4 h/day for up to 8 weeks. The MRL-*lpr/lpr* mouse is genetically predisposed to develop systemic lupus erythematosus.

Epidemiologic studies of TCE exposure and immunosuppression have been few. Byers et al. (1988) found increased concentrations of $CD4^+$ and $CD8^+$ T cells in a population with chronic domestic exposure to solvent-contaminated drinking water. Iavicoli et al. (2005) investigated the association between serum concentrations of IL-2, IL-4, and interferon gamma (IFN-γ) in workers exposed to TCE (mean urinary trichloroacetic acid concentration, 13.3 mg/g of creatinine). Serum concentrations of IL-2 and IFN-γ were increased, and that of IL-4 was reduced. Without additional immune tests, interpretation of variations in serum cytokines is currently not possible. Taken together, studies seem to be consistent in supporting the ability of TCE to suppress the immune system, at least in experimental animals. It should also be noted that the immunosuppressive effects seen in experimental animals generally occur at doses at which hepatic toxicity can be observed.

Autoimmunity

The MRL+/+ mouse model has been used historically to study TCE-induced autoimmunity. It is one of several mouse strains that have a mutation that results in the spontaneous development of systemic lupus erythematosus (SLE). The MLR+/+ strain was derived from the MRL-*lpr/lpr* mouse. The latter has a Fas mutation, a key protein responsible for cellular apoptosis, which influences the development of lupus early in life (50% mortality by the age of 6 months). The MLR+/+ mice lack the Fas mutation and develop the disease much slower (50% mortality within 17 months). Activated $CD4^+$ T cells and regulatory cytokines (such as IFN-γ) play a key role in the development of SLE in MLR+/+ mice. Khan et al. (1995) showed that TCE accelerates the autoimmune disease process in MLR+/+ mice. Numerous studies have since examined the disease characteristics and mechanisms of action.

Several mechanisms, not at all mutually exclusive, that have been proposed for TCE-induced autoimmunity are consistent with current understanding of the etiology of autoimmune disease. It has been suggested that TCE reactive metabolites, such as dichloroacetyl chloride (Khan et al. 1995, 2001) and lipid peroxidation-derived aldehydes, which form after TCE exposure (Wang et al. 2008), covalently bind to host proteins (Wang et al. 2007) and become immunogenic. Those protein adducts act as neoantigens and result in recognition by and activation of autoreactive T cells and autoantibody production. In further support of the hypothesis, Cai et al. (2007) were able to produce an immune response to adducts

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derived from TCE reactive metabolites after immunization in mice, and Wang et al. (2008) activated T cells in vitro after incubation with the protein adducts. Consistently with the formation of TCE metabolites that form protein adducts, Griffin et al. (2000a) prevented adduct formation and reversed, at least in part, the autoimmune effects in TCE-treated MRL+/+ mice by cotreatment with diallyl sulfide, an inhibitor of CYP2E1 that prevents TCE metabolism.

TCE treatment of MRL+/+ mice also has been suggested to stimulate $CD4^+$ T cells directly (Gilbert et al. 1999). The activated $CD4^+$ T cells develop a surface antigen, referred to as CD44 (Griffin et al. 2000b), that is involved in cell adhesion and is highly expressed in MRL-*lpr/lpr* mice. Treatment of MLR+/+ mice with trichloroacetaldehyde hydrate or trichloroacetic acid, major TCE metabolites, also activated CD4 T cells (Blossom et al. 2004). Consistently with the ability of CYP2E1 inhibition to reverse the autoimmune effects (Griffin et al. 2000a), the activated cells are less susceptible to a form of cellular apoptosis, referred to as activation-induced cell death, that is observed in many autoimmune diseases. TCE-mediated defects of activation-induced cell death were recently found to be associated with metalloproteinase 7, which later facilitated FasL, a receptor involved in apoptosis (Blossom and Gilbert 2006). The T cells activated by the protein adducts are believed to represent predominantly a Th1 phenotype, rather than Th2, inasmuch as they produced higher concentrations of IFN-γ, a Th1 cytokine, and lower concentrations of IL-4, a Th2 cytokine. Th1 cytokines are usually associated with systemic autoimmune diseases. Gilbert et al. (1999, 2004) also provided evidence that trichloroacetaldehyde hydrate can activate T cells through the formation of a Schiff base. Schiff-base-forming structures, such as aldehydes and ketones, can substitute for physiologic donors of carbonyl groups and directly activate CD4 cells without engaging the T-cell receptor (Rhodes et al. 1995).

The chronic effects of TCE exposure in MLR+/+ mice have been addressed in several studies. Griffin et al. (2000c) exposed MLR+/+ mice to TCE at 0.1, 0.5, or 2.5 mg/mL in drinking water (21, 100, or 400 mg/kg) for 4 or 32 weeks and showed $CD4^+$ T-cell activation and induction of autoimmune hepatitis at all doses. Cai et al. (2008) exposed mice to TCE at 0.5 mg/mL in drinking water for up to 48 weeks. In addition to increases antinuclear autoantibody titers, lymphocyte infiltration and immunoglobulin deposits were found in the liver, pancreas, lungs, and kidneys (including glomeruli); this was consistent with SLE or an SLE-like disease. Blossom et al. (2007) treated MLR+/+ mice with trichloroacetaldehyde hydrate at 0.1, 0.3, or 0.9 mg/mL (about 13, 49, or 143 mg/kg per day) in drinking water for 40 weeks. Long-term exposure promoted alopecia and skin inflammation. The lesions did not appear similar to the cutaneous lupus seen in older MLR mice or the skin conditions in patients with systemic scleroderma; rather, they may have been associated with dermal infiltration of activated T cells.

Taken together, the experimental studies suggest two mechanisms, not mutually exclusive, by which TCE modulates autoimmune disease. The first involves TCE reactive metabolites that covalently bind to host protein to produce neoantigens that stimulate the formation of autoreactive immune cells. The second involves activation of Th1 cells nonspecifically by TCE metabolites, which also leads eventually to the formation of autoreactive immune cells. Both processes, like autoimmune diseases in general, involve cellular apoptosis. The latter is a general mechanism that may be relevant to a variety of autoimmune diseases, whereas the former may be more specific to particular diseases (such as lupus).

PERCHLOROETHYLENE

Data on the toxicity of PCE were summarized in a 1985 health assessment by EPA (1985) and an addendum issued in 1986 (EPA 1986). The California Environmental Protection Agency published a public-health goal for PCE in drinking water (CalEPA 2001) that included a brief review of toxicity data. ATSDR (1997c) also published a toxicologic profile of PCE, and a draft neurotoxicity assessment was available from EPA (2003). Literature reviews were available in particular subject areas (e.g., Beliles 2002; Klaunig et al. 2003; Wernke and Schell 2004). Such references were relied on for defining the body of literature available on PCE; in addition, a literature search was done to determine whether any relevant new publications were available. Conclusions drawn for the present report were based on a review of the

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body of available literature. The data are presented below by organ system, and toxic effects are considered separately from carcinogenic effects.

Hepatic Effects

Toxicity

PCE, like TCE, has a limited ability to cause acute, subacute, or chronic hepatic injury in rodents. Klaassen and Plaa (1966) assessed the acute cytotoxicity of PCE, TCE, and several other halocarbons in male Swiss-Webster mice given each chemical in a single intraperitoneal injection. PCE was a slightly less potent hepatotoxicant than TCE. A lethal dose of PCE was required to produce a substantail increase in serum alanine aminotransferase activity. Recently, Philip et al. (2007) reported that male Swiss-Webster mice given PCE at 150 mg/kg by aqueous gavage exhibited a transient increase in serum alanine aminotransferase activity. Higher alanine aminotransferase concentrations were manifested at 500 and 1,000 mg/kg. The extent of injury regressed substantially over a 30-day dosing period, apparently because of the onset of tissue repair and PCE's inhibition of its own oxidative metabolism. Buben and O'Flaherty (1985) saw modest increases over controls in serum alanine aminotransferase, liver weight, and hepatic triglycerides in male Swiss-Cox mice dosed with PCE at 500-2,000 mg/kg per day for 6 weeks by corn-oil gavage; the lack of dose dependence reflected saturation of metabolic activation in this dosage range. Hayes et al. (1986) found no consistent dose-related effects on any hematologic or clinical-chemistry measure in male or female rats that ingested PCE at about 14, 400, or 1,440 mg/kg per day for 90 days. Rats may be less susceptible than mice, although the absence of hepatotoxicity in rats in this instance can also be attributed to differences in oral-exposure regimens. Ingestion of a bolus dose of PCE will result in a high tissue dose that exceeds the capacity of the liver's defense and repair mechanisms. Consumption of the total dose in relatively small, divided doses might not exceed such a cytotoxicity threshold.

PCE-induced hepatic injury is believed to be a consequence of oxidative metabolism of PCE (Lash and Parker 2001). The PCE oxidative pathway is described in Chapter 3 (see section on metabolic activation and inactivation of TCE and PCE). PCE is more poorly metabolized by cytochrome P-450s than TCE, but two additional intermediate metabolites of PCE also contribute to its hepatocytotoxicity: the initial oxidation product, PCE oxide (epoxide), and one of its convertants, trichloroacetyl chloride. The latter is transformed to trichloroacetic acid, the major metabolite of PCE. Some trichloroacetic acid can be dechlorinated to form dichloroacetic acid. Trichloroacetic acid and dichloroacetic acid are also products of TCE biotransformation. As described earlier, trichloroacetic acid is primarily responsible for activation of the nuclear receptor PPARα, which stimulates peroxisomal enzymes and selected cytochrome P-450s involved in lipid metabolism. That results in peroxisome proliferation, which generates reactive oxygen moieties that can cause lipid peroxidation, cellular injury, and altered expression of cell-signaling proteins (Bull 2000). Lash et al. (2007) recently demonstrated that cytochrome P-450 inhibition resulted in reduced injury of hepatocytes isolated from male F344 rats and exposed to PCE. Glutathione depletion increased cellular injury, apparently because of a shift from glutathione conjugation to the oxidative metabolism of PCE.

Humans should be less susceptible to hepatic injury by PCE than rodents because of lower internal and target-organ doses of the parent compound and its bioactive metabolites. As described in Chapter 3, rats achieve a substantially higher internal dose of PCE than humans on inhaling it. Volkel et al. (1998) subjected rats and people to identical PCE inhalation regimens. Blood trichloroacetic acid concentrations were 3- to 10-times higher in the rats. Dichloroacetic acid was not detectable in human urine, but substantial amounts were found in rat urine. A study of the urinary excretion of total trichloro-metabolites by PCE-exposed workers led Ohtsuki et al. (1983) to conclude that the capacity of men to metabolize PCE was rather rather low. Lash and Parker (2001) noted that saturation of PCE metabolism occurred at lower doses in humans than in rodents. That implies that humans have lower capacity to form biologically active metabolites from moderate to high PCE doses. The difference is reflected in the finding of much

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lower concentrations of protein adducts in the blood of humans than in the blood of rats subjected to equivalent PCE inhalation exposures (Pahler et al. 1999). Stewart et al. (1977) found no evidence of hepatotoxicity in six male and six female volunteers exposed randomly to PCE at 0, 25, or 100 ppm 5.5 h/day 5 days/week for 11 weeks. Serum alanine aminotransferase activity was not increased in 22 dry cleaners examined in Belgium (Lauwerys et al. 1983). A research group in Italy studied 141 employees exposed to PCE in small laundries and dry-cleaning shops (Gennari et al. 1992); no worker exhibited clinical signs of hepatic dysfunction or abnormal serum enzyme concentrations, although there did appear to be an increase in one isozyme of γ-glutamyltransferase, which was said to be associated with hepatobiliary impairment. Another investigation of dry cleaners failed to reveal increases in serum enzyme concentrations but did show mild to moderate changes in hepatic parenchyma revealed by ultrasonography (Brodkin et al. 1995). Considerable experience in occupational settings demonstrates that humans, like rodents, may develop mild but reversible hepatic injury on exposure to high concentrations (ATSDR 1997b).

Cancer

Exposure to PCE by inhalation (NTP 1986a) and by oral gavage (NCI 1977) has shown increases in liver cancer in $B6C3F_1$ mice (Table 4-1). Inhalation exposure of 50 $B6C3F_1$ mice of each sex at 0, 100, and 200 ppm 6 h/day 5 days/week for 103 weeks caused increased incidence of hepatocellular neoplasms (adenomas and carcinomas combined) in males and females. The incidence in males was 17 of 49, 31 of 49, and 41 of 50, respectively; in females, it was 4 of 48, 17 of 50, and 38 of 50, respectively. As also shown in Table 4-1, exposure of male $B6C3F_1$ mice to PCE at 536 and 1,072 mg/kg per day and of female mice at 386 and 722 mg/kg per day in corn oil with epichlorohydrin stabilizer by oral gavage yielded significant increases in hepatocellular carcinomas ($P < 0.001$). Thus, there is clear evidence of hepatic carcinogenicity in $B6C3F_1$ mice related to PCE exposure.

No hepatic-cancer effects were seen in F344/N rats exposed by inhalation to PCE at 200 and 400 ppm for 103 weeks (NTP 1986a).

Trichloroacetic acid is also a metabolite of PCE. As discussed in detail in the preceding section on TCE cancer bioassays, trichloroacetic acid induces peroxisome proliferation in $B6C3F_1$ mouse liver but not in rat liver. That difference should be taken into account, as discussed in greater detail in the preceding section, in considering the relevance of mouse hepatocellular tumors for humans.

As shown in Table 4-2, gavage studies to determine carcinogenicity in Osborne Mendel rats (NCI 1977) were judged inadequate because of early mortality when PCE-induced toxic nephropathy reduced survival of dosed rats. There were many early deaths, so those results precluded conclusions regarding carcinogenicity of PCE in the rats.

Renal Effects

Toxicity

PCE is somewhat more nephrotoxic in mice and rats than TCE, but high, subchronic oral bolus dosing with PCE is required to affect the kidneys adversely. Jonker et al. (1996), for example, gave female Wistar rats TCE at 500 or 600 mg/kg per day by corn-oil gavage for 32 consecutive days. PCE elicited doubling of urinary protein and activities of several enzymes released from injured renal proximal tubule cells. TCE produced slight increases in just two of the enzymes. Coadministration of TCE and PCE resulted in additive nephrotoxicity. Philip et al. (2007) recently failed to see morphologic changes in the kidneys of male Swiss-Webster mice given PCE at 150, 500, or 1,500 mg/kg per day by aqueous gavage for 30 days. Green et al. (1990) gavaged male F344 rats with PCE at 1,500 mg/kg per day in corn oil for 42 days. There were increases in urine volume and urinary enzyme activities that were indicative of

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TABLE 4-1 Animal Cancer Studies of PCE with Positive Outcomes

Species	Strain	Dose or Concentration	Route	Timing and Duration	Outcomes	LOAEL	References
Mouse	$B6C3F_1$	0, 100, 200 ppm	Inhalation	6 h/day 5 days/week, 103 weeks	Hepatocellular adenoma in males; hepatocellular carcinoma in males, females	100 ppm	NTP 1986a
Mouse	$B6C3F_1$	Males: 0, 536, 1,072 mg/kg per day; females: 0, 386, 722 mg/kg per day; epichlorohydrin stabilizer	Oral gavage (corn oil)	5 days/week, 78 weeks, observed to 90 weeks	Hepatocellular carcinoma in males, females	536 mg/kg per day (males); 386 mg/kg per day (females)	NCI 1977
Rat	F344/N	0, 200, 400 ppm	Inhalation	6 h/day 5 days/week, 103 weeks	Stage 3 mononuclear cell leukemia;[a] rare renal tubular adenoma, adenocarcinoma in males	200 ppm (males, females)	NTP 1986a; Mennear et al. 1986

[a]Mononuclear-cell leukemia is common in aging F344 rats.

TABLE 4-2 Animal Cancer Studies of PCE Determined to be Negative, Inadequate, or Incomplete

Species	Strain	Dose or Concentration	Route	Timing and Duration	Outcomes	Comment	NOAEL	Reference
Rat	Osborne Mendel	Males, 471, 941 mg/kg per day; females, 474, 949 mg/kg per day	Oral gavage (corn oil)	78 weeks	Early mortality due to PCE-induced toxic nephropathy	Inadequate study	—	NCI 1977
Rat	Sprague-Dawley	0, 300, 600 ppm, 6 h/day, 5 days/week	Inhalation	52 weeks, then held another 12 mo	Hematologic examinations and tumor outcomes negative	Short duration of exposure; unpublished	600 ppm	Rampy et al. 1978
Rat	Sprague-Dawley	0, 500 mg/kg per day	Oral gavage (olive oil)	4-5 days/week, 104 weeks	No increase in total and malignant tumors at 141 weeks	Negative study	500 mg/kg per day	Maltoni et al. 1986
Rat	Long-Evans Sherman Wistar F344	—	Oral gavage	In-life studies completed; overall findings unpublished	Study judged "inadequate," no final report available	Inadequate study	—	NTP 1986a
Mouse	Ha:ICR Swiss	1st application, 163.0 mg; 2nd application, 54.0 mg	Skin	1st application, 229 days to papilloma; 2nd application: 0 papillomas	1st application, 4/7 mice with papillomas/total papillomas; 2nd application, 0	Negative study; $P > 0.05$	—	Van Duuren et al. 1979

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mild renal proximal tubular-cell damage. Histopathologic examination revealed the presence of hyaline droplet accumulation and some regeneration in the animals' proximal tubules. Ingestion of daily doses of PCE estimated at 14, 400, or 1,400 mg/kg in drinking water for 90 days failed to produce renal damage in male or female Sprague-Dawley-derived CD rats (Hayes et al. 1986). Thus, ingestion of divided doses of PCE in water over the course of the day is much less nephrotoxic in rodents than ingestion of the total dose once a day.

Subchronic and chronic inhalation of PCE has resulted in limited evidence of nephrotoxicity in rodents. Exposure of both sexes of F344 rats and $B6C3F_1$ mice to PCE at 400 ppm 6 h/day for 28 days failed to increase renal weights or produce histopathologic changes. Tinston (1995) reported mild, progressive glomerulonephropathy and increased pleomorphism of proximal tubular nuclei in male but not female rats that inhaled PCE at 1,000 ppm for up to 19 weeks. Nephropathy was seen in rats and mice chronically given high oral bolus doses of PCE in corn oil (NCI 1977). Karyomegaly occurred in renal tubules of male and female $B6C3F_1$ mice exposed to PCE at 200-1,600 ppm by inhalation for 13 weeks (NTP 1986a); the NOAEL in mice was 100 ppm. Renal lesions were not seen in F344 rats exposed to PCE at 1,600 ppm. Dose-dependent karyomegaly was observed in each sex of rats exposed to PCE at 200 or 400 ppm and mice exposed at 100 and 200 ppm chronically (NTP 1986a); there were also low incidences of renal proximal tubular-cell hyperplasia in the male rats.

The metabolism and mode of nephrotoxicity of PCE and TCE appear to be quite similar, although PCE and its metabolites are somewhat more potent. Renal effects of both halocarbons are due primarily to metabolites formed via the glutathione conjugation pathway (Lash and Parker 2001). The sites, enzymes, and products associated with PCE biotransformation are almost identical with those associated with TCE. (The TCE and PCE glutathione conjugation pathways were described earlier in Chapter 3.) The primary difference is that *S*-(1,2,2-trichlorovinyl)glutathione (TCVG) and *S*-(1,2,2-trichlorovinyl)-L-cysteine (TCVC) are produced from PCE, and DCVG and DCVC from TCE. TCVC can be detoxified by acetylation or cleaved by renal cytosolic and mitochondrial β-lyases to trichlorothioketene, which loses a chloride ion to form dichlorothioketene. The latter is a very reactive moiety that binds to cellular proteins and DNA. TCVC, like DCVC, can be enzymatically oxidized to form the very reactive *S*-(1,2,2-trichlorovinyl)-L-cysteine sulfoxide (TCVCS) (Krause et al. 2003). TCVCS was shown to be more nephorotoxic than TCVC in male Sprague-Dawley rats on intraperitoneal injection (Elfarra and Krause 2007). TCVC caused more pronounced necrosis of renal proximal tubular cells in male Wistar rats than did DCVC after intravenous injection (Birner et al. 1997). Lash et al. (2002) similarly found that PCE and TCVG were more toxic than TCE and DCVG to renal cortical cells from F344 rats in vitro. Cells from male rats were more sensitive than cells from females to PCE-induced and TCVG-induced mitochondrial state 3 respiratory inhibition and cytotoxicity. Isolated rat hepatocytes and their mitochondria were unaffected by PCE and TCVC. Increased glutathione concentrations increased TCE-induced and PCE-induced cytotoxicity in suspensions of rat renal cortical cells but not hepatocytes (Lash et al. 2007). In summary, PCE's glutathione-pathway metabolites are more reactive and cytotoxic in the kidney than are TCE's glutathione metabolites. PCE cytotoxicity is both sex-dependent and tissue-dependent.

Occupational exposures to PCE vapor have led to several reports of mild renal tubular damage (ATSDR 1997b). Employees of dry-cleaning shops have been the subjects of a number of investigations. Increased concentrations of urinary lysozyme or increased β-glucuronidase activity was described in dry cleaners exposed to PCE at average concentrations of 10 ppm (Franchini et al. 1983) and 23 ppm (Vyskocil et al. 1990) for 9-14 years. In a more comprehensive study of renal function, a number of urinary indexes indicative of early glomerular and tubular changes were increased over controls in 50 dry cleaners who inhaled PCE at an average concentration of 15 ppm for 10 years (Mutti et al. 1992). There was a lack of association between the extent of the changes and the intensity and duration of exposure. Verplanke et al. (1999) monitored several indexes of tubular and glomerular function in Dutch dry-cleaning workers but found an increase only in retinol-binding protein in their urine. Other groups of investigators have failed to find evidence of renal effects in such populations. A laboratory study of 10 male and 10 female adults who inhaled PCE at up to 150 ppm for as long as 7.5 h/day for 5 days did not show changes from pre-exposure baseline urinary and blood urea nitrogen concentrations (Stewart et al. 1981). Hake and

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Stewart (1977) described a dry cleaner who was found unconscious in a pool of PCE, where he had been for an estimated 12 h. Laboratory tests revealed hematuria and proteinuria that lasted for 10 and 20 days, respectively. Mild hepatic damage was revealed by transient increases in serum enzymes. On the basis of the foregoing human experiences, PCE has limited ability to cause diffuse changes along the nephron, although extremely high exposures can lead to pronounced changes.

Cancer

No renal carcinomas were observed in $B6C3F_1$ mice exposed to PCE at 0, 100, and 200 ppm for 103 weeks (NTP 1986a); dose-related karyomegaly was found in both males and females, but it was not accompanied by tubular-cell hyperplasia as it was in rats (Table 4-1).

F344/N rats develop nephrologic changes as a normal condition of ageing. Both sexes showed renal tubular-cell karyomagaly and males renal tubular-cell hyperplasia after exposure to PCE at 200 and 400 ppm for 103 weeks (NTP 1986a). That effect has been seen in other strains of rats exposed to chlorinated ethylenes, so it is not necessarily specific to PCE. Renal tubular-cell adenomas and adenocarcinomas were detected in male, but not female, rats. The incidence of renal neoplasm in the males was 1 of 49 controls, 3 of 49 exposed at 200 ppm, and 4 of 49 exposed at 400 ppm. Even though the results were not statistically significant, it was noted that those particular tumors are rare in F344/N male rats, so they were believed to have been caused by PCE exposure.

Pulmonary Effects

Toxicity

Little information was available on the pulmonary toxicity of PCE in laboratory animals or humans. Epithelial degeneration was observed in mice that inhaled PCE at 300 ppm 6 h/day for 5 days (Aoki et al. 1994). That effect was more severe in the olfactory than in the respiratory mucosa. Mice exposed to PCE at 50 ppm for 3 h were more susceptible to two strains of inhaled bacteria than controls (Aranyi et al. 1986). It was hypothesized that the susceptibility occurred because PCE inhibited alveolar macrophage activity. Intermittent inhalation of of PCE at 1,600 ppm for 13 weeks produced congestion in the lungs of rats (NTP 1986a). The 800-ppm vapor concentration did not have that effect. Pulmonary congestion was seen in mice that inhaled PCE at 100 ppm or greater in the 103-week phase of the cancer bioassay. There was not an increased incidence of lung tumors in the mice or rats. The reason for the apparent lack of significant pulmonary toxicity or carcinogenicity in rodents may have been the small amounts of the cytochrome P-450 isozymes that metabolically activate PCE. Although CYP2E1 is abundant in mouse lung, it does not appear to be active in PCE metabolism in rat (Hanioka et al. 1995) or human (White et al. 2001) cells, thereby inferring that CYP2E1 is unlikely to be a factor in metabolizing PCE in the rat or human lung. A number of studies of inhaled PCE have shown that vapor concentrations as low as about 200-300 ppm can cause mild irritation of the nasal passages of humans (ATSDR 1997b). Stewart et al. (1981) subjected four male volunteers to PCE at 0, 20, 100, and 150 ppm 7.5 h/day for 5 days. The subjects were exposed sequentially to each concentration for 1 week. Pulmonary-function measurements did not reveal any decrements. Pulmonary edema has been described in a person rendered unconscious by PCE fumes (Patel et al. 1973).

Cancer

No increases in lung proliferative lesions were seen in $B6C3F_1$ mice of either sex after inhalation of PCE at 100 or 200 ppm for 103 weeks, nor were lung neoplasms seen in male or female F344/N rats exposed at 200 or 400 ppm for 103 weeks (NTP 1986a).

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Genotoxicity

The genetic toxicity of PCE has been reviewed extensively by the California Environmental Protection Agency (CalEPA 1992), the International Agency for Research on Cancer (IARC 1995), and ATSDR (1997c). In general, studies have not yielded evidence of genotoxicity of PCE. Results in prokaryotic mutation assays (principally with *Salmonella typhimurium and Escherichia coli*) have been negative with and without S-9 rat liver microsomal metabolic activation. More recently, PCE was negative in an *S. typhimurium* tester strain competent for CYP2E1 metabolizing capacity (Emmert et al. 2006). Metabolites of PCE have been shown to be mutagenic in vitro. The minor PCE urinary metabolite glutathione conjugate TCVG is mutagenic in *S. typhimurium* TA 100 with renal cytosol metabolic activation (Vamvakas et al. 1987). TCVG, the precursor of the cysteine conjugate, was also mutagenic to *S. typhimurium* TA 100 with rat kidney microsomal metabolic activation (Vamvakas et al. 1989).

Reproductive Effects

Toxicity

Only two studies have addressed the potential for reproductive toxicity of PCE: a study by Beliles et al. (1980) and a two-generation study by Tinston (1995). In the Beliles et al. (1980) study, male rats and mice were exposed to PCE by inhalation at 100 and 500 ppm 7 h/day for 5 days. No effects on sperm structure were seen in rats, but in the 500-ppm group of mice, there was a significant increase in the incidence of abnormal sperm heads 4 weeks after exposure. The timing of the appearance of the effects after exposure suggests that spermatocyte or spermatogonia were most sensitive to exposure to PCE. The NOAEL was 100 ppm.

The two-generation study by Tinston (1995) involved exposure of male and female rats (Alpk:ApfSD) to PCE at 0, 100, 300, or 1,000 ppm 6 h/day 5 days/week for 11 weeks before mating and then daily during mating and through gestation to day 20. There was no exposure from gestation day 21 through postnatal day 6, and then exposure resumed. F_1 parents were selected on postnatal day 29, and exposure continued for at least 11 weeks before mating and then through mating, gestation, and lactation until the F_2 litters were weaned. Parental animals experienced CNS depression, decreased respiration at 300 and 1,000 ppm, decreased body weight at all concentrations during lactation, and nephrotoxicity at 1,000 ppm. Later growth in the 100-ppm and 300-ppm groups was similar to that in controls. There were reductions in live births, litter size, postnatal survival, and pup weight at 1,000 ppm. Pup kidney, liver, and testis weights were reduced at 300 and 1,000 ppm but not when adjusted for body weight. The NOAEL was considered to be 100 ppm.

Cancer

PCE has not been shown to cause testicular tumors in mice or rats in chronic carcinogenicity bioassays. The potential oncogenicity of PCE was evaluated in male and female F344 rats that inhaled PCE at 0, 200, or 400 ppm 6 h/day 5 days/week for 2 years (NTP 1986a). The overall incidence of Leydig cell tumors was 70%, 80%, and 82% in the 0-, 200-, and 400-ppm groups, respectively. Haseman et al. (1998) reported that NTP control F344 rats have an extremely high spontaneous incidence (89.1%) of Leydig cell tumors. F344 rats have therefore been replaced in the NTP bioassay program with Wistar Han rats. As discussed in the foregoing PCE reproductive-cancer section, Leydig cell tumors in F344 rats are believed to be irrelevant to humans.

In summary, the effects of PCE on sperm morphology and germ cells in rats and mice suggest an effect on male reproduction (Beliles et al. 1980; Tinston 1995), but more detailed studies are needed to clarify the effects and the relationship to magnitude of exposure. On the basis of the available studies, the

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LOAEL was 300 ppm for exposure 6 h/day 5 days/week for 11 weeks before mating and then daily during mating and through gestation to day 20. The NOAEL was 100 ppm. Leydig cell tumors reported in the chronic study (NTP 1986a) were discounted because of the high background rates of such tumors in F344 rats.

Developmental Effects

Pregnancy Outcomes

Several studies in rodents have focused on the potential for developmental toxicity of PCE. Schwetz et al. (1975) exposed pregnant mice and rats to PCE at 300 ppm on gestation days 6-15 and found maternal and developmental toxicity, including lowered weight of mice, subcutaneous edema in mouse fetuses, and increased resorption in rats. Beliles et al. (1980) found only minor changes in development in rats exposed to PCE at 300 ppm 7 h/day 5 days/week, either before mating and throughout gestation or only during gestation. In rabbits exposed at 500 ppm before or during gestation, there were no significant maternal or developmental effects.

Tepe et al. (1982) studied the effects of PCE exposure at 1,000 ppm in Long-Evans female rats before mating and during pregnancy or only during pregnancy to determine the more sensitive window. Increased relative maternal hepatic weight and reduced fetal body weight were seen after exposure to PCE at 1,000 ppm by inhalation during pregnancy. An increase in skeletal variations was seen in the group exposed before mating and during pregnancy, and soft-tissue variations (such as renal dysplasia) were seen more in the group exposed only during pregnancy.

Narotsky and Kavlock (1995) evaluated the effects of PCE at 0, 900, or 1,200 mg/kg per day administered orally by intubation on gestation days 6-19. There were no live pups in the 1,200-mg/kg group; maternal ataxia and reduced weight, fewer pups per litter, full litter resorptions, and microphthalmia or anophthalmia were seen at 900 mg/kg. Because of the high doses used and incomplete anatomic evaluation of pups, this study has little utility in hazard characterization.

More recently, Carney et al. (2006), using a standard prenatal developmental-toxicity study protocol (inhalation exposure 6 h/day 7 days/week on gestation days 6-20), reported reduced uterine and placental weights, reduced body weight, and reduced ossification in the thoracic vertebral centra in rats at PCE concentrations of 250 and 600 ppm and maternal toxicity at 600 ppm. The LOAEL for reduced fetal body weight was 250 ppm in this study. Reduced fetal body weight in the rat can be considered analogous to "small for gestational age" in humans.

An in vitro study by Saillenfait et al. (1995) reported concentration-dependent decreases in growth and differentiation indexes and increases in morphologic abnormalities in rat whole-embryo culture (gestation day 10) in a medium containing PCE at 3.5 mM. However, the relevance of the data to human risk assessment is questionable.

In summary, data from recent studies do not substantially alter the conclusions of EPA (1985), which were that data "do not indicate any significant teratogenic potential of PCE" and that other observed effects reflect primarily delayed development. The 2006 study by Carney et al. confirms the lack of teratogenicity of PCE, and the developmental effects reported at the lowest concentrations were relatively minor. The LOAEL for maternal effects was 600 ppm and for developmental effects was 250 ppm. The NOAEL for maternal effects was 250 ppm and for developmental effects was 65 ppm.

Growth and Development

Concerns about the neurotoxicity of PCE prompted investigations of the potential effects of exposure during development (Nelson et al. 1980; Manson et al. 1982; Fredriksson et al. 1993; Chen et al. 2002). Nelson et al. (1980) evaluated the effects of inhalation exposure to PCE at 900 ppm 7 h/day on gestation days 7-13 or 14-20. Dams gained less weight and had lower food consumption than controls

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during exposure. Animals were allowed to litter, and pups showed signs of neurobehavioral impairment on certain days of testing. Pups exposed on gestation days 14-20 initially performed more poorly than controls but later were superior on other tests. Significant reductions in acetylcholine were seen in both exposure groups, and reductions in dopamine were seen in the group exposed on gestation days 7-13. Another group of rats exposed to PCE at 100 ppm showed no differences from controls in any of the behavioral tests. Manson et al. (1982) did a followup study on the animals from the Tepe et al. (1982) study to evaluate the potential for postnatal body-weight and skeletal or soft-tissue variants, carcinogenicity, and neurotoxicity. No effects on any of those characteristics were observed. Fredriksson et al. (1993) studied mice exposed orally to PCE (5 or 320 mg/kg per day) on postnatal days 10-16. Mice tested at on postnatal day 17 were unaffected; but at the age of 60 days, changes in all three spontaneous-activity variables (motor activity, rearing, and total activity) and an attenuation of habituation were seen at both doses of PCE. Chen et al. (2002) exposed young rats beginning at weaning (body weight, 45-50 g) to PCE orally at 5 or 50 mg/kg per day 5 days/week for 8 weeks. Effects on pain threshold, locomotor activity, reduction in body-weight gain, and seizure susceptibility were seen at both doses.

The behavioral effects reported in rats (Nelson et al. 1980; Chen et al. 2002) and mice (Fredriksson et al. 1993) exposed to PCE prenatally or postnatally suggest that there may be sensitive windows for neurobehavioral impairment during development. Further study comparing the neurobehavioral, neurochemical, and neuroanatomic changes that follow developmental exposure to PCE are needed. (See the following section.)

Neurologic Effects

Neurotoxicity and Neurobehavioral Effects

Reviews by ATSDR (1997c), the California Environmental Protection Agency (CalEPA 2001), and EPA (2003, 2004) were consulted for this review. Data on accidental and controlled human inhalation and oral exposures and on experimental animal exposures are available.

Acute inhalation and oral exposure of humans has been shown to induce symptoms of CNS depression (dizziness and drowsiness) (ATSDR 1997c). Electroencephalograpic (EEG) changes have been shown after acute inhalation exposure (Hake and Stewart 1977) and after subchronic inhalation exposure (5 days/week for 1 month; Stewart et al.1981) to PCE at 100 ppm. Neurobehavioral changes—such as changes in flash-evoked visual potentials, deficits in vigilance, and deficits in eye-hand coordination—were seen in volunteers exposed to PCE at 50 ppm 4 h/day for 4 days (Altmann et al. 1990, 1992). Oral exposure to doses of PCE ranging from 2.8 to 4 mL (about 4.2 to 6 g) given orally as an anthelminthic resulted in narcotic effects and such associated changes as inebriation, perceptual distortion, and exhilaration (ATSDR 1997c).

A number of animal studies have shown effects on neurologic symptoms and biochemical end points in the brain after exposure to PCE. Acute and short-term inhalation exposure of rats, mice, and dogs to high concentrations of PCE (over 1,000 ppm) produced neurologic signs typical of anesthetic effects, such as hyperactivity, ataxia, hypoactivity, and finally loss of consciousness (summarized by ATSDR 1997c). Savolainen et al. (1977) reported effects of PCE on open-field behavior in rats exposed to PCE at 200 ppm 6 h/day for 4 days. Activity was increased at 1 h but not 17 h after the last exposure, and reduced RNA content and increased cholinesterase were measured in the brain. Mattsson et al. (1998) showed effects of PCE on flash-evoked potentials, somatosensory evoked potentials, and EEG results after acute exposure of rats to PCE at 800 ppm 6 h/day for 4 days when the animals were tested after exposure on the fourth day. Exposure of male Swiss mice to PCE at 596, 649, 684, or 820 ppm for 4 h reduced the duration of immobility experienced by mice when immersed in water (De Ceaurriz et al. 1983); the LOAEL was 649 ppm, and the NOAEL was 596 ppm. Albee et al. (1991) reported EEG changes and decreased latency of flash-evoked potentials and somatosensory evoked potentials in male rats exposed to PCE at 800 ppm 4 h/day for 4 days.

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The effects of intermediate and subchronic inhalation exposure to PCE have also been investigated in several animal studies. Mattsson et al. (1998) found effects on flash-evoked potentials after 13 weeks of exposure of F344 rats to PCE at 800 ppm; the NOAEL was 200 ppm. Male Sprague-Dawley rats exposed continuously to PCE at 600 ppm for 4 or 12 weeks were reported to have reduced brain-weight gain, decreased regional brain weight, and decreased DNA in the frontal cortex and brainstem (Wang et al. 1993). Specific glial proteins (S100 and glial fibrillary acidic protein) and neuronal cytoskeletal proteins (neurofilament 68-kD polypeptide) were also decreased; exposure to 300 ppm had no effect (and 300 ppm was the NOAEL). The authors concluded that the frontal cerebral cortex is more sensitive to PCE exposure than other parts of the brain and that cytoskeletal elements are more sensitive than cytosolic proteins. Rosengren et al. (1986a) exposed male and female Mongolian gerbils to PCE at 60 or 300 ppm for 3 months followed by 4 months without exposure. Changes in S100 (astroglial protein) and reduction in DNA concentrations in various brain regions were observed at 300 ppm, and reduction in DNA in the frontal cortex was seen at 60 ppm. Those effects were replicated by Karlsson et al. (1987). Kyrklund et al. (1988, 1990) reported changes in brain cholesterol, lipids, and polyunsaturated fatty acids in rats after exposure to PCE at 320 ppm for 30 or 90 days. Honma et al. (1980a,b) reported a decrease in acetylcholine in the striatum and an increase in glutamine, threonine, and serine. Kjellstrand et al. (1984) reported increased plasma butyrylcholinesterase concentrations and reduced body weight in white male and female MRI mice exposed to PCE at 37 ppm or greater for 30 days. Hepatic weight was increased at all concentrations (9, 37, 75, and 150 ppm) and continued to be increased 150 days after exposure; changes in hepatic structure were detected during exposure but were reversible. Cessation of exposure reversed the increase in butyrylcholinesterase concentrations. In experiments with various exposure durations, increases in butyrylcholinesterase and hepatic weight were seen after exposure at a time-weighted average of 150 ppm for 30 days.

Three studies have investigated the inhalation exposure of rodents to PCE during development (see also the section "Developmental Effects" above). Nelson et al. (1980) exposed pregnant rats to PCE at 100 or 900 ppm on gestation days 7-13 or 14-20. No effects were seen at 100 ppm, but pup weight gain was decreased in weeks 3-5 after exposure at 900 ppm. Developmental delays of offspring were seen in the exposed groups, and offspring exposed earlier in development had changes in an ascent test and a rotorod test with some increase in motor activity. Significant reductions in acetylcholine were found in assays of the whole brain (minus the cerebellum) after both exposure periods, and there were reductions in dopamine after exposure on gestation days 7-13. The authors concluded that animals exposed late in pregnancy had more behavioral changes than those exposed earlier. Manson et al. (1982), following up on the Tepe et al. (1982) study, found no postnatal effects of exposure to PCE at 1,000 ppm before mating and during pregnancy or only during pregnancy. Pregnant guinea pigs exposed to PCE continuously at 160 ppm on gestation days 33-65 had slightly altered brain fatty acid composition (Kyrklund and Haglid 1991), but the group sizes were very small (four litters each), and the statistical analyses treated each pup as an independent unit.

Year long exposures of Mongolian gerbils to PCE at 120 ppm altered phospholipid content in cerebral cortex and hippocampus (Kyrklund et al. 1984) and caused reductions in cerebellar and hippocampal taurine and increases in hippocampal glutamine (Briving et al. 1986a). However, there was no examination of nervous system structure in those studies to allow correlation of biochemical and behavioral changes. No structural CNS changes were reported in rats and mice exposed to PCE by inhalation at 200 or 400 ppm for 2 years (NTP 1986a).

The effects of oral exposure to PCE have been investigated in only a few studies. Moser et al. (1995) examined adult female F344 rats in a functional observation-screening battery after either a single dose or repeated doses over 14 days. A single dose of PCE at 1,500 mg/kg caused increased lacrimation and gait scores and decreased motor activity; the LOAEL was 150 mg/kg. Effects were greater 4 h after dosing than 24 h after dosing. No effects were seen 24 h after dosing with PCE at 1,500 mg/kg per day for 14 days. EPA (2003) concluded that the difference in effects between single and repeated dosing may reflect behavioral adaptation to PCE exposure. Warren et al. (1996) reported a transient decrease in a 90-min fixed-ratio 40 schedule of reinforcement in male mice exposed to PCE at 480 mg/kg immediately

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before testing; no effect was seen in animals exposed at 160 mg/kg. Blood concentrations correlated with administered dose, but brain concentrations were similar in the two groups. Chen et al. (2002) reported changes in pain threshold, locomotor activity, and seizure susceptibility (after pentylenetetrazol infusion) after exposure to a single dose of PCE at 500 mg/kg in adult rats; at 50 mg/kg, there were changes only in seizure susceptibility.

The effects of PCE exposure on younger animals were reported in two studies. Exposure of young rats (45-50 g) to PCE at 5 or 50 mg/kg per day 5 days/week for 8 weeks resulted in effects on pain threshold, locomotor activity, and seizure susceptibility; changes in locomotion at the high dose; and reduced body-weight gain at 5 and 50 mg/kg (Chen et al. 2002). The review by EPA (2003) raised serious questions about the design and interpretation of the study because of its observational nature and the minor degree of change in latency scores. Fredriksson et al. (1993) exposed 10-day-old MRI mice to PCE orally at 5 or 320 mg/kg per day for 7 days and found increased locomotor activity and total activity at 60 days in both dose groups. Rearing behavior was decreased in the high-dose group. Habituation in response was seen in all three measures, PCE attenuated the response in locomotion and total activity but not rearing. Although EPA (2003) raised issues with the data interpretation in the study and the similarity of the two doses of PCE on locomotion and total activity, the effects on rearing were dose-related. In addition, its criticism of using the pup as the statistical unit ignored to some extent the fact that individual pups were treated in the study.

Two studies that used intraperitoneal exposure have evaluated the neurologic effects of PCE. Umezu et al. (1997) determined that righting reflex was affected after a single intraperitoneal dose of PCE of 4,000 mg/kg but not 2,000 mg/kg in 8-week-old male ICR mice. Ability to balance on a wooden rod was decreased at 2,000 mg/kg but not at 1,000 mg/kg or lower. Response rate on a fixed-ratio 20 schedule was affected at 2,000 mg/kg but not at 1,000 or lower 30 min after treatment. With a fixed-ratio 20 punishment schedule, mice showed an increased response rate at 1,000 mg/kg but not at 500 mg/kg or lower. Motohashi et al. (1993) reported dose-dependent changes in circadian rhythm of 6-week-old male Wistar rats measured at least 1 week after intraperitoneal doses of PCE at 100, 500, or 1,000 mg/kg per day for 3 days. Recovery occurred 3-5 days after exposure ended. Results of studies that use intraperitoneal dosing cannot easily be compared with those of oral or inhalation exposures without pharmacokinetic modeling and development of appropriate conversion metrics.

Cancer

Gliomas were found in two female and four male F344/N rats exposed to PCE at 400 ppm (highest concentration tested) and in one control male (NTP 1986a). The incidence of the tumor was not statistically significant, and one glioma was observed in the control group. Thus, the brain tumors were not considered to have been induced by exposure to PCE.

Immunologic Effects

The effects of PCE on the immune system have been studied less than the effects of TCE. For example, much work has been performed on evaluating the effects of TCE, but not PCE, on autoimmunity. Most immunologic research on PCE has been on allergic sensitization and immunosuppression.

Allergic Sensitization

There is no evidence that PCE can directly induce asthma, but there are suggestive data that it might modulate asthma. Seo et al. (2008) reported that rats given PCE by a single intraperitoneal injection at 0.1 mL/kg showed increased production of regulatory cytokines, including IL-4, and induced histamine release from basophils in animals immunized with a protein allergen. Similar effects were induced by

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PCE in vitro in cells from animals immunized with a protein allergen. Thus, PCE may act as an adjuvant to enhance existing allergic respiratory disease. Epidemiologic studies have indicated that the presence of PCE in the home environment is associated with reduced numbers of IFN-γ containing type 1 T cells (Lehmann et al. 2002). This regulatory cytokine could conceivably skew the normal ratio of type 1 to type 2 T cells to favor the development of asthma in children by allowing a greater proportion of type 2 cells to develop. Earlier studies showed that VOCs may modulate immune cells to favor induction of allergic responses in young children (Lehmann et al. 2001). Further study is needed to clarify whether PCE can induce or modulate allergic diseases.

Immunosuppression

PCE was found to inhibit natural-killer-cell and cytotoxic T-cell activity after in vitro treatment of isolated mouse and rat spleen cells but not in in vivo experiments (Schlichting et al. 1992). In other studies, inhalation of PCE vapors (50 ppm) reduced bactericidal activity against inhaled *Klebsiella pneumoniae* and reduced survival after inhalation challenge with *Streptococcus zooepidemicus* in mice (Aranyi et al. 1986). It was hypothesized that those effects occurred because PCE inhibited alveolar macrophage activity. Such pulmonary host-resistance models can be influenced by a number of factors in the lung, including pulmonary macrophage function and inflammation. The available evidence does not allow any definitive conclusions to be drawn about the immunosuppressive potential of PCE.

Hematopoietic Cancer

F344/N rats were exposed to PCE by inhalation at 0, 200, and 400 ppm 6 h/day 5 days/week for 103 weeks (Mennear et al. 1986; NTP 1986a). A statistically significant increase in mononuclear-cell leukemia in both sexes was shown at both test concentrations, but no apparent dose-response relationship was observed. The NTP concluded that there was clear evidence of carcinogenicity of PCE in male F344/N rats and some evidence in female F344/N rats.

Mononuclear-cell leukemia is a common spontaneous disease of aging F344 rats with incidences in NTP historical control males and females reported to be 50.5% and 28.1%, respectively (Haseman et al. 1998). The condition can exceed 70% in F344 controls (Caldwell 1999; Ishmael and Dugard 2006). Mononuclear-cell leukemia exhibited by F344 rats apparently arises from large granular lymphocytes; that leukemic origin is very uncommon in humans (Caldwell 1999). Given the high background incidence of mononuclear-cell leukemia and other tumors in F344 rats, a series of workshops convened by the NTP considered possible alteratives to the F344 rat as a model for use in bioassays (King-Herbert and Thayer 2006). More recently, a posting on the NTP Web site stated that the outbred Wistar Han rat will be used in standard bioassays rather than the F344 rat because of its attractive characteristics, including an overall low incidence of spontaneous background tumors (NTP 2007). The incidence of mononuclear-cell leukemia in the NTP (1986a) study showed moderate but not clearly PCE-dose-related increases. Considering those factors, induction of mononuclear-cell leukemia in F344 rats exposed to PCE is unlikely to be relevant to prediction of human leukemia risk.

SUMMARY

The purposes of this section are to summarize information from key studies of the more important health effects of TCE and PCE and to describe the scientific evidence of an association between adverse effects in humans and various exposure conditions. TCE and PCE, in contrast with most other chemicals of environmental-health interest, have been extensively studied from a health standpoint. Nonetheless, there remain potential health effects of exposure to TCE and PCE on which there are inconclusive data or no data at all. The committee used a number of criteria in assessing the evidence in human case reports

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and from clinical studies and from controlled investigations with laboratory animals. Criteria used in reaching professional judgments included quality and reliability of key supporting studies, consistency of findings of similar studies, biologic plausibility, toxicologic significance, dose dependence and duration dependence, relative bioavailability and effects after different routes of exposure, and human relevance as determined by toxicokinetic and toxicodynamic concordance. Additional criteria have been used by study authors in assessing the implications of animal cancer bioassay results. The significance of those findings increases with increasing prevalence of tumors in multiple species, strains, and sexes; tumors at multiple sites; occurrence with more than one exposure route; progression from preneoplastic to benign to malignant; metastases; dose dependence; and low or nonexistent spontaneous tumor incidence in the test species.

The primary adverse health effects of TCE and PCE and the conditions under which they were observed are presented graphically below. Figures were prepared for inhalation of TCE (Figure 4-1) and PCE (Figure 4-2) and for ingestion of TCE (Figure 4-3) and PCE (Figure 4-4). The figures are intended to give an overall view of the lowest exposures at which chemically induced anomalies of target organs were reported in reputable studies. Exposure concentrations high enough to also produce anesthesia or narcosis or nonspecific signs of general toxicity (such as malaise, reduced food consumption or reduced body-weight gain, or decreased survival) are indicated. Later in this chapter, LOAELs for selected end points are compared with estimated ranges of TCE and PCE doses by simultaneous ingestion and inhalation experienced by former residents of Camp Lejeune from exposure to contaminated water supplies.

Trichloroethylene

Hepatic Effects

Toxicity

TCE, even in very high oral doses, has little ability to damage the livers of rodents or humans. A typical LOAEL in mice is 500 mg/kg. That dose, when given five times a week for 6 weeks, resulted in a modest increase in release of cytoplasmic enzymes from some damaged hepatocytes. Mice receiving TCE at 100 mg/kg per day on this regimen exhibited only a reversible increase in hepatic weight.

The latter effect is not considered to be toxicologically significant. It should be recognized that TCE (and the other VOCs) at Camp Lejeune must undergo metabolic activation to exert cytotoxicity or mutagenicity and that mice metabolize substantially more TCE than rats and rats more TCE than humans. Reports of hepatotoxicity in patients anesthetized with TCE are rare in the medical literature. No evidence of hepatic injury was manifested in a man rendered unconscious for 5 days by ingesting about 1,370 mg/kg in a suicide attempt.

Cancer

The ability of TCE to cause cancer of the liver and other organs has been the subject of a number of lifetime oral-exposure and inhalation-exposure studies in mice and rats. Daily administration of high doses by both exposure routes resulted in an increased incidence of hepatocellular carcinoma in one strain of one species, the $B6C3F_1$ mouse. It is unlikely that that tumor response is relevant to humans, because mice metabolically activate a much larger fraction of doses of TCE than do humans, the incidence of spontaneous hepatic tumors in male $B6C3F_1$ mice is greater than 42%, and peroxisome proliferation, believed to be a major mechanism by which key TCE metabolites induce hepatic tumors, is negligible in humans. However, some have questioned whether PPARα action is the only relevant mode of hepatic carcinogenesis of such chemicals.

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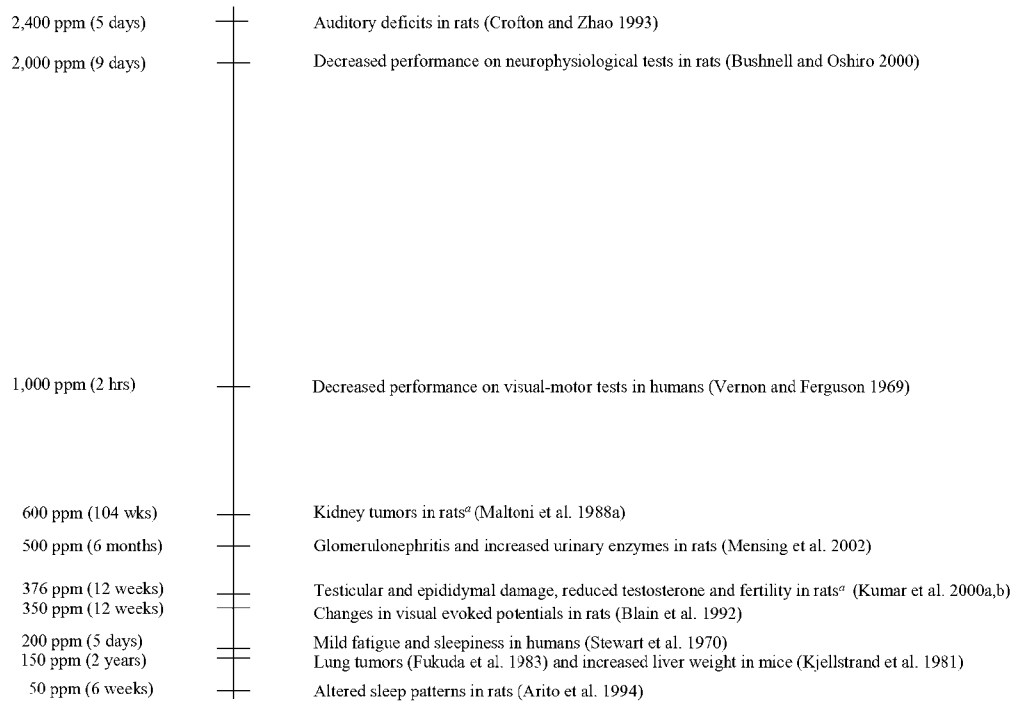
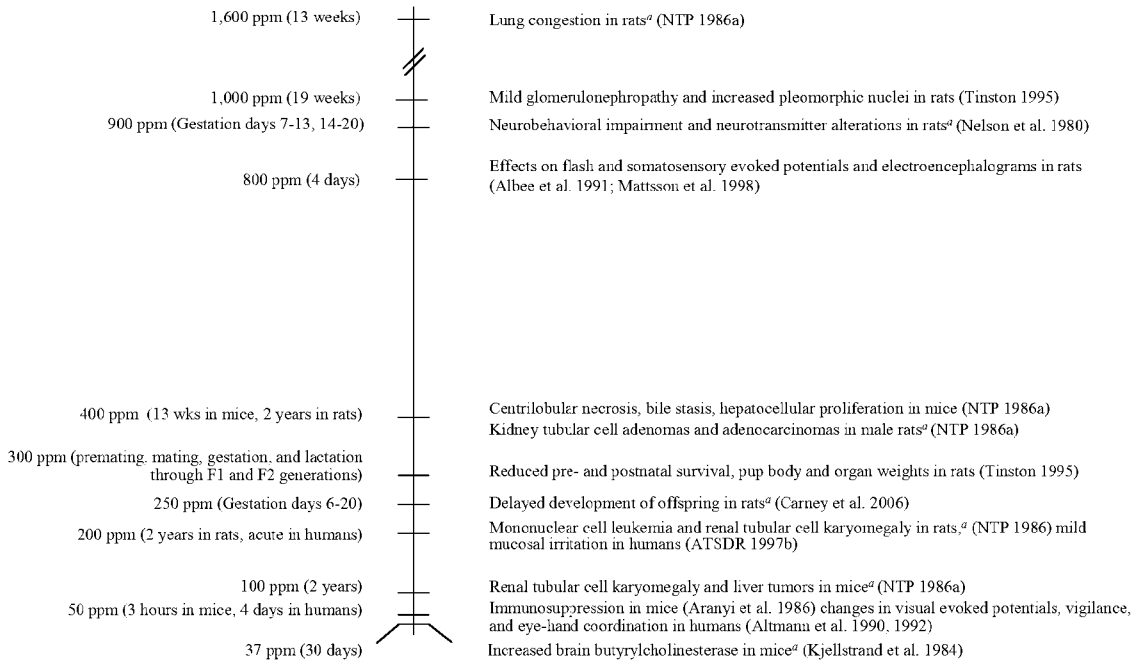


[a]General toxicity—for example, reduced body weight, weight gain, or food consumption—that may influence effects were observed in the study.

FIGURE 4-1 Effects of exposure to TCE by inhalation. Duration of exposure should be considered in comparing end points that occur after different exposures.



[a]General toxicity—for example, reduced body weight, weight gain, or food consumption—that may influence effects were observed in the study.

FIGURE 4-2 Effects of exposure to PCE by inhalation. Duration of exposure should be considered in comparing end points that occur after different exposures.

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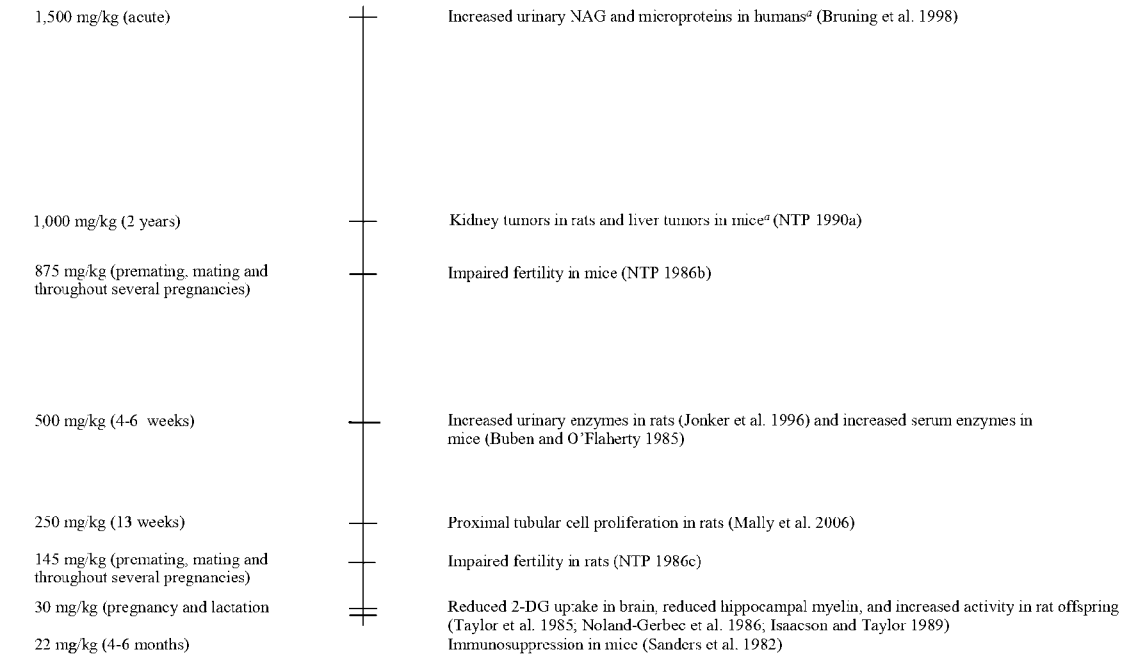
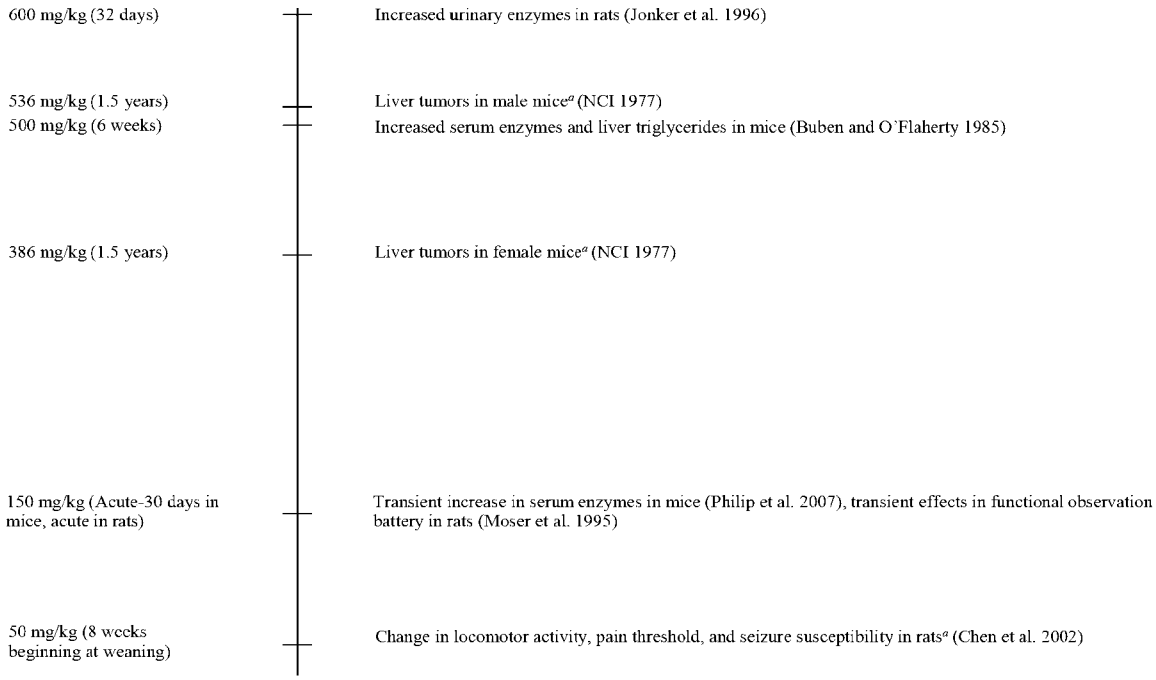


[a]General toxicity—for example, reduced body weight, weight gain, or food consumption—that may influence effects were observed in the study.

FIGURE 4-3 Effects of exposure to TCE by ingestion. Duration of exposure should be considered in comparing end points that occur after different exposures.



[a]General toxicity—for example, reduced body weight, weight gain, or food consumption—that may influence effects were observed in the study.

FIGURE 4-4 Effects of exposure to PCE by ingestion. Duration of exposure should be considered in comparing end points that occur after different exposures.

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Renal Effects

Toxicity

TCE has little ability to cause renal damage in rodents subjected to high oral or inhalation exposures for extended periods. A LOAEL of 500 mg/kg was found for mild renal injury in rats gavaged daily for 1 month. LOAELs of 250 and 500 mg/kg for proximal tubular-cell proliferation and karyomegaly, respectively, have been reported. Those responses were observed in male rats exposed orally five times a week for 13 weeks. Nephrosis occurs more commonly and is more serious in rats than in mice in lifetime cancer bioassays. The damage is apparently caused by reactive metabolites of the glutathione conjugation pathway. That pathway is similar qualitatively, but not quantitatively, in rats and humans (rats metabolically activate about 10 times as much). Some workers exposed chronically by inhalation and dermally to TCE sufficient to produce neurologic effects experience renal epithelial toxicity.

Cancer

Chronic exposure to TCE at 1,000 mg/kg per day orally or 600 ppm by inhalation causes saturation of the oxidative metabolic pathway, which leads to increased formation of metabolites via the glutathione pathway. Some of the metabolites are cytotoxic and mutagenic. Male rats, but not female rats and not mice of either sex, exhibit a low incidence of renal-cell carcinoma when subjected to TCE at the aforementioned doses for their lifetimes. Increased rates of renal-cell cancer are also reported in some workers exposed for years to concentrations of TCE high enough to produce CNS effects and renal injury. The recurring cytotoxicity and compensatory cellular proliferation are thought to be prerequisites for renal-cell carcinoma (that is, coupled with the initiating action of mutagenic glutathione metabolites they act as promoters).

Pulmonary Effects

Toxicity

Mice appear to be uniquely sensitive to pulmonary injury by TCE vapor. No reports of lung damage after TCE ingestion were located. Vacuolation of Clara cells was observed in mice that inhaled TCE at concentrations as low as 20 ppm 6 h/day for 5 days. Clara cells are nonciliated bronchiolar mucosal cells that have high CYP2E1 and CYP2F2 activities. The cytochrome P-450s catalyze the oxidation of TCE to chloral and diacetyl chloride, two putative cytotoxic and weakly mutagenic metabolites. Clara cells are numerous and are present throughout mouse airways; they are much less frequent in rats and rare in humans. CYP2E1 activity and TCE metabolism are undetectable in human lung preparations.

Cancer

Chronic TCE exposure has caused increased incidence of lung cancer in three strains of mice but not in rats. Lung tumors have not been seen in mice or rats in five oral TCE bioassays. That may be because presystemic elimination of the orally administered chemical reduced the TCE that reached pulmonary tissues. The TCE-induced mouse lung tumors are not considered relevant to humans since mouse lung tumors are associated with Clara cells containing high CYP2E1 metabolizing activity and human lung contains few Clara cells and undetectable CYP2E1 activity.

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Fertility, Reproductive, and Developmental Effects

Effects of TCE on fertility and reproduction have been seen in several investigations in rodents. In most cases, there were signs of general toxicity (such as body-weight and organ-weight changes and CNS depression) at the same exposure concentrations. Male rats exposed to TCE at 376 ppm 4 h/day 5 days/week for 12 or 24 weeks exhibited reduced body-weight gain, spermatoxicity, and reduced fecundity. CYP2E1, chloral formation, and dichloroacetyl adducts were found in testicular Leydig cells and epididymides of rats and were indicative of production of cytotoxic oxidative metabolites of TCE in the cells that were damaged. CYP2E1 has been found in human epididymal epithelium and Leydig cells. Some TCE oxidative metabolites have been identified in seminal fluid of TCE-exposed mechanics, although the relative metabolic capacities of human and rodent tissues have not been established. DuTeaux et al. (2004a,b) reported a dose-dependent reduction in the ability of sperm from TCE-treated rats to penetrate ova from untreated females in vitro. The male rats ingested TCE at estimated doses of 1.6-3.7 mg/kg per day in drinking water for 14 days. Replication of those findings and further studies of the toxicologic and human significance of that sperm effect are warranted.

Pregnancy outcomes were generally not affected by exposure to TCE at concentrations high enough to be maternally toxic, and there was no evidence of second-generation effects. Previously, there had been reports of cardiovascular defects in offspring of rodents exposed to TCE during gestation. More recently, well-conducted definitive experiments and a robust database have ruled out such developmental anomalies. The possibility of developmental neurotoxicity and immunotoxicity was raised in several publications. Further research is needed to determine whether those results can be duplicated and, if so, to expand the scope of investigation and assess the human relevance.

Cancer

Leydig cell adenoma has been found in male rats in a 2-year oral and a 2-year inhalation cancer bioassay of TCE. It is the most frequently encountered testicular tumor in mice and rats. The spontaneous incidence in old F344 rats is as high as 90%. Most human testicular cancers originate in germ cells or Sertoli cells and occur in young or middle-aged men. Leydig cell adenoma is rare in men, so spontaneous or TCE-induced Leydig cell adenoma is of questionable relevance to humans.

Neurologic Effects

TCE, like many other lipophilic VOCs, inhibits CNS functions as long as it is present at a sufficient concentration in neuronal membranes. Acute effects in humans are usually reversible and range from fatigue and dizziness to intoxication and anesthesia. A number of studies of human subjects have concurred that the inhalation LOAEL for impairment of motor or cognitive functions is 100-200 ppm for several hours. Residual neurotoxic effects (such as trigeminal and olfactory nerve impairment) have been reported in some workers exposed for years to vapor at concentrations that were probably in that range. Auditory deficits, reduced performance of tasks, and other effects were observed in more highly exposed rats, but tolerance usually developed over days or weeks of exposure. LOAELs of 350 and 50 ppm have been reported for changes in visual evoked potentials in rabbits and decreased wakefulness in rats, respectively. The toxicologic significance of those responses in rodents that inhaled TCE several hours a day for weeks has not been established. No definitive oral neurologic studies of TCE were located.

Immunologic Effects

TCE causes allergic sensitization in animal studies, including contact dermatitis and exacerbation of asthma. Some of those effects have been reported in humans after chronic occupational exposure to

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VOCs by inhalation at relatively high concentrations, but further studies are needed to determine whether TCE can induce or modulate allergic diseases in humans. Immunosuppression has also been shown in animal studies after TCE exposure, but it is unclear whether the effects are relevant to humans. Workers exposed to TCE showed increases in IL-2 and IFN-γ and an increase IL-4, but interpretation of these changes is difficult, and the data are too sparse to support definitive conclusions. Toxicologic studies have also shown exacerbation of autoimmune diseases in a genetically modified mouse model (MRL+/+). The relevance of those findings to humans is unclear, although epidemiologic studies have shown a relationship between solvent exposure and scleroderma, glomerulonephritis, and other immune-related diseases (see Chapter 5).

Tetrachloroethylene

Hepatic Effects

Toxicity

PCE, like TCE, has little ability to cause acute, subacute, or chronic hepatotoxicity in rodents or humans. PCE is somewhat more potent because of formation of some additional reactive metabolites. An acute oral LOAEL of 150 mg/kg was reported by Philip et al. (2007), but the serum concentration of a liver-specific enzyme in mice progressively declined as the mice were treated over 30 consecutive days. A NOAEL of 1,440 mg/kg per day was reported in rats that consumed PCE in drinking water for 90 days (Hayes et al. 1986). As described in Chapter 3, ingestion of a chemical in divided doses over several hours reduces its potency. In addition, rats are less susceptible than mice because of their lower capacity for activating PCE metabolically. Humans have even lower capacity than rats.

Cancer

There is clear evidence that near-lifetime inhalation or ingestion of PCE, like that of TCE, results in increased incidence of liver cancer in $B6C3F_1$ mice. Similarly exposed rats do not develop hepatic tumors. PCE's LOAEL is 386 mg/kg for 78 weeks compared with TCE's LOAEL of 1,000 mg/kg for 103 weeks. Trichloroacetic acid, a major metabolite of both PCE and TCE, produces peroxisome proliferation in mouse liver but not rat or human liver. The very high spontaneous hepatic-tumor incidence in $B6C3F_1$ mice and formation of substantially greater quantities of reactive metabolites suggest that mouse hepatic tumors may be of little relevance to humans.

Renal Effects

Toxicity

PCE is somewhat more toxic to the kidneys than TCE. A LOAEL of PCE of 600 mg/kg per day for renal damage was found in rats gavaged for 32 consecutive days. In contrast, consumption of PCE at up to 1,400 mg/kg per day in drinking water for 90 days failed to damage rats' kidneys. That discrepancy can be attributed largely to the kidneys' receipt of lower tissue doses when exposure was in drinking water. A NOAEL of 400 ppm and a LOAEL of 1,000 ppm are described for nephrotoxicity in rats that inhaled PCE several hours a day for a month or more. Karyomegaly was seen in the renal tubular cells of mice and rats that inhaled PCE chronically at as low as 100 and 200 ppm, respectively; the nuclear enlargement may be a predecessor of neoplasia, but a definite link has not been established. Renal effects of PCE are due primarily to metabolites formed via the glutathione conjugation pathway. Equivalent inha-

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lation exposures of rats and humans to PCE at 160 ppm for 6 h showed that biotransformation by the glutathione metabolic pathway was 10 times greater in the rats (Volkel et al. 1998).

Cancer

Chronic inhalation of PCE at 200 or 400 ppm produced renal tubular-cell karyomegaly, hyperplasia and a low incidence of tubular-cell adenoma and carcinoma in male rats. Renal tumors did not occur in female rats or in mice of either sex, although these animals did exhibit karyomegaly.

Pulmonary Effects

Toxicity

There is little evidence of lung injury by inhaled PCE in laboratory animals or humans. Inhalation experiments with human subjects indicate a NOAEL of 150 ppm and a LOAEL of 200-300 ppm for mild irritation of nasal passages. Pulmonary-function measurements do not reveal decrements at those concentrations. Intermittent inhalation of PCE at 1,600 ppm for 13 weeks produced pulmonary congestion in rats; 800 pm did not. There is one report (Aoki et al. 1994) of epithelial degeneration in mice that inhaled PCE at 300 ppm 6 h/day for 5 days. The change was more severe in the olfactory than in the respiratory mucosa.

Cancer

No increases in proliferative lesions or neoplasms of the respiratory tract have been seen in a chronic oral or inhalation cancer bioassay in mice and rats. Although CYP2E1 is abundant in mouse lung, that cytochrome P-450 isozyme is not active as a catalyst of PCE metabolism in the respiratory tract of other rodents or humans.

Other Cancers

An increased incidence of mononuclear-cell leukemia was found in male and female F344 rats that inhaled PCE at 200 or 400 ppm for 103 weeks. The increases were not dose-dependent and were within the incidence range of mononuclear-cell leukemia often seen in control F344 rats. The NTP is no longer using the F344 strain in its cancer bioassay program, because of its high rates of spontaneous cancer of several types. Mononuclear-cell leukemia is rare in people. Thus, that form of leukemia in F344 rats has been judged not to be relevant to humans. Animal cancer bioassay outcomes relevant to human leukemia, multiple myeloma, and non-Hodgkin lymphoma have not been reported.

Fertility, Reproductive, and Developmental Effects

Information on potential effects of PCE on fertility and reproduction is limited. Inhalation of PCE for 5 days did not affect sperm morphology in rats but did result in increased incidence of abnormal sperm heads in mice. The NOAEL and LOAEL for that effect were 100 and 500 ppm, respectively. Long-term exposure of male and female rats to PCE vapor for two generations resulted in CNS depression, decreased body weight during lactation, and nephrotoxicity at 1,000 ppm. There were reductions in live births, litter size, survival, and body weight in the F_2 progeny at that vapor concentration. Those adverse effects may be secondary to maternal body-weight loss and toxicity. More data are needed to clarify the effects of PCE on reproductive function.

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A number of oral and inhalation studies of potential developmental effects of PCE have been conducted in rodents. Experimental protocols have included inhalation of PCE at 300-1,000 ppm before, during, or after pregnancy. Manifestations of developmental delay (such as reduced ossification of vertebrae and soft-tissue dysplasias) have been reported in pups at the relatively high concentration. Ingestion of PCE at 900 mg/kg per day on days 6-19 of gestation, for example, resulted in increased resorptions, reduced weight, and microphthalmia or anophthalmia in rat pups. That daily dose was so high that maternal ataxia and weight loss occurred. Developmental effects at lower concentrations were relatively minor and were not indicative of teratogenicity.

Neurotoxicity

Neurologic Effects

Ingestion and inhalation of sufficient doses of PCE produce CNS depression in rodents and humans. Because PCE is more lipophilic than TCE, it is moderately more potent as a CNS depressant. Deficits in neurophysiologic functions have been reported in volunteers exposed to PCE at as low as 50 ppm for 4 h/day for 4 days (Altmann et al. 1990, 1992). A number of animal studies have revealed neurobehavioral and neurochemical changes in the brains of animals that inhaled PCE at several hundred parts per million for various periods. Mattsson et al. (1998), for example, found altered flash-evoked potentials in rats after 13 weeks of exposure at 800 ppm, but not at 200 ppm. Wang et al. (1993) measured decreases in regional brain weight, DNA content, and glial proteins in rats exposed continuously to PCE at 600 ppm for 4 or 12 weeks. Few researchers, however, have evaluated PCE-induced neurobehavioral and neurochemical changes in the same animals, so interpretation of many of the data is difficult.

Neurodevelopmental Effects

Concerns about possible neurodevelopmental effects in children exposed to PCE prompted several investigations in animals. Chen et al. (2002), for example, described changes in locomotor activity, pain threshold, and pentylenetetrazol-induced seizure thresholds in young rats dosed orally with PCE at 50 mg/kg per day for 8 weeks. Exposure of pregnant rats to PCE at 900 ppm resulted in pups with diminished brain acetylcholine and dopamine concentrations and with neurobehavioral changes on certain days of testing; inhalation of PCE at 100 ppm was without effect. Such reports suggest that there may be periods of neurologic development during which sufficiently high PCE exposures are detrimental. Additional research is needed to determine whether gestational, neonatal, or childhood exposure to such solvents can impair CNS development and function.

Immunologic Effects

Little information is available on the potential of PCE to suppress the immune system or to induce autoimmune diseases. In one study, PCE was found to suppress natural-killer-cell and T-cell activity in vitro but to have no effect on rats in vivo. In a second study, inhalation of PCE at 50 ppm reduced bactericidal activity in mice subjected to inhaled microorganisms. Further investigations of PCE are warranted in light of the apparent effects of TCE on the immune system.

HAZARD EVALUATION OF TRICHLOROETHYLENE AND PERCHLOROETHYLENE EXPOSURE FOR SELECTED END POINTS

The committee used several approaches to consider the health significance of the solvents found in the water supply at Camp Lejeune. Hazard can be defined as the intrinsic characteristic toxicity of a

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chemical compound. The hazard evaluation provides information on the inherent toxic potential of an exposure and is not meant to provide a quantitative estimate of risk. This approach compares the lowest doses of TCE and PCE at which adverse effects were observed in laboratory animals (the LOAELs) with a range of estimated doses from the Camp Lejeune water supply. It is one line of evidence in assessing possible relationships between exposure to TCE and PCE in water at Camp Lejeune and potential health effects.

The lowest dose at which an adverse health effect was observed, the LOAEL, may be subject to some uncertainty, depending on a number of factors, including the doses that were studied, the end point chosen, and the method used to assess the end point; for example, death as an observed LOAEL end point is more certain than a subtle change in an end point that is reversible and of unknown biologic significance. LOAELs from animal studies, on average, are associated with a 10% increase in response rate and can be associated with various risk levels because the statistical power of the studies does not allow observation of lower levels of exposure. Thus, LOAELs do not define a level below which no adverse effects can occur. Nevertheless, determination of a LOAEL generally provides a useful measure of toxic potency. NOAELs are hampered by more uncertainty. A NOAEL is the highest experimental dose at which an adverse effect did not occur. An experimentally determined NOAEL may be substantially lower than the actual NOAEL if the doses administered were too low. The present hazard evaluation was based on LOAELs for selected toxicity end points as described below.

The toxicologic databases on TCE and PCE are extensive, but some data gaps remain for a few end points. LOAELs observed in animal studies selected for this dose comparison represent a range of adverse effects and oral doses. The particular end points were chosen in part because it was assumed that they may be relevant to humans. For TCE, renal tumors in rats were chosen for a chronic high-dose end point (LOAEL, 1,000 mg/kg per day for lifetime oral exposure [NTP 1990a]), renal toxicity in rats was chosen for the medium dosage range (LOAEL, 250 mg/kg per day for 13 weeks [Mally et al. 2006]), and immunosuppression in a sensitive strain of mice was chosen at the lower end of the dosage spectrum (LOAEL, 22 mg/kg per day in drinking water for 4 or 6 months [Sanders et al. 1982]) (see Figure 4-3 and Table 4-3). For PCE: renal toxicity in rats (600 mg/kg per day for 32 days [Jonker et al. 1996]) was selected at the upper end of a series of LOAELs, and neurologic changes in young rats (50 mg/kg per day for 8 weeks [Chen et al. 2002]) at the lower end of LOAEL doses (see Figure 4-4 and Table 4-4).

Uncertainty is associated with the TCE and PCE water concentrations used in the hazard evaluation because they are based on the relatively few mixed water samples analyzed (see Chapter 2). Only a small set of water-quality measurements are available, and those were taken during the 5 years before the contaminated wells were closed, so it is unknown how well they represented the conditions during the preceding decades. In addition, concurrent exposures to organic solvents may have occurred at Camp Lejeune. Studies of mechanisms of VOC interactions (see Chapter 3) indicate that such concurrent exposure is not likely to result in greater than an additive effect. Relatively low doses of multiple VOCs are unlikely to affect the magnitude of adverse health effects appreciably. Additivity is not formally incorporated into this appraisal.

The exercise below is not a health risk assessment. Several assumptions (described below) were used to derive the comparisons, so there is uncertainty and variability in the values. The intent is to provide general comparisons of the lowest doses at which specific adverse health effects were observed in experimental toxicologic studies with a range of estimated contaminant concentrations that may have occurred in the Camp Lejeune water supply.

The following describes the assumptions in the evaluation and illustrative calculations. To provide a standardized basis for comparison, the lowest doses at which a specific adverse effect was seen in toxicologic studies and the exposure estimates are both expressed in standard terms of milligrams of chemical per kilogram of body weight per day (mg/kg per day). Standard assumptions commonly used for hazard evaluations are that adults weigh an average of 70 kg and drink an average of 2 L of water per day and that children weigh an average of 10 kg and drink 1 L of water per day. Exposure via inhalation and dermal absorption of VOCs from water during showering, bathing, dishwashing, and other household ac-

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TABLE 4-3 LOAELs from Animal Studies Used for Comparison with Estimated Daily Human Doses to TCE Related to Water-Supply Measured Concentrations

Range of Doses	End Point	LOAEL, mg/kg per day
High	Kidney cancer, rats	1,000
Medium	Kidney toxicity, rats	250
Low	Immunosuppression, mice (sensitive strain)	22

TABLE 4-4 From Animal Studies Used for Comparison with Estimated Daily Human Doses to PCE Related to Water-Supply Measured Concentrations

Range of Doses	End Point	LOAEL, mg/kg per day
High	Kidney toxicity, rats	600
Low	Neurotoxicity, rats	50

tivities has been shown experimentally to account for as much exposure as that from drinking water that contains the chemicals (see Chapter 3). Therefore, to account for potential inhalation and dermal uptake in addition to ingestion in drinking water, an intake of 4 L/day is assumed for adults and 2 L/day for children. This calculation, therefore, takes into account all three routes of exposure—ingestion, inhalation, and dermal—of both adults and children. Considerable toxicologic data on VOCs are available from inhalation studies. The range of adverse effects is presented in Figures 4-1 and 4-2, but absorbed doses were usually not determined. Duration of exposure is usually specified in animal studies. A conservative assumption used in this hazard evaluation is that humans receive the stated dose daily, although that is very unlikely inasmuch as data presented in Chapter 2 indicate that daily exposures were highly variable.

It is important to note that the evaluation has not taken into account uncertainties and additional considerations (see Chapter 3) related to potentially sensitive populations (such as fetuses and the elderly), possible human interindividual variability in response related to sex and genetic background, such lifestyle factors as level of exercise , underlying diseases, and VOC interactions. Nevertheless, as discussed in Chapter 3, rodents absorb a greater fraction of inhaled VOCs and metabolically activate a substantially greater proportion of their internal dose and are therefore more susceptible than humans to most adverse effects of TCE and PCE.

Chapter 2 summarizes the water-supply data available from the Tarawa Terrace and Hadnot Point water systems. Among the measurements with reported values, TCE concentration in mixed water samples from the Hadnot Point water supply ranged from 1 to 1,400 µg/L (see Table 2-11). Water samples with detectable PCE from the Tarawa Terrace water supply ranged from 1 to 215 µg/L (Maslia et al. 2007). Given the sparse information regarding the range and magnitude of contaminant concentrations in the Camp Lejeune water supply, values that correspond to half the highest measured value, the highest measured value, and twice the highest measured value were selected for this exercise: TCE at 700, 1,400, and 2,800 µg/L and PCE at 100, 200, and 400 µg/L.

The following calculation was carried out to obtain an estimate of human daily exposure: estimated human daily dose (mg/kg per day) = [mixed water concentration (µg/L) × estimated daily intake (oral, inhalation, and dermal) (L/day)]/[body weight (kg)]. A sample calculation follows. For Hadnot Point, the highest measured concentration of TCE in mixed water was 1,400 µg/L. For an adult human, the daily dose received from water containing TCE at 1,400 µg/L is estimated to be

$$\frac{1{,}400\ \mu g/L \times 4\ L/day}{70\ kg} = 80\ \mu g/kg\ per\ day = 0.08\ mg/kg\ per\ day.$$

Half the highest measured TCE concentration in the water supply (700 µg/L) yields an estimated dose of 0.04 mg/kg per day for adults, and twice the highest measured concentration of TCE (2,800 µg/L) yields

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an estimated dose of 0.2 mg/kg per day for adults. For a child, the daily dose received from water containing TCE at 1,400 µg/L is estimated to be

$$\frac{1{,}400\ \mu g/L \times 2\ L/day}{10\ kg} = 280\ \mu g/kg\ per\ day = 0.3\ mg/kg\ per\ day.$$

Half the highest measured TCE concentration in the water supply (700 µg/L) yields an estimated dose of 0.1 mg/kg per day for a child, and twice the highest measured concentration of TCE (2,800 µg/L) yields an estimated dose of 0.6 mg/kg per day for a child.

Table 4-3 shows the LOAELs from animal studies used to compare with the estimated human TCE doses related to a range of possible water-supply exposure concentrations. A comparison of LOAELs for health end points selected from TCE animal studies with the exposure estimates is summarized here:

- *Kidney cancer.* The LOAEL of TCE for lifetime oral exposure leading to kidney cancer in the rat is 1,000 mg/kg per day (NTP 1990a). The estimated human adult dose at Camp Lejeune is 25,000 times lower than the LOAEL for exposure at half the highest water-supply concentration, 12,500 times lower than the LOAEL for exposure at the highest concentration, and 5,000 time lower than the LOAEL for exposure at twice the highest concentration for a lifetime exposure. For a child, the comparable estimates are 10,000, 3,350, and 1,700 time lower than the LOAEL, respectively.
- *Renal toxicity.* The LOAEL of TCE for renal toxicity in the rat dosed orally for 13 weeks is 250 mg/kg per day (Mally et al. 2006). The estimated human adult dose at Camp Lejeune is 6,250 times lower than the LOAEL for exposure at half the highest water-supply concentration, 3,125 times lower than the LOAEL for exposure at the highest concentration, and 1,250 times lower than the LOAEL for exposure at twice the highest concentration. For a child, the comparable estimates are 2,500, 830, and 415 times lower than the LOAEL, respectively.
- *Immunosuppression.* The LOAEL of TCE for immunosuppression in a sensitive strain of mouse ingesting TCE for 4 or 6 months is 22 mg/kg per day (Sanders et al. 1982). The estimated human adult dose at Camp Lejeune is 550 times lower than the LOAEL for exposure at half the highest water-supply concentration, 275 times lower than the LOAEL for exposure at the highest concentration, and 110 times lower than the LOAEL for exposure at twice the highest concentration. For a child, the comparable estimates are 220, 75, and 40 times lower than the LOAEL, respectively. These differences are relatively smaller than for kidney cancer and kidney toxicity. As stated earlier in the chapter, uncertainties exist regarding this end point since there is relatively little toxicologic information on TCE and immune effects. Additional research may be needed on the potential immunosuppressive effects of TCE.

For PCE, the daily dose received from water at the maximum measured concentration (200 µg/L) in the water supply for an adult human is estimated to be

$$\frac{200\ \mu g/L \times 4\ L/day}{70\ kg} = 0.01\ mg/kg\ per\ day.$$

Exposure to half the highest measured water supply concentration (100 µg/L) yields a dose of 0.006 mg/kg per day for an adult human and exposure to twice the highest measured water supply concentration (400 µg/L) yields a dose of 0.02 mg/kg per day. For a child, the daily dose received from water containing PCE at the maximum measured concentration (200 µg/L) is estimated to be

$$\frac{200\ \mu g/L \times 2\ L/day}{10\ kg} = 0.04\ mg/kg\ per\ day.$$

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Exposure to half the highest measured water supply concentration (100 µg/L) yields a dose of 0.02 mg/kg per day for a child and exposure to twice the highest measured water supply concentration (400 µg/L) yields a dose of 0.08 mg/kg per day.

A comparison of LOAELs for each of the two health end points selected from PCE animal studies (Table 4-4) with the estimated doses from the water supply is summarized here:

- *Renal toxicity*. The LOAEL for renal toxicity in the rat dosed orally with PCE for 32 days is 600 mg/kg per day (Jonker et al. 1996). The estimated human adult dose at Camp Lejeune is 100,000 times lower than the LOAEL for exposure at half the highest water-supply concentration, 60,000 times lower than the LOAEL for exposure at the highest concentration, and 30,000 times lower than the LOAEL for exposure at twice the highest concentration. For a child, the estimates are 30,000, 15,000, and 7,500 times lower than the LOAEL, respectively.
- *Neurotoxicity*. The LOAEL of PCE for neurotoxic effects in rats is 50 mg/kg per day for 8 weeks (Chen et al. 2002). The estimated human adult dose at Camp Lejeune is 8,300 times lower than the LOAEL for exposure at half the highest water-supply concentration, 5,000 times lower than the LOAEL for exposure at the highest concentration, and 2,500 times lower than the LOAEL for exposure at twice the highest concentration. For a child, the comparable estimates are 2,500, 1,250, and 625 times lower than the LOAEL, respectively. As noted earlier in this chapter, there is a need for additional research to clarify the neurotoxic effects of PCE.

The comparisons above included health end points observed in animals that were considered relevant to humans. Renal toxicity and cancer, neurotoxicity, and immune-related effects have been reported in some epidemiology studies and in clinical reports. The dose comparisons[1] suggest considerable differences between the estimated doses from human exposure to contaminated water supplies at Camp Lejeune under conservative assumptions of exposure and the lowest doses associated with the development of renal toxicity, kidney cancer, neurotoxicity, and immunosuppression in rodents. The drinking-water doses at Camp Lejeune are substantially lower. As pointed out in this section, however, each and

[1]One member, Lianne Sheppard, objected to inclusion of the hazard evaluation in the report as written and offered the following explanation: "Comparison of toxicology-based LOAEL values with estimated exposures to the Camp Lejeune population uses questionable logic to support inference that adverse health effects are unlikely to have occurred. Although LOAEL estimates give evidence about the presence of a hazard, they should not be used to make inference about the absence of hazard at lower doses. The absence of evidence of a hazard (e.g., at levels below the LOAEL) cannot be equated with evidence of the absence of hazard (Altman and Bland 1995; Fleming 2008). Because of their small sample size, animal studies are only able to identify hazards that induce high levels of response (on average 10% increase in response for the LOAEL). Moreover, levels of excess response considered acceptable in humans are much lower than 1 in 10, typically on the order of 1 in 10,000 to 1 in 1 million (EPA 2005). While low-dose extrapolation involves additional untestable assumptions, dividing the LOAELs by 1,000 to 100,000 provides an alternative approach to the informal hazard evaluation presented above. This second approach compares Camp Lejeune exposures with an acceptable hazard in humans, as extrapolated from toxicologic studies. The results lead to strikingly different conclusions because they yield acceptable hazards that are both larger and smaller than the estimated exposures; indeed, some are several orders of magnitude lower than Camp Lejeune exposures. Alternatively, standard practice would replace informal hazard evaluation with a formal risk assessment, although this task was outside the committee charge. Despite my reservations on this one area of the assessment, I support the overarching findings and recommendations of the report."

Other members disagree with Dr. Sheppard's characterization that the hazard evaluation is based on questionable logic. The reasons for this are stated in the text. The validity of results using the approach she outlines above is questioned by some committee members. There were varying views among committee members on the value of the information generated by the hazard evaluation effort, ranging from members who found it quite useful because it provided a rough benchmark for speculating about the likelihood of adverse health effects, to members who placed less reliance on results, given limited exposure information and their uncertainty about the applicability of toxicologic information. Regardless of the approach taken to the hazard evaluation, however, all committee members strongly support the overarching findings and recommendations of the report.

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Contaminated Water Supplies at Camp Lejeune: Assessing Potential Health Effects

every source of uncertainty (e.g., interindividual variability, lifestyle, genetic background, exposure assessment, completeness of the database) has not been factored into this estimate since it is a hazard evaluation procedure and not a health risk assessment.

ALLOWABLE LIMITS OF VOLATILE ORGANIC COMPOUNDS IN DRINKING WATER

Current regulatory standards termed maximum contaminant levels (MCLs) for several VOCs in drinking water, including TCE and PCE, were developed by EPA in the middle 1980s (50 Fed. Reg. 46880 [1985]; 52 Fed. Reg. 25690 [1987]; Cotruvo 1988). Under the U.S. Safe Drinking Water Act, the public-health goal or maximum contaminant level goal (MCLG) for a compound was initially determined. The MCLG is the concentration that would result in "no known or anticipated adverse effect on health" with a large margin of safety. Second, an MCL, or enforceable standard, was set as close as feasible to the MCLG; technical and economic factors were taken into consideration. EPA consulted the International Agency for Research on Cancer guidelines when assessing epidemiologic and animal cancer data and in its own qualitative weight-of-evidence scheme for determining the potential for a compound to increase cancer risk in humans. TCE and PCE fell into category I in the latter scheme, in which the MCLG by definition equals zero as an aspirational goal. Economic considerations for water treatment were also deliberated. Technical feasibility focused on analytic considerations; the lowest concentrations that can be reliably detected within specified limits of precision and accuracy during routine laboratory operations (practical quantitation limits) were determined. With that approach, an MCL of 0.005 mg/L (5 µg/L or 5 ppb) was set for selected VOCs, including TCE and PCE.

In 2005, EPA issued new guidelines for carcinogen risk assessment in which incorporation of increased scientific understanding of the biologic mechanisms that can cause cancer was supported for inclusion in risk assessments with other improved risk-assessment practices (EPA 2005). In the more than 20 years since the original MCLs were established, considerable kinetic and biologic mechanism-of-action information on TCE and PCE has been published, as reviewed in the present report. There are different approaches to risk assessment that yield different results. At least one recent study has explored different approaches, including the use of contemporary published elements of TCE's biologic mode of action and a cancer-risk model that was the best fit to the data (Clewell and Andersen 2004). The latter approach yielded a TCE concentration of 265 µg/L in drinking water; below this concentration, a carcinogenic hazard to human health was deemed unlikely. This is one example of the possible application of toxicologic and mechanistic biologic data to a cancer health risk assessment for TCE, which yields a value greater than one based on analytical limits of detection. EPA is currently updating its risk assessments on TCE and PCE and is considering new data and different assessment approaches as part of its reassessments. In summary, the few TCE and PCE measurements available from mixed drinking-water samples at Camp Lejeune (see Chapter 2) indicated that some samples exceeded the MCLs derived as briefly described above.

CONCLUSIONS

TCE and PCE are well-studied compounds compared with most other compounds of environmental concern. On the basis of the review presented above, the committee concludes that the strongest evidence of health effects of relevance to humans are renal toxicity, kidney cancer, neurobehavioral effects, and immunologic effects, which have generally been observed at high concentrations in a workplace setting and in exposure to tens to thousands of milligrams per kilogram of body weight in animal studies. Discussion of the toxicologic evidence in context with the epidemiologic evidence on TCE and PCE (presented in Chapter 5) is provided in Chapter 7. The evidence on renal toxicity and cancer is particularly convincing because concordance has been found in the bioactivation of TCE and PCE and in their modes of action in rodents and humans. However, gaps in the toxicologic database preclude drawing conclusions about some other health effects related to the nervous system and the immune system, par-

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ticularly with regard to potential effects on the developing or young animal. Implicit inherent limitations of toxicologic studies are that relatively homogeneous populations of laboratory animals are used and exposures are typically to single chemicals. On average, the lowest increase in effect that can usually be detected (LOAEL) is around 10% due to statistical power related to the number of animals that can be tested in any one study. In the instances of TCE and PCE, however, rodents are more susceptible to toxic effects.

A central issue in toxicology (and at Camp Lejeune) is whether doses were sufficient to produce specific adverse effects. The lowest doses at which adverse health effects have been seen in animal or clinical studies are many times higher than the worst-case (highest) assumed exposures at Camp Lejeune. However, that does not rule out the possibility that other, more subtle health effects that have not been well studied could occur, although it somewhat diminishes their likelihood.

Another important issue is whether any adverse effects that may have occurred were reversible or permanent and (still) detectable when an epidemiology study might be conducted. Observations in animal studies indicate that very high acute or chronic doses of TCE or PCE are necessary to injure renal proximal tubular cells. Results of occupational-exposure studies indicate that relatively high, chronic exposures result in modest, reversible changes in the most sensitive indexes of renal injury in workers. Thus, it is unlikely that renal toxicity would be a useful end point to examine in future epidemiology study of Camp Lejeune residents. A similar conclusion can be drawn with regard to the occurrence and detection of hepatic toxicity. Reproductive and developmental effects in rodents were quite modest and often secondary to general toxicity, decreased food intake, and reduced body-weight gain resulting from high maternal doses of TCE and PCE. The toxicologic data provide strong evidence that neither solvent is associated with congenital malformations in rats. Thus, on the basis of this review, reproductive effects and hepatorenal toxicity are probably not of great concern at Camp Lejeune.

There is reasonable interspecies concordance between rats and humans in the bioactivation of TCE and PCE and in their mode of induction of kidney cancer. A low incidence of kidney cancer has been seen in workers exposed for many years to TCE at concentrations high enough to cause dizziness, headache, and other reversible neurologic effects. The background incidence of kidney cancers in unexposed persons is minimal. Nevertheless, there is little likelihood of identifying any increased incidence of renal tumors in the relatively small population that may be available for study at Camp Lejeune.

Irreversible neurobehavioral effects associated with solvent exposure generally are chronic and result from high doses. Solvent abusers and workers chronically exposed to high vapor concentrations may exhibit various neurobehavioral effects and residual brain damage. Fetuses, infants, and young children exposed to such organic solvents as TCE and PCE at lower concentrations may experience subtle neurodevelopmental effects, but no relevant investigations were identified. There are few data from animal studies on this topic.

Immune suppression and autoimmunity related to TCE exposure have been demonstrated in some sensitive animal models. TCE-induced glomerulonephritis and scleroderma occur in low incidences in highly exposed worker populations. Much less is known about the potential immunologic effects of PCE (particularly as related to exposures during development), which may warrant further consideration for inclusion in studies of populations exposed to TCE or PCE.

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5

Review of Epidemiologic Studies

This chapter reviews a large body of epidemiologic literature on specific drinking-water contaminants at Camp Lejeune, focusing primarily on trichloroethylene (TCE) and tetrachloroethylene (perchloroethylene, PCE). Most of the literature involves populations exposed occupationally to those solvents and other industrial chemicals. The goal is to determine whether exposure to TCE or PCE is associated with specific health outcomes. (Appendix D provides brief reviews of the epidemiologic literature on the six additional drinking-water contaminants identified in Chapter 2 as of possible concern—vinyl chloride, 1,1-dichloroethylene, 1,2-dichloroethylene, methylene chloride, benzene, and toluene.) Chapter 6 gives special consideration to studies of other communities whose populations and exposure to contaminants in drinking water are similar to those at Camp Lejeune. Chapter 7 provides an integrated discussion of the epidemiologic evidence in context with the toxicologic evidence on TCE and PCE presented in Chapter 4. Epidemiologic studies of former residents of Camp Lejeune are reviewed separately in Chapter 8.

EVALUATING THE EPIDEMIOLOGIC LITERATURE

To manage the review of the vast literature on the chemicals of concern at Camp Lejeune, the committee decided to use a categorization approached developed by the Institute of Medicine (IOM) for evaluating epidemiologic data on chemicals. The approach involves a comprehensive review of the epidemiologic literature on individual chemicals and assigning one of five categories to the evidence (see Box 5-1 for IOM's categories of association). An assessment of whether the data indicate a *statistical association* between the chemicals and various cancer and noncancer health outcomes is the basis for the categorizations, except for the highest category of sufficient evidence of a causal relationship, which is also based on experimental data and evidence of causality. IOM's approach has been used to evaluate exposure of veterans of the Vietnam War (IOM 1994, 1996, 1999) and the Gulf War (IOM 2003).

Statistical associations are generally estimated by calculating relative risks (RRs) or odds ratios (ORs). In our review, a "statistical association" does not imply that the measure of association is statistically significant or causal, only that an association of potential interest has been reported. The committee reviewed the conclusions of each study in light of its strengths and weaknesses, taking into account the strength of the association (the magnitude of the OR or RR estimate), the influence of exposure-measurement error, selection bias, statistical precision, and confounding bias. The coherence of the epidemiologic evidence was then assessed, and an assignment made to a category of association.

In the sections below, the committee used the conclusions drawn by IOM (2003) on cancer and noncancer health end points of TCE or PCE exposure as a starting point for its evaluation. Literature searches were performed on Medline to identify new (2003-2008) peer-reviewed epidemiologic studies of exposure to TCE, PCE, or mixtures of chlorinated solvents and various health outcomes. The committee weighed the strengths and weaknesses of the new evidence to draw conclusions about whether IOM's

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BOX 5-1 Five Categories Used by IOM to Classify Associations (IOM 2003)

Sufficient Evidence of a Causal Relationship

Evidence from available studies is sufficient to conclude that a causal relationship exists between exposure to a specific agent and a specific health outcome in humans, and the evidence is supported by experimental data. The evidence fulfills the guidelines for sufficient evidence of an association (below) and satisfies several of the guidelines used to assess causality: strength of association, dose-response relationship, consistency of association, biologic plausibility, and a temporal relationship.

Sufficient Evidence of an Association

Evidence from available studies is sufficient to conclude that there is a positive association. A consistent positive association has been observed between exposure to a specific agent and a specific health outcome in human studies in which chance and bias, including confounding, could be ruled out with reasonable confidence. For example, several high-quality studies report consistent positive associations, and the studies are sufficiently free of bias, including adequate control for confounding.

Limited/Suggestive Evidence of an Association

Evidence from available studies suggests an association between exposure to a specific agent and a specific health outcome in human studies, but the body of evidence is limited by the inability to rule out chance and bias, including confounding, with confidence. For example, at least one high-quality study reports a positive association that is sufficiently free of bias, including adequate control for confounding. Other corroborating studies provide support for the association, but they were not sufficiently free of bias, including confounding. Alternatively, several studies of less quality show consistent positive associations, and the results are probably not due to bias, including confounding.

Inadequate/Insufficient Evidence to Determine Whether an Association Exists

Evidence from available studies is of insufficient quantity, quality, or consistency to permit a conclusion regarding the existence of an association between exposure to a specific agent and a specific health outcome in humans.

Limited/Suggestive Evidence of No Association

Evidence from well-conducted studies is consistent in not showing a positive association between exposure to a specific agent and a specific health outcome after exposure of any magnitude. A conclusion of no association is inevitably limited to the conditions, magnitudes of exposure, and length of observation in the available studies. The possibility of a very small increase in risk after exposure studied cannot be excluded.

categorizations are still valid or should be changed. Each health-outcome section below brief summarizes the evidence as described in the 2003 IOM report, reviews the new evidence, and presents conclusions drawn from the totality of the epidemiologic evidence. Appendix E presents tables of details on each of the new studies. Whenever possible, the committee evaluated the associations between TCE or PCE and the end points and reported findings specifically on those solvents. If a study addressed solvent mixtures, the evidence was examined and a category of association was determined with the default presumption that there was not information specifically on TCE or PCE. The committee expands on IOM's approach in Chapter 7 by explicitly considering how the toxicologic evidence presented in Chapter 4 adds to the weight of evidence in characterizing health risks related to the TCE and PCE.

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STUDIES OF TRICHLOROETHYLENE AND PERCHLOROETHYLENE

Cancer End Points

Oral and Pharyngeal Cancer

IOM 2003 Conclusions

IOM (2003) found little evidence of a consistent association between chronic exposure to PCE and an increased risk of oral or pharyngeal cancer ("oral cancer"). The studies evaluated often involved only a small number of exposed persons. No studies specifically assessed TCE in relation to oral cancer, and no increase in risk was found in connection with solvent mixtures. IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between chronic exposure to solvents and oral cancer.

2008 Evaluation

The updated literature on TCE and oral cancer included five cohort studies with cancer incidence or mortality data (Hansen et al. 2001; Chang et al. 2003, 2005; Raaschou-Nielsen et al. 2003; Boice et al. 2006; Sung et al. 2007). Two studies of Danish workers (Hansen et al. 2001; Raaschou-Nielsen et al. 2003) evaluated the risk of oral cancer. Hansen et al. found an increased risk in exposed male workers based on only seven exposed cases. In the larger study by Raaschou-Nielsen et al. (2003), a standard incidence ratio (SIR) of 1.8 (95% confidence interval [CI], 0.84-3.24) was found for women employed at least 3 mo; the SIR for men (95 exposed cases) was only 1.1 (95% CI, 0.90-1.36). Other studies of workers in different industries did not report a consistently increased risk, although most involved only a small number of exposed persons. There was an indication of an increased risk in women potentially exposed to TCE in the Raaschou-Nielsen study, but the totality of the evidence does not indicate a consistent pattern of increased risk in TCE-exposed persons.

The updated literature on PCE and oral cancer included two cohort studies with cancer mortality or incidence data (Blair et al. 2003; Chang et al. 2003, 2005). Neither study reported an increased risk posed by PCE exposure, but they involved only small numbers of exposed persons.

- The updated literature on PCE and TCE continues to support a conclusion that there is inadequate/insufficient evidence to determine whether an association exists between chronic exposure to these solvents and oral cancer.

Nasal Cancer

IOM 2003 Conclusions

IOM (2003) found no studies that specifically evaluated TCE or PCE but reviewed a few studies that examined other solvents and nasal cancer. Increased but imprecise RR estimates were found in a Chinese study of benzene exposure and a study of shoemakers in England and France (Fu et al. 1996; Yin et al. 1996). IOM concluded that the evidence was inadequate/insufficient to determine whether an association exists between chronic exposure to solvents and oral cancer.

2008 Evaluation

No new studies of chronic exposure to solvents and nasal cancer were found.

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- There continues to be inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE or PCE and nasal cancer.

Laryngeal Cancer

IOM 2003 Conclusions

Two studies (Blair et al. 1990; Vaughan et al. 1997) found an increased but imprecise risk posed by PCE and dry-cleaning solvents. IOM (2003) concluded that there was inadequate/insufficient evidence to determine whether an association exists between chronic exposure to PCE, TCE, or other solvents and laryngeal cancer.

2008 Evaluation

The updated literature on TCE and laryngeal cancer included four cohort studies with cancer incidence or mortality data (Hansen et al. 2001; Chang et al. 2003; Raaschou-Nielsen et al. 2003; Boice et al. 2006; Sung et al. 2007). One study of Danish workers (Raaschou-Nielsen et al. 2003) found an SIR of 1.7 (95% CI, 0.33-4.82) for women employed at least 3 months (on the basis of three exposed cases); the SIR for men was 1.2 (95% CI, 0.87-1.52) on the basis of 53 exposed cases. Boice et al. (2006) reported a standardized mortality ratio (SMR) of 1.45 (95% CI, 0.18-5.25) on the basis of two exposed cases.

The updated literature on PCE and laryngeal cancer included two cohort studies with cancer mortality data (Blair et al. 2003; Chang et al. 2003). Blair et al. (2003) performed an updated mortality assessment of a cohort of dry cleaners and found an increased risk in workers with medium to high exposure (SMR, 2.7; 95% CI, 1.0-5.8) on the basis of only six exposed cases. Chang et al. (2003) did not find any exposed cases in a Taiwanese cohort of electronics manufacturing workers.

- The updated literature on TCE and PCE continues to support a conclusion that there is inadequate/insufficient evidence to determine whether an association exists between chronic exposure to these solvents and laryngeal cancer.

Esophageal Cancer

IOM 2003 Conclusions

IOM (2003) considered evidence from several cohort and case-control studies of esophageal cancer in relation to chronic exposure to solvents, including TCE and PCE. Although several studies had positive results (Blair et al. 1990; Vaughan et al. 1997; Boice et al. 1999; Ruder et al. 2001), IOM was unable to reach a consensus on PCE but concluded that there was inadequate/insufficient evidence to determine whether an association exists between TCE and other solvents and solvent mixtures and esophageal cancer.

2008 Evaluation

The new literature on TCE and esophageal cancer included an update on the Danish worker cohort (Raaschou-Nielsen et al. 2003) and three cohorts studies with cancer incidence or mortality data (Chang et al. 2003; Zhao et al. 2005; Boice et al. 2006; Sung et al. 2007). One study of Danish workers (Raaschou-Nielsen et al. 2003) found an SIR of 1.9 for men employed at least 3 months. Other studies did not find a pattern of increased risk.

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The updated literature on PCE and esophageal cancer included two cohort studies with cancer mortality data and one case-control study (Blair et al. 2003; Chang et al. 2003; Lynge et al. 2006). Blair et al. (2003) performed an updated mortality assessment of a cohort of dry cleaners and found an increased risk in workers (SMR, 2.2; 95% CI, 1.5-3.3) on the basis of 26 exposed cases. No exposure-response pattern of increased risk was found when results were examined by exposure group. Chang et al. (2003) did not find any exposed cases in a Taiwanese cohort of electronics manufacturing workers, and Lynge et al. (2006) found a decreased risk.

- The updated literature on TCE continues to support a conclusion that there is inadequate/insufficient evidence to determine whether an association exists between chronic exposure to the solvent and esophageal cancer.
- On the basis of the results of the Blair et al. (2003) study of dry cleaners and other studies, the committee concludes that there is limited/suggestive evidence of an association between chronic exposure to PCE and esophageal cancer. This constitutes a new conclusion, in that a consensus was not reached in the 2003 IOM report.

Stomach Cancer

IOM 2003 Conclusions

IOM (2003) reviewed five occupational-cohort studies assessing the association between TCE and stomach cancer (Wilcosky et al. 1984; Anttila et al. 1995; Blair et al. 1998; Boice et al. 1999; Hansen et al. 2001). A study of Finnish workers biologically monitored for exposure (on the basis of urinary trichloroacetic acid) showed an increased risk of stomach cancer (SIR, 1.28; 95% CI, 0.75-2.04), and the risk was greater in workers who had their first measurement 20 years before (SIR, 2.98; 95% CI, 1.20-6.13). However, there was no evidence of an exposure-response relationship with urinary trichloroacetic acid concentrations (Anttila et al. 1995). The overall conclusions drawn from the other studies were mixed. Similarly, the results of the three cohort studies of PCE-exposed populations were mixed (SMR, 0.61-1.42) (Blair et al. 1990; Ruder et al. 1994; Boice et al. 1999). Results of three mortality cohort studies (Garabrant et al. 1988; Costantini et al. 1989; Acquavella et al. 1993) and a case-control study (Ekstrom et al. 1999) of workers exposed to unspecified mixtures of organic solvents and a cohort study of Swedish patients with acute solvent-related disorders (Berlin et al. 1995) were predominantly null except for increased risk of stomach cancer in a cohort of shoemakers in England and Florence (Fu et al. 1996). IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between chronic exposure to the solvents reviewed and stomach cancer.

2008 Evaluation

The committee identified several new cohort studies of occupational groups exposed to TCE or PCE (Blair et al. 2003; Chang et al. 2003, 2005; Raaschou-Nielsen et al. 2003; Boice et al. 2006; Sung et al. 2007). The reported results on stomach cancer were mixed, as were those in the IOM (2003) report. However, in a case-control study of a community living downstream of an electronics factory and potentially exposed to PCE, the mortality odds ratio (MOR) for stomach cancer was increased (2.18; 95% CI, 0.97-4.89) (Lee et al. 2003).

- The updated literature on TCE and PCE continues to support a conclusion that there is inadequate/insufficient evidence to determine whether an association exists between chronic exposure to these solvents and stomach cancer.

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Colon Cancer

IOM 2003 Conclusions

IOM (2003) reviewed five cohort studies with incidence or mortality data (Anttila et al. 1995; Blair et al. 1998; Boice et al. 1999; Hansen et al. 2001) and one case-control study (Fredriksson et al. 1989) on the association between TCE exposure and colon cancer. The Blair et al. study showed a positive association between TCE exposure and both mortality and incidence, but there was evidence of an exposure-response relationship only between years of work and incidence (Blair et al. 1998). The results of the other studies were mixed, and IOM was not able to reach a consensus opinion about chronic exposure to TCE and colon cancer. For PCE, IOM included one cohort study of intestinal-cancer mortality in dry cleaners (Ruder et al. 2001) and two case-control studies—one defining exposure on the basis of work as a dry cleaner (Fredriksson et al. 1989) and the other on the basis of exposure to contaminated drinking water on Cape Cod (Paulu et al. 1999). The results showed evidence of increased risk, but there was no evidence of an exposure-response relationship, the numbers were small, and diseases were not well defined. Therefore, IOM concluded that the literature was inadequate/insufficient to determine whether an association exists between PCE exposure and colon cancer. IOM also reviewed three studies of unspecified mixtures of organic solvents (Fredriksson et al. 1989; Anttila et al. 1995; Berlin et al. 1995). Increased risks were observed only in the Fredriksson study, and in all three the numbers of exposed cases were small. IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between chronic exposure to unspecified solvents and colon cancer.

2008 Evaluation

The updated literature on TCE and colon cancer includes six occupational-cohort studies with incidence or mortality data on colon cancer or colon and rectal cancer. In most studies, the SIRs or SMRs were around 1.1 (Raaschou-Nielson et al. 2003; Boice et al. 2006; Sung et al. 2007). Zhao et al. (2005) assessed incidence and mortality in a cohort of aerospace workers. The SMRs were also around 1.1, but the SIRs were not increased, and there was no evidence of an exposure-response relationship (exposure was defined by an industrial-hygiene review). In a study of test-stand mechanics determined by an industrial-hygiene review to be exposed to TCE, the SMR was 1.66 (95% CI, 0.54-3.87) (Boice et al. 2006). A study of electronics and mechanical workers in Taiwan exposed to TCE and PCE found an SMR of 1.36 (95% CI, 0.82-2.13) on the basis of 19 cases (Chang et al. 2003). In an incidence study of the same population, there was no clear evidence of an association (Chang et al. 2005). Two studies of community exposures to TCE and PCE in drinking water did not find increased risks of colon cancer (Morgan and Cassady 2002; Lee et al. 2003). IOM also reviewed one cohort of dry cleaners exposed to PCE (Blair et al. 2003). The SMR was 1.2 (95% CI, 0.9-1.5) and there was some evidence of an exposure-response relationship. No new studies on exposure to unspecified mixtures of organic solvents and colon cancer were found.

- The committee concludes that there is inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE or PCE and colon cancer. The conclusion regarding TCE constitutes a new conclusion, in that a consensus was not reached in the 2003 IOM report.

Rectal Cancer

IOM 2003 Conclusions

IOM (2003) reviewed five cohort studies with incidence or mortality data (Anttila et al. 1995;

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Blair et al. 1998; Morgan et al. 1998; Boice et al. 1999; Hansen et al. 2001) and one case-control study (Dumas et al. 2000) on the association between exposure to TCE and rectal cancer. Although increased risks were observed in all but the Blair et al. study, the numbers of cancers in exposed persons were small, no more than 12 in each study. IOM included two studies in its review of PCE and dry-cleaning solvents: a cohort study of intestinal cancer in dry-cleaning workers (Ruder et al. 2001) and a study of colon and rectal cancer in Cape Cod residents exposed to contaminated water (Paulu et al. 1999). Both studies were discussed above under "Colon Cancer." Three cohort studies assessed the incidence of or mortality from rectal cancer and exposure to unspecified mixtures of organic solvents (Garabrant et al. 1988; Anttila et al. 1995; Berlin et al. 1995). Excess risks were observed only in the Anttila et al. study. IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE, PCE, or solvent mixtures and rectal cancer.

2008 Evaluation

The updated literature on TCE and rectal cancer included two cohort studies. Raaschau-Nielsen et al. (2003) observed SIRs of 1.1 in men and women working in jobs involving TCE exposure. Chang et al. (2003) assessed mortality in a cohort of electronics manufacturers exposed to TCE and PCE. On the basis of only 15 exposed cases (13 in women and two in men), the SMR for women was increased (1.67; 95% CI, 0.89-2.85), but the SMR for men was not (0.73; 95% CI, 0.08-2.65). An additional cohort study reported an increased risk of rectal-cancer mortality in dry cleaners (SMR, 1.3; 95% CI, 0.7-2.2) (Blair et al. 2003).

- The updated literature on TCE and PCE continues to support a conclusion that there is inadequate/insufficient evidence to determine whether an association exists between chronic exposure to these solvents and rectal cancer.

Pancreatic Cancer

IOM 2003 Conclusions

IOM (2003) reviewed five occupational-cohort studies with incidence or mortality data on the association between TCE exposure and pancreatic cancer (Anttila et al. 1995; Blair et al. 1998; Morgan et al. 1998; Boice et al. 1999; Hansen et al. 2001). The results were mixed, and there was no evidence of an exposure-response relationship. The Anttila et al. study also assessed exposure to PCE, dry-cleaning solvents, and unspecified mixtures of organic solvents and observed increased SIRs. Ruder et al. (2001) observed increased SMRs in 18 exposed dry-cleaning labor-union workers. IOM reviewed an additional case-control study (Kauppinen et al. 1995) and six mortality cohort studies of exposure to unspecified mixtures of organic solvents (McMichael et al. 1976; Pippard and Acheson 1985; Garabrant et al. 1988; Costantini et al. 1989; Acquavella et al. 1993; Fu et al. 1996). The numbers of exposed cases were small, and the results were mixed. IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE, PCE, or other solvents and pancreatic cancer.

2008 Evaluation

The updated literature on TCE and pancreatic cancer included five cohort studies with cancer incidence or mortality data (Chang et al. 2003; Raaschou-Nielsen et al. 2003; Zhao et al. 2005; Boice et al. 2006; Sung et al. 2007). Two studies of electronics workers (Chang et al. 2003; Sung et al. 2007) reported

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increased risk of pancreatic cancer in women, but the number of cases was small (16 in the two studies combined), and in one study TCE exposure was not distinguished from PCE exposure (Chang et al. 2003). Two studies of dry cleaners with data on PCE exposure and pancreatic cancer were identified; the SMR in a cohort study was 1.1 (95% CI, 0.7-1.5) (Blair et al. 2003), and the OR in a case-control study was 1.27 (95% CI, 0.90-1.80) (Lynge et al. 2006).

- The updated literature on TCE and PCE continues to support a conclusion that there is inadequate/insufficient evidence to determine whether an association exists between chronic exposure to these solvents and pancreatic cancer.

Hepatobiliary Cancer

IOM 2003 Conclusions

IOM (2003) did not find a consistent association between chronic exposure to TCE, PCE, or unspecified mixtures of organic solvents and an increased risk of hepatobiliary cancer (liver cancer and cancers of the gallbladder and biliary tract). IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between chronic exposure to solvents and hepatobiliary cancer.

2008 Evaluation

The updated literature on TCE and hepatobiliary cancer included five cohort studies with incidence or mortality data (Morgan and Cassady 2002; Chang et al. 2003; Raaschou-Nielsen et al. 2003; Boice et al. 2006; Sung et al. 2007) and one case-control study (Lee et al. 2003). The updated Danish study of workers with TCE exposure showed some increased SIRs for women (for example, 2.8 and a 95% CI of 1.13-5.80 for women employed at least 3 months; seven cases in exposed people), but most estimates were based on small numbers of cases in exposed people (Raaschou-Nielsen et al. 2003). The updated literature on PCE and hepatobiliary cancer included three cohort studies with cancer incidence or mortality data (Morgan and Cassady 2002; Blair et al. 2003; Chang et al. 2003) and two case-control studies (Lee et al. 2003; Lynge et al. 2006). Lynge et al. (2006) reported an RR of 0.76 (95% CI, 0.38-1.52) in a cohort of Nordic dry-cleaning workers. The case-control study by Lee et al. (2003) of a Taiwanese community exposed to solvents from an electronics factory reported an increased MOR for men (2.57; 95% CI, 1.21-5.46), but the exposure assessment was weak.

- The updated literature on TCE and PCE continues to support a conclusion that there is inadequate/insufficient evidence to determine whether an association exists between chronic exposure to these solvents and hepatobiliary cancer.

Lung Cancer

IOM 2003 Conclusions

IOM (2003) determined that the cohort and case-control studies of TCE and lung cancer were limited by exposure assessment and inadequate control for confounding factors, especially smoking. The studies generally did not show any increased risk, so the evidence regarding chronic exposure to TCE and lung cancer was considered inadequate/insufficient for determining whether an association exists. Although several studies of PCE exposure had positive results (Blair et al. 1990; Brownson et al. 1993; Anttila et al. 1995; Paulu et al. 1999; Pohlabeln et al. 2000; Ruder et al. 2001), IOM was unable to reach a

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consensus, because of some committee members' concerns regarding confounding by cigarette-smoking and the small numbers of exposed persons.

2008 Evaluation

The updated literature on TCE and lung cancer included seven cohort studies with lung-cancer incidence or mortality data (Hansen et al. 2001; Morgan and Cassady 2002; Chang et al. 2003, 2005; Raaschou-Nielsen et al. 2003; Zhao et al. 2005; Boice et al. 2006; Sung et al. 2007) and one case-control study (Lee et al. 2003). The new papers on PCE and lung cancer include three cohort studies (Morgan and Cassady 2002; Blair et al. 2003; Chang et al. 2003, 2005) and a case-control study (Lee et al. 2003). The updated Danish study of workers with TCE exposure (Raaschou-Nielsen et al. 2003) found increased SIRs for men and women (for example, 1.9 with a 95% CI of 1.48-2.35 for women employed at least 3 months), although there was no appearance of a trend with years of employment. Other studies did not report an increased risk with TCE exposure. The small number of studies of PCE exposure generally showed no increase in risk. However, the Blair et al. (2003) updated mortality analysis of dry cleaners showed increased SMRs, including an SMR of 1.5 (95% CI, 1.2-1.9) for workers with presumed medium or high PCE exposure. On the basis of the strengths of that study, including its size and exposure assessment, and the previous studies that had positive results, the committee determined that the evidence of an association was limited/suggestive.

- The updated literature on TCE continues to support a conclusion that there is inadequate/insufficient evidence to determine whether an association exists between chronic exposure to that solvent and lung cancer.
- On the basis of new data, the committee concludes that there is limited/suggestive evidence of an association between chronic exposure to PCE and lung cancer. This constitutes a new conclusion, in that a consensus was not reached in the 2003 IOM report.

Bone Cancer

IOM 2003 Conclusions

IOM (2003) identified one cohort study that reported on the association between occupational exposure to TCE and bone cancer (Blair et al 1998). On the basis of five exposed cases, the SMR was 2.1 (95% CI, 0.2-18.8). Two cohort studies reported on incidence of (Nielsen et al. 1996) or mortality from (Fu et al. 1996) bone cancer after occupational exposure to unspecified mixtures of organic solvents. Increased risks were reported, but a total of only seven exposed cases were identified. There were no studies of the association of PCE with bone cancer. Because of the small number of studies and the unstable estimates, IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE, PCE, or other solvents and bone cancer.

2008 Evaluation

The committee found two cohort studies that yielded no evidence of an association between occupational exposure to TCE and bone-cancer incidence (three cases in exposed people) (Sung et al. 2007) or bone-cancer mortality (no cases in exposed people) (Boice et al. 2006). In a mortality study of electronics workers with indeterminate exposure to TCE and PCE, the SMR was 1.63 (95% CI, 0.44-4.18) on the basis of four cases in exposed people (Chang et al. 2003). In an incidence study of the same population, the SIR in female workers (six cases in exposed people) was 1.28 (05% CI, 0.47-2.78) (Chang et al. 2005). Only one male worker was exposed.

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- The updated literature on TCE and PCE continues to support a conclusion that there is inadequate/insufficient evidence to determine whether an association exists between chronic exposure to these solvents and bone cancer.

Soft-Tissue Sarcoma

IOM 2003 Conclusions

IOM (2003) could not draw any conclusion regarding an association between chronic exposure to solvents and soft-tissue sarcoma because of the lack of available studies (only one study was identified).

2008 Evaluation

The updated literature on soft-tissue sarcoma included a cancer-mortality study (Chang et al. 2003) and an incidence analysis (Chang et al. 2005) of a cohort of workers in a Taiwanese electronics factory exposed to TCE and PCE. The mortality analysis did not find any deaths from connective-tissue and other soft-tissue cancer. The incidence study found an increased but imprecise SIR for connective-tissue and other soft-tissue cancer in men (1.43; 95% CI, 0.29-4.17); no increase in risk was found in women.

- The committee concludes that there is inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE or PCE and soft-tissue sarcoma. This constitutes a new conclusion, in that no conclusion was drawn in the 2003 IOM report.

Melanoma

IOM 2003 Conclusions

IOM (2003) concluded that there was inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE, PCE, or unspecified mixtures of solvents and melanoma.

2008 Evaluation

The updated literature on TCE and melanoma included seven cohort studies with cancer incidence or mortality data (Hansen et al. 2001; Morgan and Cassady 2002; Chang et al. 2003, 2005; Raaschou-Nielsen et al. 2003; Boice et al. 2006; Sung et al. 2007). The updated publications on PCE and melanoma included three cohort studies (Morgan and Cassady 2002; Blair et al. 2003; Chang et al. 2003). The study by Morgan and Cassady found a significantly increased SIR for residents in a community exposed to drinking water contaminated with TCE and PCE (SIR, 1.42; 99% CI, 1.13-1.77), but the authors attributed the observation to the high socioeconomic status (SES) of the residents of the community. The incidence patterns of other cancers in the community—especially those of lung, colorectal, and uterine cancer—appeared to be consistent with and supportive of the authors' explanation. None of the other studies reported an increased risk of melanoma in those exposed to TCE or PCE.

- The updated literature on TCE and PCE continues to support a conclusion that there is inadequate/insufficient evidence to determine whether an association exists between chronic exposure to these solvents and melanoma.

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Nonmelanoma Skin Cancer

IOM 2003 Conclusions

IOM (2003) concluded that there was inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE, PCE, or unspecified mixtures of solvents and non-melanoma skin cancer.

2008 Evaluation

No studies of TCE or PCE and nonmelanoma skin cancer were identified.

- There continues to be inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE or PCE and nonmelanoma skin cancer.

Breast Cancer

IOM 2003 Conclusions

IOM (2003) concluded that there was inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE, PCE, or unspecified mixtures of organic solvents and breast cancer. Results of occupational-cohort studies of breast-cancer risk were mixed (Garabrant et al. 1988; Shannon et al. 1988; Blair et al. 1990, 1998; Anttila et al. 1995; Morgan et al. 1998; Boice et al. 1999; Hansen et al. 2001; Ruder et al. 2001). Those studies were limited by exposure misclassification, poor control for confounding, and low statistical power due to small numbers. Information on reproductive risk factors was available in the three case-control studies (including one community study), and their results showed positive associations between exposure to PCE and unspecified mixtures and breast cancer (Aschengrau et al. 1998; Hansen 1999; Band et al. 2000). The one case-control study of male breast cancer observed no association with exposure to solvents.

2008 Evaluation

The committee identified five new or updated occupational-cohort studies that assesse breast-cancer incidence or mortality associated with TCE or PCE (Blair et al. 2003; Chang et al. 2003, 2005; Raaschou-Nielsen et al. 2003; Sung et al 2007). The reported SIRs and SMRs ranged from 1.1 to 1.2 in most studies. Sung et al. (2007) found an SIR of 1.38 (95% CI, 1.11-1.70) in electronics workers employed before June 1974 and exposed to TCE and mixed solvents. Chang et al. (2003) reported an increased incidence of breast cancer in employees exposed to TCE and PCE at an electronics factory in Taiwan. The highest SIR was associated with 5-10 years of exposure (SIR, 1.69; 95% CI, 1.02-2.64), but the association was stronger for more recent employment than for employment 5 or 10 years before diagnosis. In an update of their 1998 case-control study in a community exposed to PCE-contaminated drinking water, Aschengrau et al. (2003) continued to see increased, but attenuated, associations with breast cancer (ORs ranged from 0.9 to 1.9 depending on exposure). There was no clear evidence of the appropriate latency period (Vieira et al. 2005). In a community-based cohort study of PCE and TCE contamination of the public drinking-water supply, the SIR was consistent with that in the occupational studies (1.09; 99% CI, 0.97-1.21) (Morgan and Cassady 2002). The Aschengrau et al. study was the only new study that controlled for confounding by reproductive risk factors. No new studies included cases of male breast cancer.

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- There continues to be inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE and female breast cancer.
- On the basis of the new Aschengrau et al. (2003) study, the committee concludes that there is limited/suggestive evidence of an association between chronic exposure to PCE and breast cancer. This conclusion constitutes a change in the one drawn by IOM (2003).

Cervical Cancer

IOM 2003 Conclusions

IOM (2003) identified five cohort studies with data on the incidence of or mortality from cervical cancer after TCE exposure (Anttila et al. 1995; Blair et al. 1998; Morgan et al. 1998; Boice et al. 1999; Hansen et al. 2001). All had fewer than five exposed cases. Increased risks were observed in three studies that used biologic monitoring (Anttila et al. 1995; Blair et al. 1998; Hansen et al. 2001), and two of the three reported an exposure-response relationship (Anttila et al. 1995; Blair et al. 1998). The followup in the other two studies was not long enough to observe any deaths from cervical cancer (Morgan et al. 1998; Boice et al. 1999). Because of the concern about lack of control for SES and exposure to the human papilloma virus, IOM was not able to come to a consensus opinion on TCE exposure and cervical cancer.

The Anttila et al. (1995) study observed an association between exposure to PCE and incidence of cervical cancer. Two mortality cohorts of dry-cleaning workers also observed increased risks, but there was no evidence of an exposure-response relationship (Blair et al. 1990; Ruder et al. 2001). A study of Swedish patients with solvent-related disorders reported an increased SMR for cervical cancer (Berlin et al. 1995). IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between chronic exposure to PCE or unspecified mixtures of organic solvents and cervical cancer.

2008 Evaluation

The updated literature on TCE exposure and cervical cancer included several occupational-cohort studies with incidence data (Chang et al. 2003, 2005; Raaschou-Nielsen et al. 2003; Sung et al. 2007). Raaschou-Nielsen et al. (2003) observed an SIR of 1.9 (95% CI, 1.4-2.4) in Danish workers; however, there was no evidence of an exposure-response relationship. The SIR in over 300 exposed electronics workers in Taiwan was not increased (Sung et al. 2007). In a mortality study of electronics manufacturing workers exposed to TCE and PCE, an association with cervical cancer was not observed (Chang et al. 2003). In an incidence study of the same population, however, there was some indication of an exposure-response relationship (Chang et al. 2005). There was no association with cervical cancer in an incidence study of a community exposed to TCE and PCE in drinking water (Morgan and Cassady 2002). A cohort study of dry cleaners exposed to PCE and other dry-cleaning solvents found an increased SMR for cervical cancer, but there was no evidence of an exposure-response relationship. A case-control study of Nordic dry cleaners did not observe an association between PCE and cervical cancer in 36 cases in exposed people (Lynge et al. 2006).

- The committee concludes that there is insufficient/inadequate evidence to determine whether an association exists between chronic exposure to TCE or PCE and cervical cancer. This constitutes a new conclusion for TCE, in that a consensus was not reached in the 2003 IOM report.

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Ovarian and Uterine Cancer

IOM 2003 Conclusions

IOM (2003) reviewed four cohort studies with incidence or mortality data on ovarian or uterine cancer and exposure to TCE, PCE, or mixed solvents (Blair et al. 1990; Morgan et al. 1998; Boice et al. 1999; Hansen et al. 2001). No studies showed meaningful increases in the risk of those cancers. Furthermore, the number of cases in exposed people was extremely small: nine or fewer of either type in each study. Thus, IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE or PCE and ovarian or uterine cancer.

2008 Evaluation

The updated literature for TCE and PCE exposure and ovarian and uterine cancer included several occupational-cohort studies with incidence or mortality data (Blair et al. 2003; Chang et al. 2003, 2005; Raaschou-Nielsen et al. 2003; Sung et al. 2007). With the exception of increased but unstable rates of uterine and ovarian cancer reported in the incidence study of Taiwanese electronics workers (Chang et al. 2005), the studies did not indicate evidence of an association with TCE or PCE. Numbers of exposed cases in all studies were small. In a study of a community exposed to TCE and PCE in the public drinking-water supply, the SIRs for ovarian and uterine cancer were 1.16 (99% CI, 0.85-1.53) and 1.35 (99% CI, 106-1.70), respectively (Morgan and Cassady 2002).

- The committee concludes that there continues to be inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE or PCE and ovarian or uterine cancer.

Prostate Cancer

IOM 2003 Conclusions

IOM (2003) reviewed nine cohort studies with incidence or mortality data on an association between TCE and prostate cancer (Wilcosky et al. 1984; Greenland et al. 1994; Anttila et al. 1995; Blair et al. 1998; Morgan et al. 1998; Boice et al. 1999; Ritz 1999; Hansen et al. 2001). The results were mixed. Two cohort studies of dry-cleaning workers did not find an association between PCE and dry-cleaning solvents and prostate cancer (Blair et al. 1990; Ruder et al. 1994). Five cohort studies assessed exposure to unspecified mixtures of organic solvents and incidence of or mortality from prostatic cancer (Morgan et al. 1981; Matanoski et al. 1986; Garabrant et al. 1988; Greenland et al. 1994; Anttila et al. 1995; Boice et al. 1999). With the exception of the Anttila et al. study, which reported an SIR of 1.38 (95% CI, 0.73-2.35) in all workers (13 cases in exposed people) and an SIR of 3.57 (95% CI, 1.54-7.02) in workers with over 20 years of exposure (eight cases), the risks were not increased. IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE or PCE and prostate cancer.

2008 Evaluation

The updated literature on occupational exposure to TCE and PCE and prostate cancer includes two cohort studies (Raaschou-Nielsen et al. 2003; Boice et al. 2006) and one case-control study (Krishnadasan et al. 2007) of workers exposed to TCE, one cohort study of dry cleaners exposed to PCE and dry-cleaning solvents (Blair et al 2003), and one study of electronics workers exposed to TCE and PCE (Chang et al. 2003). Positive risks were observed only for TCE in the Krishnadasan study; ORs for low-

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moderate exposure and high exposure were 1.3 (95% CI, 0.81-2.1) and 2.1 (95% CI, 1.2-3.9), respectively. A study of a community exposed to TCE and PCE in drinking water reported an SIR of 1.11 (99% CI, 0.98-1.25) (Morgan and Cassady 2002).

- There continues to be inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE and prostate cancer.

Bladder Cancer

IOM 2003 Conclusions

IOM (2003) reviewed seven cohort studies of occupational exposure to TCE that evaluated bladder-cancer incidence or mortality and one case-control study and concluded that there was insufficient/inadequate evidence to determine whether an association exists. That conclusion was based on weak and imprecise associations, low statistical power, and probable exposure misclassification. However, IOM concluded that there is limited/suggestive evidence of an association between chronic exposure to PCE and dry-cleaning solvents and bladder cancer. That conclusion was based on cohort studies (Blair et al. 1990; Ruder et al. 2001) and case-control studies (Schoenberg et al. 1984; Smith et al. 1985; Teschke et al. 1997; Pesch et al. 2000a) of dry cleaners that found increased risks of bladder cancer. In addition, a community study of PCE-contaminated drinking water found evidence of a positive exposure-response relationship (Aschengrau et al. 1993). The evidence of an association with chronic exposure to unspecified mixtures of organic solvents was also determined to be limited/suggestive on the basis of consistent positive findings in four case-control studies (Schoenberg et al. 1984; Morrison et al. 1985; Jensen et al. 1987; Pesch et al. 2000b) and cohort studies of painters (Steenland and Palu 1999) and aircraft workers (Garabrant et al. 1988).

2008 Evaluation

The committee identified four new cohort studies of occupational groups potentially exposed to TCE (Raaschou-Nielsen et al. 2003; Zhao et al. 2005; Boice et al. 2006; Sung et al. 2007) and one in which exposures to TCE and to PCE were not distinguished (Chang et al. 2003). The results were inconsistent. In the continued followup study of dry-cleaning workers (Blair et al 2003), the SMR for bladder cancer was increased at 1.3 (95% CI, 0.7-2.4) but lower than in the first report. A new cohort study of dry cleaners found a positive association between exposure and bladder cancer with some evidence of a positive exposure-response relationship (Lynge et al. 2006). A study of a community exposed to TCE and PCE in the public drinking-water supply found no evidence of an increased risk of bladder cancer after exposure (Morgan and Cassady 2002). There were no new studies of unspecified mixtures.

- The committee concludes that there continues to be inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE and bladder cancer. The evidence on PCE and mixtures of organic solvents continues to support a conclusion that there is limited/suggestive evidence of an association between chronic exposure to PCE or mixtures of organic solvents and bladder cancer.

Kidney Cancer

IOM 2003 Conclusions

For TCE, positive associations with kidney cancer were suggested by three studies (Henschler et

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al. 1995; Vamvakas et al. 1998; Pesch et al. 2000b). On the basis of an apparent cluster of cases, Henschler et al. (1995) conducted a retrospective cohort study in a cardboard factory in Germany to examine the association between TCE exposure and renal cell cancer. The study group included 169 men who had been exposed to TCE for at least 1 year between 1956 and 1975. The study reported incident kidney cancer among five exposed men (RR of 7.9; 95% CI, 2.59-8.59). A case-control study in the same region of Germany reported an elevated risk of kidney cancer (OR of 10.8; 95% CI, 3.36-34.7) (Vamvakas et al. 1998). The findings from the German cohort study raised interest because of the long employment period (an average of 34 years) and the potential for high exposure to TCE. Another case-control study in multiple regions of Germany reported an increased risk of kidney cancer among men with presumed substantial TCE exposure (Pesch et al. 2000b). Collectively, the IOM committee judged the studies insufficient for drawing conclusions because they had small sample sizes, one had poor exposure data (self reports in Vamvakas et al. 1998), one was a cluster investigation (Henschler et al. 1995), and the results of the Pesch et al. (2000b) study were not persuasive.

However, the results of several well-conducted epidemiologic studies of PCE (McCredie and Stewart 1993; Mandel et al. 1995; Pesch et al. 2000b) warranted a conclusion that there was limited/suggestive evidence of an association between chronic exposure to PCE and kidney cancer. IOM was unable to reach a consensus conclusion on unspecified mixtures of organic solvents.

2008 Evaluation

The updated literature on TCE and kidney cancer included six cohort studies with cancer incidence or mortality data (Morgan and Cassady 2002; Chang et al. 2003; Raaschou-Nielsen et al. 2003; Zhao et al. 2005; Boice et al. 2006; Sung et al. 2007) and two case-control studies (Bruning et al. 2003; Charbotel et al. 2006). The updated literature on PCE and kidney cancer included three cohort studies (Morgan and Cassady 2002; Blair et al. 2003; Chang et al. 2003) and two case-control studies (Bruning et al. 2003; Lynge et al. 2006). Several of the cohort studies of TCE reported an increased risk of kidney cancer, including in some the appearance of a dose-response relationship on the basis of years of employment or presumed higher exposure levels. For example, Raaschou-Nielsen et al. (2003) reported an SIR of 1.6 (95% CI, 1.1-2.3) in men employed for 5 years or more; Zhao et al. (2005) found an SIR of 4.90 (95% CI, 1.23-19.6) for an estimated high level of TCE exposure of aerospace workers. The results were often based on a relatively small number of exposed persons and varied quality of exposure data and methods of exposure assessment. The few studies of PCE largely showed no increase in risk, although most effect estimates are imprecise because of the very small number of exposed cases.

- On the basis of the available data, the committee concludes that there is limited/suggestive evidence of an association between chronic exposure to TCE or PCE and kidney cancer. In the case of TCE, that conclusion constitutes a change in the one drawn by IOM (2003).
- Because consensus was not reached on a characterization of the data on mixtures of organic solvents and kidney cancer, the committee performed its own evaluation of the data in the IOM (2003) report. The committee concluded that reports of positive associations in multiple studies, even in the context of study limitations and negative studies, were sufficient to state that the evidence of an association between mixtures of organic solvents and kidney cancer is limited/suggestive.

Cancer of the Brain or Central Nervous System

IOM 2003 Conclusions

Some studies found some positive associations between TCE and brain cancer (Heineman et al. 1994; Rodvall et al. 1996; Ritz 1999), but IOM (2003) judged that the cohort and case-control studies

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were limited by confounding by other exposures, imprecise effect estimates, and lack of specificity of brain-tumor type. Thus, the evidence on chronic exposure to TCE and brain or central nervous system (CNS) cancer was characterized as inadequate/insufficient to determine whether an association exists. With regard to PCE, no consistent pattern of increased relative risk was found, so the evidence was judged to be inadequate/insufficient to determine whether there is an association between chronic exposure to PCE and brain or CNS cancer. Although some positive associations were reported in studies of unspecified mixtures of solvents, the evidence was considered inadequate/insufficient to determine whether an association exists.

2008 Evaluation

The updated literature on TCE and brain or CNS cancer included several cohort studies with cancer incidence or mortality data (Hansen et al. 2001; Morgan and Cassady 2002; Chang et al. 2003, 2005; Raaschou-Nielsen et al. 2003; Zhao et al. 2005; Boice et al. 2006; Sung et al. 2007). The updated literature on PCE and brain or CNS cancer included three cohort studies (Morgan and Cassady 2002; Blair et al. 2003; Chang et al. 2003). The studies of TCE did not show an increase in risk except the Morgan and Cassady study of drinking water contaminated with TCE and perchlorate, which reported a weakly increased SIR of 1.54 (95% CI, 0.96-2.31). The small number of studies of PCE generally showed no increase in risk.

- There continues to be inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE or PCE and brain or CNS cancer.

Non-Hodgkin Lymphoma

IOM 2003 Conclusions

IOM (2003) reviewed two cohort studies that involved exposure to TCE (Wilcosky et al. 1984; Blair et al. 1998) and that suggested an increased risk of dying from non-Hodgkin lymphoma. In the Wilcosky et al. study, rubber workers were exposed to numerous other chemicals. The Blair et al. study found no evidence of a dose-response relationship with respect to mortality and no association in relation to incidence. A case-control study showed a strong association between TCE and non-Hodgkin lymphoma, but IOM judged it highly probable that the RRs were overstated. Thus, IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE, PCE, or unspecified mixtures of solvents and non-Hodgkin lymphoma. Statistical fluctuation was cited as an important reason for drawing that conclusion.

2008 Evaluation

The updated literature on TCE and non-Hodgkin lymphoma included four cohort studies with cancer incidence or mortality data (Morgan and Cassady 2002; Raaschou-Nielsen et al. 2003; Zhao et al. 2005; Boice et al. 2006) and two case-control studies (Miligi et al. 2006; Seidler et al 2007). In an occupational-cohort study, male Danish workers exposed to TCE had a weakly increased risk of non-Hodgkin lymphoma, and there appeared to be a dose-response relationship—the SIRs for those employed for less than 1 year, for 1-4.9 years, and for 5 years or more were 1.1 (95% CI, 0.7-1.6), 1.3 (95% CI, 0.9-1.8), and 1.4 (95% CI, 0.9-2.0), respectively (Raaschou-Nielsen et al. 2003). A similar pattern was observed in female workers in the same study. The case-control study by Seidler et al. (2007) found that German workers exposed to TCE at concentrations greater than 35 ppm/year had an increased risk of B-cell non-Hodgkin lymphoma (OR, 2.3; 95% CI, 1.0-5.3). The updated literature on PCE and non-Hodgkin lym-

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phoma included two cohort studies (Morgan and Cassady 2002; Blair et al. 2003) and three case-control studies (Lynge et al. 2006; Miligi et al. 2006; Seidler et al. 2007). None of the studies reported an association between exposure to PCE and non-Hodgkin lymphoma.

- There continues to be inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE or PCE and non-Hodgkin lymphoma.

Hodgkin Disease

IOM 2003 Conclusions

Because of the small numbers of exposed cases in the available studies and a lack of specific or validated exposure-assessment information in the studies reviewed, IOM (2003) concluded that there was inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE, PCE, or unspecified mixtures of solvents and Hodgkin disease.

2008 Evaluation

The updated literature on TCE and Hodgkin disease included five cohort studies with cancer incidence or mortality data (Hansen et al. 2001; Morgan and Cassady 2002; Chang et al. 2003; Raaschou-Nielsen et al. 2003; Boice et al. 2006) and one case-control study (Seidler et al. 2007). The updated literature on PCE and Hodgkin disease included three cohort studies (Morgan and Cassady 2002; Blair et al. 2003; Chang et al. 2003) and one case-control study (Seidler et al. 2007). The newer studies were still characterized by small numbers of exposed cases and provided no persuasive evidence of an association between TCE or PCE and Hodgkin disease.

- There continues to be inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE or PCE and Hodgkin disease.

Multiple Myeloma

IOM 2003 Conclusions

Given a lack of positive findings, IOM (2003) concluded that there was inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE or PCE and multiple myeloma. A number of studies of painters found an increased risk of multiple myeloma after exposure to solvent mixtures. Thus, IOM concluded that there was limited/suggestive evidence of an association between chronic exposure to solvents (as observed in studies of painters) and multiple myeloma.

2008 Evaluation

The updated literature on TCE and multiple myeloma included two cohort studies with cancer incidence or mortality data (Raaschou-Nielsen et al. 2003; Boice et al. 2006) and one case-control study (Seidler et al. 2007). None of the three studies suggested an association between exposure to TCE and multiple myeloma. The SIR in male Danish workers who held jobs with TCE exposure for at least 3 months was 1.1 (95% CI, 0.70-1.52). The updated literature on PCE and multiple myeloma included one

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cohort study (Blair et al. 2003) and one case-control study (Seidler et al. 2007). Both studies had small numbers of exposed cases (seven or fewer) and found no persuasive evidence of an association.

- There continues to be inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE or PCE and multiple myeloma. IOM's conclusion that there is limited/suggestive evidence of an association between chronic exposure to solvents and multiple myeloma also remains unchanged.

Adult Leukemia

IOM 2003 Conclusions

Owing to the small number of relevant studies and the lack of consistently positive findings, IOM (2003) concluded that there was inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE or PCE and adult leukemia. However, the findings on unspecified mixtures of organic solvents and adult leukemia showed increased RRs, including two studies that found evidence of a dose-response relationship. IOM concluded that there was limited/suggestive evidence of an association between chronic exposure to unspecified mixtures of organic solvents and adult leukemia.

2008 Evaluation

The updated literature on TCE and adult leukemia included five cohort studies with cancer incidence or mortality data (Morgan and Cassady 2002; Chang et al. 2003; Raaschou-Nielsen et al. 2003; Boice et al. 2006; Sung et al. 2007) and one case-control study (Seidler et al. 2007). The updated literature on PCE and adult leukemia included three cohort studies (Morgan and Cassady 2002; Blair et al. 2003; Chang et al. 2003) and one case-control study (Seidler et al. 2007). The study by Morgan and Cassady (2002) did not find any change in leukemia incidence in residents of a community exposed to drinking water contaminated with TCE and PCE (SIR, 1.02; 99% CI, 0.74-1.35). The risk of adult leukemia was not linked to exposure to TCE or PCE in any of the other newly identified studies.

- There continues to be inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE or PCE and adult leukemia. IOM's conclusion that there is limited/suggestive evidence of an association between chronic exposure to unspecified mixtures of organic solvents and adult leukemia also remains unchanged.

Myelodysplastic Syndromes

IOM 2003 Conclusions

All the studies reviewed in the IOM (2003) report were case-control studies. None focused specifically on TCE or PCE. Most of the studies evaluated unspecified mixtures of organic solvents and relied on self-reported exposures. All but one study found consistently positive ORs. IOM concluded that there was limited/suggestive evidence of an association between chronic exposure to unspecified mixtures of organic solvents and myelodysplastic syndromes but drew no conclusions about individual solvents.

2008 Evaluation

No new studies focusing on TCE or PCE and myelodysplastic syndromes were identified.

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- The committee concludes there is inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE or PCE and myelodysplastic syndromes. IOM's conclusion that there was limited/suggestive evidence of an association between chronic exposure to unspecified mixtures of organic solvents and myelodysplastic syndromes remains unchanged.

Childhood Leukemia

IOM 2003 Conclusions

IOM (2003) was unable to reach a consensus conclusion regarding the relationship between exposure to organic solvents and childhood leukemia. Several studies found positive associations with exposure to solvents. Some studies were limited by misclassification bias related to self-reporting of exposure, and some were limited by looking at all childhood leukemia or focusing on specific cell types. Because of these factors, some IOM committee members believed that the evidence fulfilled the category of inadequate/insufficient evidence to determine whether an association exists; others believed that it was limited/suggestive of an association.

2008 Evaluation

The updated literature on TCE and childhood leukemia included one cohort study with incidence data (Morgan and Cassady 2002) and one case-control study (Costas et al. 2002). Updated literature on PCE and childhood leukemia included one cohort study with incidence data (Morgan and Cassady 2002) and two case-control studies (Costas et al. 2002; Infante-Rivard et al. 2005). The cohort study by Morgan and Cassady (2002) did not find any change in the incidence of childhood leukemia in residents of a community exposed to drinking water contaminated with TCE and PCE (SIR, 1.09; 99% CI, 0.38-2.31). The case-control study found no association between maternal occupational exposure to PCE and leukemia in offspring (Infante-Rivard et al. 2005). The OR for maternal PCE exposure from 2 years before pregnancy to birth was 0.96 (95% CI, 0.41-2.25), and the OR for maternal PCE exposure during pregnancy was 0.84 (95% CI, 0.30-2.34). The case-control study by Costas et al. (2002) suggested a dose-response relationship between cumulative exposure to water from municipal drinking water contaminated with TCE, PCE, and other chemicals and childhood leukemia. However, the interpretation of such a finding is limited by the small number of exposed cases (10) and the uncertainty in exposure assessment.

- On the basis of the available literature, the committee concludes that there is inadequate/insufficient evidence to determine whether an association exists between TCE or PCE and childhood leukemia. This constitutes a new conclusion, in that consensus was not reached in the 2003 IOM report.

Childhood Neuroblastoma

IOM 2003 Conclusions

A case-control study found few associations between maternal or paternal occupational exposure to solvents, including TCE or PCE, and neuroblastoma in offspring (De Roos et al. 2001). IOM (2003) concluded that there was inadequate/insufficient evidence to determine whether an association exists between chronic exposure to solvents and neuroblastoma.

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2008 Evaluation

No new studies on solvent exposure and neuroblastoma were found.

- There continues to be inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE or PCE and neuroblastoma.

Childhood Brain Cancer

IOM 2003 Conclusions

One of two case-control studies found some associations between maternal (OR, 0.9-3.2) or paternal (OR, 0.4-2.3) occupational exposure to solvents (as a group) and childhood brain cancer in offspring (Cordier et al. 1997). IOM (2003) concluded that there was inadequate/insufficient evidence to determine whether an association exists between chronic exposure to solvents and childhood brain cancer.

2008 Evaluation

A study by Morgan and Cassady (2002) study did not find an association between community exposure to water contaminated with TCE and PCE and childhood brain cancer.

- There continues to be inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE or PCE and childhood brain cancer.

Noncancer End Points

Aplastic Anemia

IOM 2003 Conclusions

The IOM (2003) report included a total of three studies (all case-control studies) of organic solvents (other than benzene) and aplastic anemia. One study reported a significantly increased risk, and the other two did not find an association. None of the three studies focused on TCE or PCE. On the basis of results, IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between exposure to specific organic solvents (other than benzene) or solvent mixtures and aplastic anemia.

2008 Evaluation

No additional studies of TCE or PCE and aplastic anemia were identified.

- There continues to be inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE or PCE and aplastic anemia.

Congenital Malformations

IOM 2003 Conclusions

A small number of studies that examined parental solvent exposure before or during pregnancy

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did not find a pattern of association except for a study of gastroschisis that reported several increased but imprecise ORs (Torfs et al. 1996). IOM (2003) concluded that there was inadequate/insufficient evidence to determine whether an association exists between chronic exposure to solvents and congenital malformations.

2008 Evaluation

A community study that assessed residential proximity to a TCE-emitting facility did not find an overall association with congenital heart defects but reported an association with presumed TCE exposure among older mothers (among exposed mothers 38 years or older) and such defects (OR, 4.1; 95% CI, 1.5-11.2) (Yauck et al. 2004). A case-control study of maternal occupational exposure to organic solvent mixtures found an increased but very imprecise OR (9.2; 95% CI, 2.5-35.3) for oral clefts among offspring (Chevrier et al. 2006).

- There continues to be inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE or PCE and congenital malformations.

Male Fertility

IOM 2003 Conclusions

Many studies have investigated potential paternal occupational exposure to solvents and male infertility. They used occupation or industry as a surrogate for solvent exposure. IOM (2003) reviewed only studies that had a better characterization of solvent exposure. Nonetheless, only one study performed a specific assessment of TCE or PCE exposure. The five studies reviewed by IOM that examined male solvent exposure and effects that persisted after cessation of exposure had inconsistent results, including some associations with poorer semen quality. Most studies tended to be small and recruited men from infertility clinics or couples seeking an infertility consultation. Others reported inconsistent associations between solvents and indirect measures of fertility, including hormone concentrations and time to pregnancy. IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between chronic exposure to solvents and male infertility.

2008 Evaluation

A study of men occupationally exposed to solvents (painters and millwrights) reported an association between increasing follicle-stimulating hormone and indexes of exposure to all solvents and to chlorinated solvents (Luderer et al. 2004). No association with luteinizing hormone concentration or time to pregnancy was found.

- The committee concludes that there continues to be inadequate/insufficient evidence to determine whether an association exists between chronic exposure to TCE or PCE and male infertility.

Female Fertility

IOM 2003 Conclusions

A few studies have evaluated miscellaneous solvent exposure, not TCE or PCE specifically, in relation to fecundability (ability to become pregnant), typically measured as time to pregnancy. In those studies, a lower hazard ratio means that conception was less likely in exposed than in unexposed women.

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Reduced fecundability was found in female printing-industry workers (fecundability ratio, 0.52; 95% CI, 0.28-0.99) (Plenge-Bonig and Karmaus 1999), women in jobs determined by biologic monitoring to have high solvent exposure (fecundability ratio, 0.41; 95% CI, 0.27-0.62) (Sallmen et al. 1995), and semiconductor-industry workers exposed to ethylene glycol ethers (fecundability ratio, 0.37; 95% CI, 0.11-1.19) (Eskenazi et al. 1995). One additional study used subfertility, the inability to conceive within 1 year, as the outcome measure and found an increased risk in female semiconductor workers (OR, 4.6; 95% CI, 1.6-13.3) (Correa et al. 1996). The only reported estimates of effects of TCE and PCE exposure come from the study by Sallmen et al. (1995), who found fecundability ratios of 0.61 (95% CI, 0.28-1.33) and 0.69 (95% CI, 0.31-1.52), respectively, consistent with the pattern for solvents in general. IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between exposure to TCE, PCE, or other solvents reviewed and female infertility after cessation of exposure. It drew no conclusions about the evidence on concurrent exposure to solvents and effects on fertility, because its review focused on fertility risks to veterans after deployment (after cessation of exposure).

2008 Evaluation

No additional studies addressing female infertility were identified after the 2003 IOM report. The committee evaluated the studies included in that review (see above) to draw conclusions about the evidence on concurrent exposure to solvents and female fertility.

- There continues to be inadequate/insufficient evidence to determine whether an association exists between exposure to TCE or PCE and female infertility after exposure cessation; this agrees with IOM (2003).
- The committee concludes that there is limited/suggestive evidence of an association between *concurrent* exposure to solvents and female infertility, which was not addressed in the 2003 IOM report.

Pregnancy Outcomes (Maternal Exposure)

IOM 2003 Conclusions

The IOM (2003) report focused on delayed or chronic effects of exposure that are manifested in adverse pregnancy outcomes after cessation of exposure. IOM summarized the available evidence, which was primarily on exposure during pregnancy. Preconception exposure of women and later adverse pregnancy outcomes were not addressed in any of the studies. A number of studies have suggested that maternal exposure to solvents in general and dry-cleaning work in particular are associated with miscarriage. Four studies that reported some evidence of an association between maternal dry-cleaning employment and miscarriage were cited (Kyyronen et al. 1989; Ahlborg 1990; Olsen et al. 1990; Doyle et al. 1997), and a greater number of other reports suggested an association with other sources of occupational solvent exposure, including work in semiconductor plants, shoe factories, and laboratories. Although consistent among studies, the quality of exposure assessment in all the studies is limited, and there are difficulties to identifying and documenting the occurrence of miscarriage accurately. Few studies have considered other pregnancy outcomes (such as preterm birth and fetal growth restriction), and they yielded little support of an association. IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between maternal preconception exposure to TCE, PCE, or other solvents reviewed and miscarriage or other adverse pregnancy outcomes. It drew no conclusions about the evidence on exposure during pregnancy, because its review was focused on risks to veterans of war and it was assumed that no female soldiers were pregnant while deployed.

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2008 Evaluation

No additional studies of maternal solvent exposure and miscarriage were identified.

- There continues to be inadequate/insufficient evidence to determine whether an association exists between maternal preconception exposure to TCE or PCE and miscarriage or other adverse pregnancy outcomes (such as preterm birth and fetal growth restriction).
- The committee concludes there is inadequate/insufficient evidence to determine whether an association exists between maternal solvent exposure during pregnancy and preterm birth or fetal growth restriction.
- The committee concludes that there is limited/suggestive evidence of an association between maternal exposure to PCE (and to solvents in general) during pregnancy and miscarriage.

Pregnancy Outcomes (Paternal Exposure)

IOM 2003 Conclusions

Four studies that addressed paternal exposure to solvents and pregnancy outcomes were identified. Scattered positive associations were reported but no consistent evidence of an association with miscarriage, the most frequently studied pregnancy outcome. The studies tended to be small, relied on self-reported exposure, and had indirect assessment of solvent exposure (and not specifically exposure to TCE or PCE). The one study of dry-cleaning workers (Eskenazi et al. 1991) did not find a positive association. IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between paternal exposure to TCE, PCE, or other solvents reviewed and miscarriage or other adverse pregnancy outcomes.

2008 Evaluation

No additional studies of paternal solvent exposure and pregnancy outcomes were identified.

- There continues to be inadequate/insufficient evidence to determine whether an association exists between paternal exposure to TCE, PCE, and other solvents and adverse pregnancy outcomes.

Cardiovascular Effects

IOM 2003 Conclusions

IOM found a number of studies of short-term effects of acute, relatively high-dose exposure to solvents. Effects tended to be exacerbation of symptoms of underlying cardiovascular disease that were reversible. Many cohort mortality studies of solvent-exposed workers have been conducted, but they were limited by the healthy-worker effect to various degrees, and none provided much support of increased mortality from cardiovascular disease associated with solvent exposure. The magnitude of solvent exposure encountered in occupational settings would be substantially greater than that in the community, and the solvents would be inhaled or absorbed dermally, unlike the ingestion found in community studies. IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between exposure to specific solvents and cardiovascular disease.

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2008 Evaluation

Several studies have extended the followup of dry-cleaning workers (Ruder et al. 2001; Blair et al. 2003) and continue to generate evidence of no increase in mortality from cardiovascular disease.

- The committee concludes that there continues to be inadequate/insufficient evidence to determine whether an association exists between solvent exposure and cardiovascular disease.

Hepatic Effects

IOM 2003 Conclusions

Liver function. Acute, high-level TCE exposure has effects on liver function, as does exposure to other solvents, but there is little evidence of lingering effects of chronic low-level exposure. Studies of workers with chronic exposure to solvents (such as painters and dry-cleaning workers) have not shown abnormal enzyme concentrations indicative of deleterious effects on liver function. Mild increases in hepatic enzymes have been noted in a few studies, but the studies did not differentiate past and current, continuous solvent exposure, so it was not possible to distinguish long- and short-term effects.

Hepatic steatosis. Acute, high-level exposure to such solvents as chloroform and carbon tetrachloride causes injury to the liver. Case series and some small epidemiologic studies of petrochemical and dry-cleaning workers indicate that a variety of solvents can cause fatty changes in the liver (steatosis) and that the problem persists after exposure ceases (Dossing et al. 1983; Redlich et al. 1990; Cotrim et al. 1999). The association seems clear for acute effects of high-level solvent exposure, but the dose-response gradient and the temporal course of exposure, response, and potential reversal are not well established.

Cirrhosis. Except for some case reports of cirrhosis associated with high-level solvent exposure, there are few informative data on solvent exposure and cirrhosis. Some studies of solvent-exposed workers have suggested an increased risk of cirrhosis, but the substantial influence of alcohol use and viral exposure on risk leaves open the potential for serious confounding.

- IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between exposure to TCE, PCE, or other solvents reviewed and chronic changes in hepatic function or cirrhosis.
- IOM concluded there was limited/suggestive evidence of an association between chronic exposure to solvents in general and hepatic steatosis that "could persist" after cessation of exposure.

2008 Evaluation

Extended followup of dry-cleaning workers continues to show no increased risk of hepatic effects (Ruder et al. 2001; Blair et al. 2003).

- The committee concludes that there continues to be inadequate/insufficient evidence determine whether an association exists between solvent exposure and changes in hepatic function or cirrhosis and limited/suggestive evidence of an association between chronic exposure to solvents and hepatic steatosis, which may persist after cessation of exposure.

Gastrointestinal Effects

IOM 2003 Conclusions

The only gastrointestinal effect that has been investigated as a possible consequence of solvent

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exposure is chronic pancreatitis. It is a persistent inflammatory condition strongly affected by alcohol consumption. One study examined a variety of occupational exposures in relation to chronic pancreatitis (McNamee et al. 1994), including solvent-exposed occupations, but found only an imprecise suggestion of a possible association with high cumulative exposure to chlorinated solvents. IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between exposure to TCE, PCE, or other solvents reviewed and chronic pancreatitis.

2008 Evaluation

No additional studies of solvent exposure and gastrointestinal effects were identified.

- There continues to be inadequate/insufficient evidence to determine whether an association exists between solvent exposure and gastrointestinal effects.

Renal Effects

IOM 2003 Conclusions

Several renal diseases have been examined in epidemiologic studies, including such specific conditions as acute tubular necrosis and chronic glomerulonephritis and such nonspecific conditions as indicators of renal function and end-stage renal disease. Studies of the effects of short-term and long-term solvent exposure on renal function below the threshold of clinical disease have yielded some support of an association between exposure to high concentrations of solvents and acute tubular necrosis. A series of case-control studies have evaluated chronic glomerulonephritis, an immune-mediated disease, in relation to solvent exposure and have yielded mixed evidence of an association, including several reasonably strong positive studies showing dose-response gradients. None of the studies addressed TCE or PCE directly; the closest any came was one that reported an association with "degreasing agents" (Porro et al. 1992). IOM concluded that there was limited/suggestive evidence of an association between exposure to solvent mixtures and chronic glomerulonephritis. Several studies have addressed the effect of solvent exposure on indicators of renal function; they used various magnitudes of exposure and had varied quality of exposure assessment. One study (Steenland et al. 1990) reported a fairly strong association between degreasing solvents and end-stage renal disease.

2008 Evaluation

No new studies of solvent exposure and glomerulonephritis were identified. An occupational-cohort study of aircraft-maintenance employees implicates solvents and points toward TCE more than PCE in relation to end-stage renal disease (Radican et al. 2006). Retrospective exposure assessment was detailed and identified greater than two-fold increases in risk with higher exposure. Study of renal function in workers exposed to TCE showed decrements in renal function in the clinically normal range (Green et al. 2004). The additional evidence strengthens the quantity and quality of information on TCE.

- The committee concludes that there continues to be limited/suggestive evidence of an association between mixed solvent exposure and chronic glomerulonephritis but inadequate/insufficient evidence to determine whether an association exists specifically between TCE or PCE and chronic glomerulonephritis.

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Systemic Rheumatic Disease

IOM 2003 Conclusions

Scleroderma, an autoimmune disease resulting in abnormal growth of connective tissue, has been addressed in several epidemiologic studies in relation to occupational solvent exposure, most of which relied on job-exposure matrices to infer solvent exposure. A report by Nietert et al. (1998) found an OR of 3.3 (95% CI, 1.0-10.3) for TCE and scleroderma in men but not in women, who have a higher overall risk of this disease. Other small, relatively crude studies with limited exposure assessment have generated mixed findings regarding the existence of an association. IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between solvent exposure and scleroderma.

2008 Evaluation

Since the IOM review, there have been four studies of solvent exposure and scleroderma that used more sophisticated methods of assessing exposure. A case-control study of women in Michigan considered self-reported and expert-confirmed exposure and found a two-fold increased risk associated with TCE exposure but no association with PCE exposure (Garabrant et al. 2003). A case-control study in France found markedly increased risk of scleroderma associated with solvents, which challenges the plausibility of the findings, but the list of implicated solvents included TCE (Diot et al. 2002). A small study of women in Hungary found an increased risk associated with solvent exposure (Czirják and Kumanovics 2002). Finally, a case-control study in Italy found that solvent exposure increased the risk of scleroderma by a factor of 2.5 (Bovenzi et al. 2004).

- On the basis of the findings of new studies, the committee concludes that the evidence of an association between mixed solvent exposure and scleroderma is limited/suggestive and that some evidence points toward TCE exposure in particular. This constitutes a change in IOM's 2003 conclusion.

Amyotrophic Lateral Sclerosis

IOM 2003 Conclusions

IOM (2003) considered four case-control studies in evaluating the association between solvent exposure and amyotrophic lateral sclerosis (ALS) (Chio et al. 1991; Gunnarsson et al. 1992; Strickland et al. 1996; McGuire et al. 1997). Chio et al. defined exposure by using occupational information drawn from hospital charts and municipal records. Gunnarsson et al. and Strickland et al. used only self-reported exposure. Only McGuire et al. (1997) used a more sophisticated assessment of exposure by a panel of industrial hygienists. In that study, the age- and education-adjusted OR for self-reported exposure to solvents in both men and women was 1.6 (95% CI, 1.1-2.5). However, when the industrial-hygiene assessment was used, the association was attenuated (OR, 1.2; 95% CI, 0.8-1.9). Of 28 specific agents assessed, only "cleaning solvents or degreasers" had a positive association with both self-reported exposure (OR, 1.8; 95% CI, 1.2-2.8) and industrial-hygiene assessment (OR, 1.9; 95%: CI 1.1-3.3). The association was limited to females in stratified models, and there was no evidence of a dose-response relationship. On the basis of the results of that study and the insufficiency of exposure assessment in the other studies, IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between exposure to solvents and ALS.

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2008 Evaluation

No new studies of exposure to solvents and ALS 2003 were identified.

- There continues to be inadequate/insufficient evidence to determine whether an association exists between exposure to solvents and ALS.

Parkinson Disease

IOM 2003 Conclusions

IOM (2003) evaluated studies with only Parkinson disease as the outcome measure rather than the more generic diagnosis of parkinsonism. Only two studies were found to be sufficiently rigorous in design to be useful in providing evidence on the relationship between solvent exposure and Parkinson disease (Hertzman et al. 1994; Seidler et al. 1996). Both were case-control studies that used prevalent cases, and one of the studies (Hertzman et al. 1994) focused on pesticides and presented little pertaining to solvent exposure. Although both studies found an association between past exposure to solvents and Parkinson disease, they were likely to have been subject to recall bias. Overall, little attention has been focused on solvent exposure as a risk factor for Parkinson disease. IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between exposure to the solvents reviewed and Parkinson disease.

2008 Evaluation

The relationship between exposure to solvents and Parkinson disease was assessed in a case-control study in the United Kingdom that was restricted to men (McDonnell et al. 2003). Potential cases (176) were obtained by searching the pension-fund archive of a major engineering company for death certificates that mentioned Parkinson disease, and potential controls (599) were identified from the same database. Exposure to solvents was determined on the basis of occupational records, which were not available for many subjects. In the end, 57 people with the diagnosis (32% of the 176) and 206 controls (34% of the 599) were included in the analysis. Thirty-one people with the disease and 93 controls had worked in jobs involving exposure to solvents; the OR was 1.53 (95% CI, 0.81-2.87). There was a significant trend in the odds of disease with increasing duration of exposure. The study included a small number of cases and lacked information on other possible risk factors or confounders.

Another case-control study of Parkinson disease assessed the role of solvent exposure (Dick et al. 2007). It was conducted in five European countries and included 767 prevalent cases and 1,989 controls. Cases were ascertained through clinical visits or by reviewing medical records, and the control group included a mixture of hospital controls and community controls. Subjects were interviewed about lifetime occupational and hobby-related exposure to solvents. The OR was 1.01 (95% CI, 0.84-1.23) for any exposure to solvents. When average annual intensity of exposure was evaluated, the ORs for those with low and high exposure were 1.17 (95% CI, 0.92-1.50) and 0.88 (95% CI, 0.69-1.12), respectively. This study is characterized by a large number of subjects and provided no evidence of an association between solvent exposure and Parkinson disease.

A study by Gash et al. (2008) included a group of 30 workers at a single factory who had long-term (8-33 years) chronic exposure to TCE. The study was initiated because one of the workers had received a diagnosis of Parkinson disease and suspected that his occupational exposure to TCE was a factor in his disease. The investigators mailed questionnaires to 134 former workers, of whom 65 responded and 27 agreed to a clinical examination. Three workers with workstations adjacent to the TCE source and subjected to chronic inhalation and dermal exposure from the handling of TCE-soaked metal parts had Parkinson disease, whereas workers more distant from the TCE source and receiving chronic respiratory expo-

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sure displayed features of parkinsonism. Because of the "cluster investigation" type of design, the significance of the study is difficult to judge.

- The committee concludes that there continues to be inadequate/insufficient evidence to determine whether an association exists between solvent exposure and Parkinson disease.

Multiple Sclerosis

IOM 2003 Conclusions

At the time of the IOM (2003) report, four case-control studies of solvent exposure (in general) and multiple sclerosis (MS) had been conducted in Scandinavia. Two had negative results, and the other two, conducted in Sweden and based on overlapping populations, reported some positive associations between self-reported occupational and leisure-time solvent exposure and MS in men. The positive findings are tempered by the limited quality of exposure assessment, the lack of adjustment for potential confounders, and small sample and were thus short of "limited/suggestive" evidence of an association. No studies focused specifically on TCE or PCE were found. IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between exposure to TCE, PCE, or other solvents reviewed and MS.

2008 Evaluation

No additional studies of solvent exposure and MS were identified.

- There continues to be inadequate/insufficient evidence to determine whether an association exists between solvent exposure and MS.

Alzheimer Disease

IOM 2003 Conclusions

After evaluating five studies of solvent exposure and Alzheimer disease, all of which were case-control studies, IOM (2003) concluded that there was inadequate/insufficient evidence to determine whether an association exists between exposure to the solvents under review and the disease. The very nature of the disease—late onset and dementia leading to the need for proxy respondents—makes it extremely difficult to study the association. Several authors commented that occupational solvent exposure is most likely to occur in men, but population-based studies suggest that women are at greater risk for Alzheimer disease.

2008 Evaluation

The committee identified a study that was not included in the 2003 IOM review (Tyas et al. 2001). It evaluated the relationship between solvent exposure and Alzheimer disease in a prospective cohort. Cognitively intact subjects completed a questionnaire that assessed many potential risk factors, including exposure to solvents. Five years later, 36 subjects developed the disease, and 694 remained cognitively intact. The analysis for exposure to solvents (degreasers), which included 28 cases and 531 noncases, resulted in an OR of 0.88 (95% CI, 0.31-2.50). Although the study had a unique design, it does not have a major effect on the overall evidence to determine whether an association exists between solvent exposure and Alzheimer disease.

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- The committee concludes that there continues to be inadequate/insufficient evidence to determine whether an association exists between solvent exposure and Alzheimer disease.

Neurobehavioral Effects

IOM 2003 Conclusions

Review of over 300 studies of solvent exposure and neurobehavioral symptoms (such as fatigue, lack of coordination, and sensory disturbances) or neurobehavioral test results (such as results of tests of attention, reaction time, and visuomotor coordination) by IOM (2003) yielded only seven studies that had isolated former exposure from current exposure. The only way to identify chronic effects that continue past the period of active exposure is through studies that consider formerly (but not currently) solvent-exposed people. Of those studies, several (Mikkelsen et al. 1988; Parkinson et al. 1990; Hanninen et al. 1991; Daniell et al. 1993; Lundberg et al. 1995; Stollery 1996) found evidence of continued deficits in formerly solvent-exposed workers compared with reasonably constituted unexposed groups. Many studies compared painters or other solvent-exposed workers with people in similar occupations (such as carpentry) that did not have the same exposure history. The most specific and sophisticated evaluation of those previously exposed to solvents was conducted by Daniell et al. (1999), who found dose-dependent effects on neurobehavioral function some time after cessation of exposure. Although each of the studies found that one or more symptoms or test realms showed a deficit in function, there is not much consistency among the studies in which specific symptom or test was found to be affected, the comparison groups are not necessarily precisely comparable, and confounding factors were controlled to various degrees, so even relatively consistent evidence of some effects falls short of conclusive data. IOM concluded that there is limited/suggestive evidence of an association between past exposure to solvents and neurobehavioral outcomes, with the most support for decrements in visuomotor and motor function, for fatigue, for headache, and for difficulty in concentrating.

2008 Evaluation

Recent studies have addressed the relationship between solvent exposure and neurobehavioral outcomes, including one focused on TCE (Reif et al. 2003) and one on PCE (Janulewicz et al. 2008). The study by Reif et al. (2003) evaluated neurobehavioral function in 184 adults who had been exposed through contaminated drinking water many years before testing. Higher exposure was associated with poorer performance on several tests (such as digit symbol and contrast sensitivity) and with increased symptoms (such as confusion, depression, and tension). The study of PCE (Janulewicz et al. 2008) addressed prenatal exposure in the Cape Cod water-contamination episode and evaluated school records for indications of learning or behavioral disorders. It found essentially no support of such an association. The studies of community water-supply contamination continue to provide mixed findings, as was found in the 2003 IOM report.

- The committee concludes that there continues to be limited/suggestive evidence of an association between past solvent exposure and neurobehavioral outcomes.

Long-Term Reduction in Color Discrimination

IOM 2003 Conclusions

IOM (2003) reviewed a series of studies of occupational solvent exposure that addressed an ill-defined combination of past and present solvent exposure in relation to measures of color discrimination.

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Because the exposure was continuing, it is not possible from these studies, a number of which provide evidence of a relationship between solvent exposure and reduction in color discrimination, to address the question of whether there is a long-term effect that continues beyond the period of exposure. One report addressed dry-cleaning workers exposed to PCE (Gobba et al. 1998) and found that there was a dose-related decrement in visual discrimination that did not decline after a period of diminishing exposure but, as in other studies, there was no exposure-free interval before visual testing, so the study results do not address whether PCE's effects were short-term or long-term. IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between exposure to TCE, PCE, or other solvents reviewed and long-term reduction in color discrimination.

2008 Evaluation

A report by Schreiber et al. (2002) that was not included in the IOM review evaluated residents who lived in an apartment building or attended day care above a dry-cleaning facility. Changes in visual contrast sensitivity and visual acuity were addressed but not color discrimination itself. The authors reported that visual contrast sensitivity but not visual acuity was reduced. No additional reports on reduction in color discrimination were identified.

- The committee concludes that there continues to be inadequate/insufficient evidence to determine whether an association exists between exposure to TCE or PCE and long-term reduction in color discrimination.

Long-Term Hearing Loss

IOM 2003 Conclusions

IOM (2003) reviewed a series of studies addressing the potential for occupational solvent exposure to exacerbate the well-established adverse effect of noise exposure on hearing. Several of the studies that were reviewed yielded evidence that supported the hypothesis that workers exposed to solvents and noise would experience greater hearing loss than those exposed to noise alone (Bergström and Nyström 1986; Morata et al. 1993, 1997), but none considered whether there is a long-term effect of solvents that continues beyond the period of exposure, and there is some evidence that the effect is a short-term one. IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between exposure to TCE, PCE, or other solvents and long-term hearing loss.

2008 Evaluation

No additional studies of solvent exposure and long-term hearing loss were identified.

- There continues to be inadequate/insufficient evidence to determine whether an association exists between exposure to TCE, PCE, or other solvents and long-term hearing loss.

Long-Term Reduction in Olfactory Function

IOM 2003 Conclusions

Several cross-sectional studies addressed occupational solvent exposure and reduction in olfactory function. Studies of paint manufacturing were mixed—one positive (Schwartz et al. 1990) and the other negative (Sandmark et al. 1989)—and the one study of toluene exposure reported a positive associa-

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tion (Hotz et al. 1992). In all cases, exposure was current, and no study could evaluate whether any adverse effects persisted beyond the period of exposure. IOM concluded that there was inadequate/insufficient evidence to determine whether an association exists between exposure to TCE, PCE, or other solvents and long-term reduction in olfactory function.

2008 Evaluation

No additional studies of solvent exposure and long-term reduction in olfactory function were identified.

- There continues to be inadequate/insufficient evidence to determine whether an association exists between exposure to TCE, PCE, or other solvents and long-term reduction in olfactory function.

CONCLUSIONS

The committee undertook a general review of the epidemiologic evidence on TCE, PCE, and solvent mixtures. On the basis of the reviews referred to in this chapter, the committee concludes that the strongest evidence of an association between TCE or PCE and health outcomes is in the category of *limited/suggestive evidence of an association* related to the following end points:

- Esophageal cancer (PCE)
- Lung cancer (PCE)
- Breast cancer (PCE)
- Bladder cancer (PCE)
- Kidney cancer (TCE, PCE)
- Miscarriage (PCE)

The strongest evidence of an association between solvent mixtures and health outcomes is in the category of *limited/suggestive evidence of an association* related to the following end points:

- Adult leukemia
- Multiple myeloma
- Kidney toxicity
- Liver toxicity (hepatic steatosis)
- Female infertility
- Scleroderma
- Neurobehavioral effects

For all other outcomes considered, the committee categorized the evidence as *inadequate/insufficient* for determining whether associations exit.

Chapter 6 presents a more detailed review of the epidemiologic studies that involved community exposure to drinking water contaminated with TCE or PCE, and Chapter 8 reviews studies of former Camp Lejeune residents. Chapter 7 provides an integrated discussion of the epidemiologic evidence in context with the toxicologic evidence on TCE and PCE.

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6

Epidemiologic Studies of Solvent-Contaminated Water Supplies

The results of studies of human populations that were exposed to solvents through water supplies were included as part of the comprehensive evaluations of the epidemiologic literature provided in Chapter 5. In those evaluations, the epidemiologic literature was considered comprehensively to evaluate a global question: What is the evidence that a particular chemical may be associated with a specific health outcome? The studies were dominated by occupational studies of dry cleaners and other workers, which typically have greater exposures that are well documented but are restricted to populations of relatively healthy men and involve exposure pathways that differ from those at Camp Lejeune.

This chapter focuses more on studies that addressed situations that approximate the circumstances at Camp Lejeune more closely (see Table 6-1). Those situations involve episodes of solvent contamination of water used by a community's population for drinking, bathing, and other purposes. As at Camp Lejeune, a population's water supply was contaminated with solvents from industrial sources, distributed to the public, and used for household purposes. Thus, such studies have had to grapple with the same methodologic challenges that face investigators of the Camp Lejeune situation, including exposure assessment, population identification, potential confounding factors, and small study size and statistical power. The exposed populations typically include the full spectrum of people—all ages, both sexes, and varied health status (including pregnancy)—with varied behavior related to water use and widely varying background influences on disease risk.

An examination of those studies in more detail contributes to the context and strategy for addressing environmental health concerns at Camp Lejeune. First, there may be methodologic lessons to be learned, such as beneficial research strategies that would be suitable for application to epidemiologic studies of Camp Lejeune. Second, as noted above, the studies share some important characteristics with the Camp Lejeune situation. Thus, in setting priorities for outcomes warranting attention at Camp Lejeune, the committee considered the studies of contaminated community water supplies as a distinctively relevant group of epidemiologic studies. Unfortunately, as noted below, methodologic limitations limited the contribution of such studies despite their advantages in being somewhat analogous to the Camp Lejeune water-contamination situation.

METHODS

Study Designs

The contamination events whose study is in Table 6-1 came to attention in a variety of ways. In one instance, a disease cluster raised attention (Mallin 1990), but it appears that all the others came to notice because environmental contamination raised concern about potential health effects among exposed

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TABLE 6-1 Summary of Epidemiologic Studies Involving Drinking-Water Contamination with TCE, PCE, and Other Solvents

Exposure Source	Study Design	Primary Exposure Assessment	Health Outcomes Evaluated	Relative Risk (95% CI); n = exposed cases	Potential Confounders Considered	Reference and Comments
Tucson, AZ (well contamination, 1969-1981)						
TCE, dichloroethylene and chromium in groundwater from dumping of military, industrial wastes	Case-control	Parental residence or employment in census tracts likely to receive contaminated water at least 1 month before and during first trimester of pregnancy[a]	Congenital heart defects	1969-1987: relative OR estimated to be 3 times greater in exposed group; n = 246 1969-1981: Bove et al. (2002) reanalyzed data to restrict analysis to contamination period; prevalence ratio, 2.6 (2.0-3.4)		Goldberg et al. 1990, Bove et al. 2002; used inappropriate controls; imprecise geographic delineation of contaminated area
	Ecologic	Maternal address at delivery linked by GIS to census tracts served by contaminated wells, identified with groundwater transport and fate model	Low birth weight, very low birth weight, term low birth weight	1979-1981 (years with computerized records): very low birth weight (n = 13): adj OR, 3.3 (0.5-20.6)	Gestational time, prenatal-care index, pregnancy complications, pregnancy illness, congenital abnormalities, sex of baby, race of baby, Hispanic origin of baby, parity, age of mother, mother's education, marital status	Rodenbeck et al. 2000
San Bernardino County, CA (well contamination, 1980-1990; study period, 1988-1998)						
TCE, ammonium perchlorate in groundwater (unspecified source)	Ecologic	Residential location (13 census tracts served by contaminated wells)[a]	16 cancer types	Significantly higher number of cases than expected for uterine cancer (n = 124): RR, 1.4 (99% CI, 1.1-1.7); melanoma (n = 137): RR, 1.4 (99% CI, 1.1-1.8)		Morgan and Cassady 2002; authors attribute excess uterine cancer, melanoma to higher SES of exposed population[b]
Santa Clara, CA (well contamination, 1980-1981; study period, 1980-1985)						
Trichloroethane in groundwater contaminated by underground waste-solvent storage tank at semiconductor plant	Cohort	Maternal residence in census tract served by contaminated well[a]	Spontaneous abortion, congenital abnormalities, low birth weight	Spontaneous abortion (n = 64): adj RR, 2.3 (1.3-4.2); congenital malformations (n = 10): RR, 3.1 (1.1-10.4); no low-birth-weight babies born in contaminated area	Maternal age, alcohol consumption, smoking, prior fetal loss, number previous pregnancies, ethnicity, maternal exposure to organic solvents, petrochemicals, pesticides, x rays	Deane et al. 1989

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	Cohort	Residential proximity to contaminated well, defined by census tracts, period [a] For 1981, groundwater fate and transport model coupled to water-distribution model to estimate maternal first-month, first-trimester exposures	Spontaneous abortion, congenital abnormalities, low birth weight	Original study area: spontaneous abortion (n = 89): RR, 3.5 (1.2-10.3); congenital malformations (n = 96): RR, 4.3 (1.2-14.7); low birth weight (n = 281): RR, 0.7 (0.2-1.8) Adjacent census tract likely to have been exposed to water from contaminated wells: spontaneous abortion (n = 86): RR, 0.3 (0,1-1.1); congenital malformations (n = 105): RR, 0.9 (0,1-6.6); low birth weight (n = 294): RR, 1.7 (0.5-6.0)		Wrensch et al. 1990
	Case-control	Consumption of tap, bottled water during first trimester (mostly tap water vs mostly bottled water); among women consuming mostly tap water, source (groundwater vs surface water) by county	Adverse pregnancy outcomes	Telephone respondents: spontaneous abortion: OR, 2.2 (1.4, 3.6); anomalies: OR, 1.8 (95% CI: 0.8, 4.1) Mail respondents: spontaneous abortion: OR, 1.3 (0.8, 2.0); anomalies: OR, 0.8 (0.4, 1.7)		Hertz-Picciotto et al. 1992; (unadjusted) ORs are for consumption of tap, bottled water; hazard ratios also reported for spontaneous abortion by county (San Mateo, Alameda, Santa Clara), source of water (ground vs surface) in women consuming mostly tap water
	Case-control	Maternal address at delivery linked to areas in (exposed), outside (unexposed) distribution system[a]	Congenital cardiac abnormalities	1981-1982: RR, 2.2 (1.2-4.0), n = 12		Swan et al. 1989
				1981-1983: adj RR, 1.5 (0.8-3.0), n = 143	Mother's education, race	Shaw et al. 1990
Denver, CO						
TCE, PCE contamination of municipal wells from hazardous-waste sites	Cohort	Hydraulic simulation model, GIS used to assign mean TCE levels based on residential (census block) location	Neurobehavioral effects	Higher exposure (>15 µg/L; n = 20) associated with poorer performance on digit-symbol test (P = 0.07), contrast-sensitivity tests C, D (P = 0.06, 0.07); 37-83% higher mean scores for confusion, depression, tension; strong interaction with alcohol consumption	Self-reported consumption of seafood once a week or more, years of education, smoking, alcohol consumption	Reif et al. 2003

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TABLE 6-1 Continued

Exposure Source	Study Design	Primary Exposure Assessment	Health Outcomes Evaluated	Relative Risk (95% CI); n = exposed cases	Potential Confounders Considered	Reference and Comments
Denver, CO						
TCE, PCE contamination of municipal wells from hazardous-waste sites	Cohort	Hydraulic simulation model, GIS used to assign mean TCE levels based on residential (census block) location	Neurobehavioral effects	Higher exposure (>15 µg/L; n = 20) associated with poorer performance on digit-symbol test (P = 0.07), contrast-sensitivity tests C, D (P = 0.06, 0.07); 37-83% higher mean scores for confusion, depression, tension; strong interaction with alcohol consumption	Self-reported consumption of seafood once a week or more, years of education, smoking, alcohol consumption	Reif et al. 2003
Northwestern Illinois						
Groundwater contamination (organic chemicals, heavy metals) due to dumping of solid, liquid wastes	Ecologic	Residence by county, ZIP code in nine-county area[a]	Bladder cancer	RR in males (n = 21), 1.7 (1.1-2.6); females (n = 10), 2.6 (1.2-4.7)		Mallin 1990
Woburn, MA, 1964-1983						
TCE, PCE in municipal wells contaminated by industrial wastes	Cohort	Annual estimates of fraction of water supply served by contaminated wells; residential history[a]	Childhood leukemia, adverse pregnancy outcomes, childhood disorders	Positive associations reported for childhood leukemia (n = 20; P = 0.001), eye or ear anomalies (n = 9; P < 0.0001), CNS or chromosomal or oral cleft anomalies (n = 8; P = 0.01), kidney or urinary tract disorders (n = 43; P = 0.02), lung or respiratory disorders (n = 192; P = 0.05), perinatal deaths, 1970-1982 (n = 4; P = 0.003)	Smoking, age, prior fetal loss, prior perinatal death, prior low birth weight, prior musculoskeletal anomaly, SES, year pregnancy ended	Lagakos et al. 1986
	Case-control	Average, cumulative exposure metrics[a]	Childhood leukemia	RR, 8.3 (0.7-94.7); n = 19; dose-response trend (P < 0.05)		Costas et al. 2002
Cape Cod, MA						
Leaching of PCE from inner vinyl lining of asbestos cement water-distribution pipes	Case-control	Residential history, water flow, pipe characteristics to predict PCE in distribution system[a]	Leukemia and lung, breast, colorectal, bladder, kidney, pancreatic, brain, liver cancer	Cancers with increased risk: leukemia (no latency): adj OR, 2.1 (0.9-5.2); n = 34	Sex, age at diagnosis or index year, vital status, education level, occupational exposure to solvents, prior medical treatment with irradiation	Aschengrau et al. 1993

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	Case-control	See Aschengrau et al. (1993)	Breast cancer	Adj OR (for latency of 0-15 years), 1.6 (1.1-2.4) to 1.9 (1.1-3.2); n = 930	Age at diagnosis or index year, vital status, family history of breast cancer, age at first live birth or stillbirth, prior breast cancer or benign breast disease, occupational exposure to solvents	Aschengrau et al. 1998, 2003 (combined data presented)[c]
	Case-control	Annual PCE levels (see Aschengrau et al. [1993]) coupled to information on tap water consumption and bathing habits	Breast cancer	Adj OR (for latency of 0-15 years), 1.4 (0.8-2.5) to 1.9 (0.6-5.9); n = 154[d]	Age at diagnosis or index year, family history of breast cancer, prior breast cancer, age at first live birth or stillbirth, occupational exposure to PCE	Vieira et al. 2005
	Case-control	See Aschengrau et al. (1993)	Colorectal, lung, brain, pancreatic cancer	Cancers with increased risk: colorectal cancer (11-year latency): adj OR, 1.7 (0.8-3.8); n = 311	Age at diagnosis or index year, vital status, sex, occupational exposure to solvents, history of polyps, inflammatory bowel disease, or ulcerative colitis, occupational history associated with colorectal cancer (exposure to asbestos, solvents)	Paulu et al. 1999
	Cohort	Residential history; leaching, transport model; water-distribution model, GIS to predict monthly levels at nodes in distribution system	Birth weight, gestation duration	No associations found between exposure and birth weight or gestational duration; n = 1,353	Gestational age, maternal race, education level, history of low-birth-weight child, occupational exposure to solvents, use of self-service dry cleaning, residential proximity to dry-cleaning establishments, prior preterm delivery, obstetrical complications in current pregnancy	Aschengrau et al. 2008
Upper New Jersey (Bergen, Essex, Morris, Passaic Counties)						
TCE, PCE	Ecologic	Residential location[a]	Leukemia	Leukemia, males: SIR, 1.0 (0.7-1.5), n = 25; females: SIR,= 1.5 (1.0-2.2), n = 28		Fagliano et al. 1990

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TABLE 6-1 Continued

Exposure Source	Study Design	Primary Exposure Assessment	Health Outcomes Evaluated	Relative Risk (95% CI); n = exposed cases	Potential Confounders Considered	Reference and Comments
TCE, PCE	Ecologic	Average 1984-85 levels from quarterly monitoring data for 75 towns	Leukemia, NHL	For highest exposure stratum: leukemia in males: RR, 1.1 (0.8-1.4), n = 63; females: RR, 1.4 (1.1-1.9), n = 56; acute lymphocytic leukemia in females <20 years old: RR, 3.3 (1.3-8.2), n = 6; NHL in males: RR, 1.2 (0.9-1.5), n = 78; females: RR, 1.4 (1.1-1.7), n = 87; diffuse large-cell NHL in males: 1.6 (1.0-2.4), n = 26; females: RR, 1.7 (1.1-2.6), n = 24; non-Burkitt's in males: RR, 1.9 (0.5-6.8), n = 3; females: RR, 3.2 (1.2-8.2), n = 6		Cohn et al. 1994
TCE, PCE from landfill leachate, industrial waste disposal, leaking underground storage tanks	Case-control	Maternal address at delivery; monthly estimates from quarterly monitoring data from 75 municipalities[a]	SGA, preterm birth, birth weight, birth defects, fetal death	TCE: CNS defects: OR, 1.7 (90% CI, 0.8-3.5), n = 6; neural-tube defects: OR, 2.5 (90% CI, 0.9-6.4), n = 4; oral-cleft defects: OR, 2.2 (90% CI, 1.2-4.2), n = 9 PCE: oral-cleft defects: OR, 3.5 (90% CI, 1.3-8.8), n = 4	Maternal age, race, education level, primipara, prior fetal loss or stillbirth, sex of child, adequacy of prenatal care	Bove et al. 1995; if adjusted OR differed by more than 15%, adjusted value was reported as OR; no distinction made between adjusted and unadjusted values
Southern Finland						
TCE, PCE from industrial sources, dump site	Ecologic	Residence at diagnosis (Hausjarvi and Hattula)[a]	Liver cancer, NHL, Hodgkin disease, multiple myeloma, leukemia	Increaseded risks in Hausjarvi: leukemia: RR, 1.2 (0.8-1.7), n = 33; Hattula: NHL: RR, 1.4 (1.0-2.0), n = 31; Hodgkin disease: RR, 1.4 (0.7-2.5), n = 11		Vartiainen et al. 1993
Taoyuan County, Taiwan						
Hazardous-waste site (formerly electronics factory)	Case-control	Residential proximity to contaminated wells, period of death[a]	Cancers	Leading causes of cancer deaths in all male population: liver: adj MOR, 2.6 (1.2-5.5), n = 53; stomach: adj MOR, 2.2 (1.0-4.9), n = 39; lung: adj MOR, 1.8 (0.8-3.9), n = 41; colorectal: adj MOR, 0.8 (0.2-2.9), n = 26; all: adj, MOR, 2.1 (1.3-3.3), n = 266		Lee et al. 2003

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Indiana, Illinois, Michigan						
Superfund sites	Cohort	Listed in TCE exposure registry[a]	Multiple health outcomes	Statistically significant results for stroke: adj OR, 3.2 (1.1-9.0) to 4.1 (1.5-11) for max. TCE quartiles, n = 60; respiratory allergies: adj OR, 2.2 (1.1-4.2), n = NR; asthma, emphysema: adj OR, 1.8 (1.0-3.3) for cumulative exposure, n = NR	Age, sex, smoking, occupational exposure, education level for stroke; age, sex for asthma, emphysema	Burg and Gist 1999
Michigan, Indiana, Pennsylvania, Arizona						
Superfund sites	Cohort	Listed in TCE exposure registry[a]	Multiple health outcomes	Excess cases over lifetime of registry for anemia, other blood disorders, liver problems, rashes, eczema, other skin allergies		Davis et al. 2005
Iowa						
Water-disinfection byproducts	Ecologic	Water-supply source	Bladder, breast, colon, lung, prostatic, rectal cancer	No associations between TCE or PCE and cancers		Isacson et al. 1985

[a]See Table 6-2 for more detailed exposure data.
[b]Higher than average SES predicts access to health care, which enhances detection of melanoma. Access to health care also makes it more likely that postmenopausal women will receive estrogen-replacement therapy, which is linked to increased endometrial cancer (main form of uterine cancer).
[c]Adjusted OR in Aschengrau et al. (1998) ranged from 0.6 (0.0-3.7) to 2.3 (0.6-8.8), n = 258; adjusted OR in Aschengrau et al. (2003) ranged from 1.5 (1.0-2.4) to 1.9 (1.0-3.5) for 0-15 years of latency, n = 672.
[d]Analysis restricted to nonproxy subjects.
Abbreviations: CI = confidence interval, CNS = central nervous system, GIS = geographic information system, MOR = mortality odds ratio, NHL = non-Hodgkin lymphoma, NR = not reported, OR = odds ratio, PCE = perchloroethylene, RR = relative risk, SES = socioeconomic status, SGA = small for gestational age, SIR = standardized incidence ratio, SRR = standardized rate ratio, TCE = trichloroethylene.

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residents. All the studies included a broad enough geographic area or period to contrast disease risks in people with greater and smaller degrees of exposure associated with the contamination, and the quality of the exposure assessment varied widely among the studies. A time element was also used to define exposure, such as residence in a specific location over a specific calendar period. In some instances, people were asked detailed questions to help to characterize exposure beyond the geography and the period of contamination related to water use. Because exposure was driven largely by residential location, the studies are susceptible to confounding by the many geographically based attributes that affect disease other than the exposure of interest, such as socioeconomic differences or associated lifestyle factors, for example, tobacco or alcohol use and quality of medical care that might affect diagnoses. Some studies (Hertz-Picciotto et al. 1992; Aschengrau et al. 1993, 1998; Costas et al. 2002; Reif et al. 2003) included individual interviews, which made it possible to assess and consider a variety of potential confounders in the analysis.

Exposure Assessment

Table 6-2 presents exposure data from the studies in Table 6-1 that monitored concentrations of trichloroethylene (TCE), perchloroethylene (PCE), and other solvents in production wells from which water was pumped for delivery to the distribution systems of the affected communities. The way in which the episodes studied were identified (the discovery of contaminated water supplies at some time) means that monitoring data on a water supply for the putative agents were largely nonexistent except for periods close to or right after identification of the problem, as was the case at Camp Lejeune. In Woburn, Massachusetts, for example, concerns about possible contamination from industrial wastes in the late 1970s led to the testing and closing of wells in which increased concentrations of TCE (267 ppb) and PCE (21 ppb) were detected (Lagakos et al. 1986). The Santa Clara County contamination incident in California is another example of a well's being shut down immediately after the detection of high concentrations of trichloroethane (1,700 ppb) (Deane et al. 1989). Another well-known contamination episode occurred in Cape Cod, Massachusetts, as a result of leaching of PCE from the vinyl lining of asbestos-cement water-distribution pipes. The lining of the pipes had been applied in the late 1960s, but the contamination was discovered only after sampling was carried out more than 10 years later. In that instance, the range of the measurements collected throughout the distribution system constituted evidence of spatial variability in contaminant concentrations: concentrations at low-use locations (1,600-7,750 μg/L) were 20-5,000 times higher than those at high-use locations (1.5-80 μg/L).

To compensate for the lack of monitoring data in studies of increased health risks associated with contaminated drinking water, investigators used exposure assessments whose complexity depended on the sources of data and the metrics. One of the simplest surrogates of exposure relied on residential proximity to the source of contamination. In those cases, exposure was inferred from residence in areas served by contaminated wells (Deane et al. 1989; Swan et al. 1989; Goldberg et al. 1990; Wrensch et al. 1990; Lee et al. 2003); in one study, the inference was aided by groundwater transport and fate models to define potentially exposed areas (Rodenbeck et al. 2000) and in another by groundwater sampling (albeit later than the study period) to verify the classification of exposed areas downstream of the source (hazardous-waste site) of the contamination (Lee et al. 2003). In the only study that relied on biologic monitoring to evaluate potential solvent exposure, Vartiainen et al. (1993) compared urinary metabolites of TCE and PCE (dichloroacetic acid and trichloroacetic acid) in residents of municipalities with and without groundwater contamination.

More sophisticated exposure-assessment approaches have used hydraulic modeling of the water-distribution system that accounts for the pumping of water from both contaminated and uncontaminated wells and for characteristics of the pipe network (such as geometry, age, diameter, and leaks). For example, several studies of the potentially affected community in Woburn, Massachusetts, used a hydraulic mixing model to estimate the fraction of water received by each residence weekly (Lagakos et al. 1986) or monthly (MDPH/CDC/MHRI 1996; Costas et al. 2002) from contaminated wells. Wrensch et al. (1990)

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TABLE 6-2 Summary of Reported Water-Monitoring Data in Published Epidemiologic Studies[a]

Source of Contamination	Sampling Period	Sampling Location	Contaminant	Concentrations	Reference and Comment
Tucson Valley, AZ					
Industrial wastes	1981	9 public wells	TCE	6-239 ppb	Goldberg et al. 1990
San Bernardino County, CA					
Unspecified	1980 and later 2001	20 public wells	TCE	0.09-97 ppb (<5 ppb in distribution system since 1991)	Morgan and Cassady 2002
		Public wells (number not specified)	Ammonium perchlorate	5-98 ppb (<18 ppb since 2001)	
Santa Clara County, CA					
Underground waste-solvent storage tank (near semiconductor plant)	Dec. 7, 1981	Public well 13	1,1,1-TCA	1,700 ppb	Deane et al. 1989; Swan et al. 1989; Wrensch et al. 1990; well 13 removed from service on Dec. 7, 1981
	Dec. 14, 1981		1,1,1-TCA	8,800 ppb	
	Mar. 1982		1,1,1-DCE	8.8 ppb	
	Mar. 1982	Public well 8	TCA	33.5 ppb	
			DCE	9.6 ppb	
Northwestern Illinois					
Dumping of solid, liquid wastes	1982-1988	Public well 1	Benzene	<1 ppb	Mallin 1990
			1,2-Dichlorocthanc	1.6-2.1 ppb	
			1,1,1-TCA	7 ppb	
			1,1-Dichlorocthanc	2-11 ppb	
			trans-1,2-DCE	8-42 ppb	
			Methylene chloride	<1 ppb	
			PCE	<1ppb	
			TCE	2-10 ppb	
			Chloroform	1.3 ppb	
			Dibromochloromethane	<1 ppb	
		Public well 2	Benzene	1.3-2 ppb	
			1,2-Dichloroethane	1.7-2 ppb	
			1,1,1-TCA	1 ppb	
			1,1-Dichloroethane	1-4.6 ppb	
			trans-1,2-DCE	14-38 ppb	
			Methylene chloride	1-5 ppb	

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TABLE 6-2 Continued

Source of Contamination	Sampling Period	Sampling Location	Contaminant	Concentrations	Reference and Comment
			PCE	5.1 ppb	
			TCE	2-15 ppb	
			Chloroform	27 ppb	
			Dibromochloromethane	12 ppb	
Woburn, MA					
Industrial wastes	1979	Public wellsG and H	TCE	267 ppb	Lagakos et al. 1986; Costas et al. 2002; Byers et al. 1988; wells closed after sampling in May 1979
			PCE	21 ppb	
			Trichlorofluoroethane	23 ppb	
			DCE	28 ppb	
			Arsenic	0.0020 ppm	
			Chloroform	11.8 ppb	
Cape Cod, MA					
TCE in inner vinyl lining of asbestos-cement water-distribution pipes	~1980	Water-distribution pipes Low-use sites Medium- and high-use sites	PCE	1,600-7,750 µg/L 1.5-80 µg/L High value of 18,000 µg/L at dead-end sites in Falmouth reported in Paulu et al. (1999)	Aschengrau et al. 1993, 1998, 2003, 2008; Paulu et al. 1999; Massachusetts Department of Environmental Protection began program of flushing, continuous bleeding in 1980 to lower PCE concentrations
Rhode Island	1976	Water-distribution systems	PCE	800-2,000 µg/L	Paulu et al. 1999
Upper New Jersey (Bergen, Essex, Morris, Passaic Counties)					
Landfill leachate; industrial waste disposal, leaking underground storage tanks	1985-1988	49 distribution systems serving 75 towns		Monthly estimates:	Bove et al. 1995
			TCE	55 ppb	
			PCE	26 ppb	
			1,1,1-TCA	18 ppb	
			Carbon tetrachloride	7 ppb	
			1,2-Dichloroethane	19 ppb	
			Total DCE	16 ppb	
			Benzene	2 ppb	
			Total trihalomethanes	299 ppb	

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	1984-1985	Routine sampling in distribution systems of 27 towns in Lower Passaic River and Saddle River drainage basin	14 unspecified compounds	Sum of average of nontrihalomethane VOCs (no. towns) 72 µg/L (1) 67 µg/L (1) 47 µg/L (1) 40 µg/L (1) 37 µg/L (1) 12 µg/L (1) 9 µg/L (1) 7 µg/L (1) 5 µg/L (4) 3 µg/L (2) 2 µg/L (2) 1 µg/L (9) 0 µg/L (2)	Fagliano et al. (1990)
Southern Finland					
Industrial sources (Oitti)	1992	Drinking-water samples	TCE, PCE (Oitti)	100-200 µg/L	Vartiainen et al. 1993
Dump site (Hattula)	July 1992		TCE (Hattula)	212 µg/L 66 µg/L	
Taoyuan County, Taiwan					
Hazardous-waste site (formerly electronics factory)	Oct. 1999-May 2000	Residential wells		Median (range)	Lee et al. 2003; previous reports of off-site groundwater contamination indicated up to 930 and 4,800 µg/L for TCE and PCE, respectively
			Vinyl chloride	0.003 µg/L (ND-72.3)	
			Tetrachloroethene	2.95 µg/L (ND-5,228.3)	
			TCE	28.43 µg/L (ND-1,790.7)	
			1,1-DCE	1.35 µg/L (ND-1,240.4)	
			1,1,1-TCA	0.67 µg/L (ND-1,504.4)	
			cis-1,2-DCE	3.05 µg/L (ND-1,376.0)	
			1,1-Dichloroethane	1.81 µg/L (ND-227.9)	
Indiana, Illinois, Michigan					
National Priorities List sites		TCE subregistry site	TCE	Maximum/median (no. household samples)	Burg and Gist 1999
		Verona Well Field and Dowaglac (MI)		2,000/6.0 ppb (66)	
		McGraw-Edison Corporation (MI)		733/1.0 ppb	
		Superior Street (IN)		19,380/84.0 ppb (134)	
		Central Area (IN)		114/0.4 ppb (28)	
		Gemeinhardt Piccolo Company (IN)		1,600/4.0 ppb (100)	

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TABLE 6-2 Continued

Source of Contamination	Sampling Period	Sampling Location	Contaminant	Concentrations	Reference and Comment
		Conrail Rail Yard (IN)		1,520/78.0 ppb (49)	
		Acme Solvents Reclamation, Inc. (IL)		100/1 ppb (13)	
		Beloit Corporation (IL)		3/2 ppb (3)	
		Byron Johnson Salvage Yard (IL)		249/9.1 ppb (25)	
		Frinks Industrial Waste (IL)		16/14.0 ppb (5)	
		Southeast Rockford groundwater contamination (IL)		122/15.0 ppb (331)	
		Warner Electronic Brake and Clutch Company (IL)		5,220/234.0 ppb (74)	
Michigan, Indiana, Illinois, Pennsylvania, Arizona					
National Priorities List sites (n = 15)		Residential sites	TCE	Median concentrations, 0.4-234 ppb; maximum concentrations, 3-24,000 ppb	Davis et al. 2005
Iowa					
		Sampling of drinking water from treatment plants at municipalities in Iowa serving 1,000 or more residents	TCE PCE 1,2-Dichloroethane 1,1,1-TCA	Data reported as % of towns with detectable VOC concentrations by source of supply water (surface, <46 m, 46-152 m, >152 m)	Isacson et al. 1985

[a]Following studies were also evaluated for water-monitoring data, but none were found: Cohn et al. (1994); Hertz-Picciotto et al. (1992); Reif et al. (2003); Rodenbeck et al. (2000); Shaw et al. (1990); Viera et al. (2005).

Abbreviations: DCE = dichloroethylene, ND = not detected, PCE = perchloroethylene, TCA = trichloroacetic acid, TCE = trichloroethylene, VOC = volatile organic compound.

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developed a groundwater fate and transport model to estimate concentrations of trichloroethane in the aquifer that supplied water to the production well (in which the contamination was detected); the results were coupled to a water-distribution model to estimate the probability that water from the contaminated well reached specific locations in the distribution system. In studies carried out to investigate the cancer risk posed by PCE-contaminated drinking water in Cape Cod, Massachusetts, investigators used a water-distribution model (the Webler-Brown model) that predicted the amount of PCE leaching from the vinyl-lined pipes and then transported to residences served by the distribution systems (Aschengrau et al. 1993, 1998; Paulu et al. 1999); the modeling effort was later improved on by using geographic information systems (GISs) (rather than tax-assessor maps) to geocode key elements of the water-distribution system and study participants' residences (Aschengrau et al. 2003). Reif et al. (2003) also took advantage of the capabilities of GISs and linked residences of persons living near the Rocky Mountain Arsenal whose water supply had been contaminated with TCE to results from a hydraulic model (EPANET) to reconstruct 1985 contaminant concentrations at specific nodes in the distribution system.

Cognizant that exposure is influenced not only by concentrations of a contaminant in drinking water but by the amount of water consumed or used in other ways, investigators have also gathered individual-level information about consumption patterns, bathing and showering habits, and other water-related behavior with questionnaires or interviews. The resulting data have been used to form the primary exposure measure for evaluating the associations between contaminated drinking water and adverse health outcomes (for example, consumption of cold tap water by source and year) (Shaw et al. 1990) and have been incorporated as covariates in the multiple logistic regression models that have been applied. For example, in addition to evaluating the effect of living in an area served by a contaminated well in Santa Clara, California, consumption of cold tap water at home (Deane et al. 1989; Wrensch et al. 1990) and water-filter use (Wrensch et al. 1990) were assessed. To evaluate heterogeneity in the effects of contaminated water on cancer risk due to water-related behavior, stratified analyses by usual bathing habits (mostly showers, mostly baths, or about equal baths and showers) were conducted in the studies carried out in the Upper Cape region of Massachusetts (Ashengrau et al. 1993, 1998; Paulu et al. 1999). It would be of interest to examine results of studies that used more and less sophisticated approaches to assess exposure, but the contamination episodes are so different from one another that it is impossible to isolate the quality of exposure assessment as an independent influence on the final results.

Health-Outcome Assessment

With few exceptions (such as the study of neurobehavioral function in a Colorado population exposed to solvents [Reif et al. 2003] and the study of pregnancy outcome in Santa Clara, California [Hertz-Picciotto et al. 1992]), all the studies have assessed health outcomes on the basis of existing records. Much of the attention in those studies has been on birth outcomes, including the information obtainable through birth records, which constitute one of the few universal health registry systems available in the United States and eliminate concerns about nonresponse. For all geographic areas and for all periods going back several decades, birth weight, duration of gestation, and selected social and demographic factors can be ascertained. Thus, a number of studies addressed birth weight, preterm birth, and stillbirth.

Some areas have population-based registries of congenital defects and cancer that provide comprehensive coverage of geographically defined populations and periods and allow evaluation of associations with exposures also defined by geography and time. Studies of cancer in Massachusetts, Illinois, and New Jersey have relied on outcome ascertainment from population-based registries (Fagliano et al. 1990; Burg and Gist 1999; Aschengrau et al. 2003). The advantage of using established birth or disease registries is efficiency in time and expense of the studies, but they are limited by the quality of the registries (with respect to comprehensiveness and accuracy of diagnoses) and constrain the scope of studies to the subset of health outcomes on which data are available. Pregnancy outcomes and cancer are often important concerns in episodes of solvent-contaminated water, but they are rarely the only concerns, and other outcomes remain unaddressed.

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The alternative approach, applied in Colorado (Reif et al. 2003) and California (Deane et al. 1989; Hertz-Picciotto et al. 1992) is to identify the population of concern on the basis of exposure (a product of location and time), sample that population to include the desired exposure contrasts, and conduct more detailed health assessments of individuals. Reif et al. (2003) selected residentially exposed persons and tested neurobehavioral characteristics, outcomes not otherwise assessable with existing registries. Similarly, miscarriage assessment requires collecting information directly from potentially affected people, as was done in Santa Clara, California. There is a marked increase in the expense, but the approach allows a focus on the health outcomes of greatest concern rather than those on which data are readily available. In contrast, the need to rely on respondent cooperation to identify people and include them in a study incurs a cost in the potential for bias due to nonparticipation, which is not a problem with registry-based studies. The quality of self-reported data may also be lower for some outcomes.

RESULTS

The studies of populations exposed to contaminated water supplies have generated a wide array of positive associations, as reflected in Table 6-1. Among the most increased relative risks were those for congenital heart defects (odds ratio [OR], 2.6; 95% confidence interval [CI], 2.0-3.4) in Tucson, Arizona (Bove et al. 2002); spontaneous abortion (OR, 2.3; 95% CI, 1.3-4.2) and congenital defects (OR, 3.1; 95% CI, 1.1-10.4) in Santa Clara, California (Deane et al. 1989); and liver cancer (OR, 2.6; 95% CI, 1.2-5.5) in Taoyuan County, Taiwan (Lee et al. 2003).

Although the evidence linking solvents in water supplies to individual outcomes seems impressive in specific studies, the lack of corroboration among studies (or even attempted corroboration in many instances) weakens their credibility. Furthermore, these largely opportunistic studies typically considered the full array of available outcomes from birth certificates, registries, and other available sources and reported the positive findings that emerged from such broad explorations. The universe of other outcomes considered in the studies is not always clear, and the broader universe of investigations of water-contamination episodes that did not identify "interesting" associations and were therefore never published is also unknown and could be substantial. In addition, the focus in many cases on rare outcomes (such as individual birth defects and childhood cancers) renders the resulting risk estimates highly imprecise and driven by as few as two or three cases. Although it is possible that some of the scattered, isolated findings are meaningful and could eventually be proved to indicate a replicable association with a specific health outcome, the results presented in Table 6-1 do not support such a conclusion. Therefore, even acknowledging that the studies are more directly comparable with the Camp Lejeune circumstances than the methodologically stronger studies discussed in Chapter 5, the committee concluded that the epidemiologic literature would be most effectively used if all of it, rather than only studies of community water-contamination episodes, were comprehensively evaluated. The studies reviewed in this chapter were given extra attention because of their applicability, and in some instances (such as the evidence linking water solvents to breast cancer on Cape Cod [Aschengrau et al. 1998, 2003]) the findings contributed substantially to identifying priorities. However, our interpretation of the epidemiologic studies in their totality was not dominated by them.

DISCUSSION

The studies discussed in this chapter yielded reports that were deemed by the investigators and scientific journals to be worthy of publication and that might have generated a disproportionate representation of positive findings. The findings of those studies should not be viewed as a representative or comprehensive set of findings, because investigation of contamination episodes is commonly undertaken by health departments but rarely reported in the literature. Relative to studies of occupational cohorts, which often have much higher and better documented exposures and large populations, the community studies

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are limited by the quality of exposure data and to various extents by the low size of their populations, particularly if such rare outcomes as childhood leukemia and congenital defects are being addressed. Even if the different routes of exposure—inhalation vs ingestion—are recognized, the occupational studies tend to dominate the evidence. The committee has incorporated the information from solvent water-contamination studies, as warranted, into the overall assessments of the epidemiologic evidence as reflected in the tables and categorization of evidence in Chapter 5 and focuses here on any special contributions as a function of the more direct relevance of water contamination as the source of exposure.

With regard to methods, the studies in this chapter have largely started with the conventional approach of characterizing a broad geographic area and period and relating health outcomes to estimated exposure. However, several have gone further in refining the exposure estimates by using sophisticated engineering models (particularly in Woburn, Massachusetts) in ways that are broadly applicable to the situation at Camp Lejeune. Similarly, the Cape Cod studies have gone beyond routinely available information on water source to estimate delivered dose.

The strategy pursued by Reif et al. (2003) and in the series of Santa Clara, California, studies (for example, Wrensch et al. 1990) also warrants consideration. They began with an episode of environmental contamination but proceeded to conduct individual data collection with interviews, medical records, and, in the case of the Denver, Colorado, episode, direct evaluation of potentially affected individuals. Available records have merit as a starting point, but for many health outcomes of interest it is essential to go further to collect new data.

CONCLUSIONS

Collectively, the epidemiologic studies of solvent contamination of water supplies and adverse health effects are of limited quality. If their distinctive strengths and limitations are taken into account, such studies contribute to the overall assessment of the epidemiologic literature, but the committee has judged that their strengths (comparability with Camp Lejeune in exposure pathways and diversity of exposed population) do not overcome their limitations (especially quality of exposure assessment, lower range of exposure, and imprecision in measures of association) to allow identification of high-priority outcomes on the basis of their results alone.

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7

Integration of Findings from the Toxicologic and Epidemiologic Literature

The charge to the committee was to review the scientific evidence concerning associations between exposure to contaminated water and adverse health effects applicable to the population at Camp Lejeune. To address the general evidence on health effects of trichloroethylene (TCE) and perchloroethylene (PCE), the committee reviewed the toxicologic literature (see Chapters 3 and 4) and the epidemiologic literature (see Chapters 5 and 6) for a comprehensive array of health outcomes, drawing on recent authoritative reviews where feasible and appropriate. This chapter considers those sets of literature together to identify health outcomes that are most plausibly due to TCE and PCE, focusing on health outcomes on which the lines of evidence converge.

In evaluating the potential for toxic effects in humans from a chemical exposure, data from human studies are usually considered the most relevant. However, human data are often limited by the size of the population(s) studied, the information on actual exposure concentrations, and other confounding factors. Thus, data from toxicologic studies are also used to evaluate the potential for various health effects from exposure to chemicals under more controlled conditions and usually at higher exposure concentrations than in the human population. The strength of the toxicologic data is dependent on the size, number, and types of studies conducted, as well as replication of study designs and results. The relevance of the animal data to humans is dependent on those factors as well as a number of toxicokinetic and dynamic factors, and they must be weighed carefully in evaluating the potential for environmental exposures to cause various health effects in humans.

In the following sections, the human and animal toxicologic data are discussed briefly for those health outcomes for which some information was available from both types of evidence. In some cases, the human data weighed more heavily because of the strength of the data and/or the association with the exposure. In other cases, the animal data weighed more heavily because of greater integrity of the data or more in-depth evaluation of the dose-response relationship and mechanisms involved.

CANCER OUTCOMES

Chapter 5 reviewed the epidemiologic studies and concluded that there was limited/suggestive evidence of an association between chronic exposure to TCE or PCE and cancers of the breast, bladder, kidneys, esophagus, and lungs. Toxicologic studies did not report significantly increased cancers of the breast, bladder, or esophagus, and rodent lung cancers were judged not to be relevant to humans because of known species differences in metabolism and organ sensitivity. Thus, for outcomes having limited/suggestive epidemiologic evidence of an association, positive concordance with the toxicologic evidence was strongest for kidney cancer. Studies of TCE and PCE found increases in kidney cancer in rats treated chronically at high doses. The mechanism by which the solvents exert their effects on the

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kidneys appears to be similar in rats and humans, and this strengthens the plausibility that these solvents caused kidney cancer in the occupational studies that found suggestive evidence of associations.

Toxicologic studies have reported findings of liver cancer, lung cancer, male reproductive cancers, and mononuclear-cell leukemia in mice or rats exposed to high concentrations of TCE or PCE, but species differences in metabolism and response indicate that these cancers are not relevant to humans (see more detailed discussion in Chapter 4). The epidemiologic evidence on these cancers (except lung cancer) was judged to be inadequate/insufficient to determine whether associations exist.

NONCANCER OUTCOMES

Hepatic Toxicity

Animal toxicity studies indicate that high concentrations of TCE and PCE are required to induce hepatocellular injury (cell replication, peroxisome proliferation, DNA adducts, and increase in serum enzymes released from damaged cells). Mice have a greater capacity to oxidize these solvents than humans. The epidemiologic evidence also shows clear effects of acute, high-level exposure to TCE and other solvents on the liver, but there is little evidence of persistent effects of chronic low-level exposure. The strongest evidence in the epidemiologic literature is limited/suggestive evidence of an association between chronic exposure to solvents and hepatic steatosis.

Renal Toxicity

TCE and PCE have some nephrotoxic potential in rodents and humans. Animal toxicity studies indicate that high concentrations of TCE and PCE are required to induce nephrotoxicity, such as injury to the proximal tubules, glomerulonephropathy, and karyomegaly. Chronic injury to cells of the proximal tubule is considered a prerequisite for the development of kidney cancer caused by TCE. The metabolism and mode of nephrotoxic action of TCE and PCE appear to be similar, although PCE and its metabolites appear to be more potent. Renal effects are due primarily to metabolites formed via the glutathione conjugation pathway. This metabolic pathway is similar qualitatively, but not quantitatively, in rats and humans. Humans have been shown to have a lower capacity than rats to convert TCE and PCE to reactive derivatives of glutathione conjugates. Epidemiologic studies of the effects of short-term and long-term solvent exposure on renal function have yielded limited/suggestive evidence of an association between high levels of solvent exposure, but not chronic low-level exposure, and acute tubular necrosis. A series of case-control studies of chronic glomerulonephritis in relation to solvent exposure have generated mixed evidence regarding an association; several reasonably strong positive studies showed dose-response gradients.

Reproductive Outcomes

The committee found independent toxicologic and epidemiologic evidence of associations between exposure to solvents and reproductive outcomes, but there was limited convergence for specific reproductive end points. For example, toxicologic studies have reported adverse effects on indicators of male fertility in rats and mice after high-dose exposure to TCE and PCE, respectively. Findings in human studies were not sufficiently consistent to support any firm conclusions, but a few studies showed a potential association with male infertility. With regard to female fertility, the epidemiologic evidence suggested an association between solvents in general and reduced fecundability (the ability to become pregnant), but there was little evidence in the toxicology literature to support female infertility, even after exposure at high concentrations.

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The human evidence of an association between chronic exposure to TCE or PCE and congenital malformations was judged to be inadequate to support conclusions. However, the toxicologic data provide strong evidence that neither solvent is associated with congenital malformations in rats. Adverse pregnancy outcomes (other than congenital malformations) were not seen in toxicologic studies of maternal exposure to TCE in rats, but reduced fetal weight in rats was seen in studies of maternal exposure to PCE. Data on female rats exposed before mating and during pregnancy indicate reduced offspring survival at high concentrations. Studies of mating pairs of rats or mice exposed during mating and throughout one or more pregnancies also showed reduced numbers of litters and increased perinatal mortality. Epidemiologic evidence provides some indication that solvent exposure during but not before pregnancy is associated with miscarriage but not with preterm birth or reduced birth weight, and there is no direct evidence on perinatal mortality. Although specific parallels between reduced litter size and perinatal mortality in rodent models and increased miscarriage in humans should not be drawn, the data suggest some corroboration of adverse reproductive effects of exposure during gestation. Pregnancy outcomes in rats after high maternal inhalation exposure to PCE indicate a reduction in intrauterine growth. Epidemiologic studies have addressed fetal growth after exposure to solvents in general and have not found sufficient evidence of an adverse effect. Only a few toxicologic studies of pregnancy outcomes after exposure of males before mating are available, and they indicate a reduction in number of litters at high inhalation concentrations. The epidemiologic evidence on paternal exposure to TCE and adverse pregnancy outcomes was inadequate/insufficient to support any conclusions.

Neurologic Effects

Epidemiologic studies of solvent exposure and neurobehavioral outcomes have for the most part addressed nonspecific solvents or solvents in the aggregate. Overall, there is limited/suggestive evidence of an association between principally inhalation exposure to solvents and neurobehavioral outcomes; the most support is of visuomotor and motor function, fatigue, headache, and deficits in concentration. Most of those effects were reported concurrently with exposure, and there has been little study of whether effects persist after exposure ceases. Animal toxicologic studies also report effects on the nervous system, such as depression of the central nervous system, attention deficits, deficits in visual discrimination, alterations in visual evoked potentials, altered sleep pattern, and reduced exploratory behavior in rats and rabbits exposed for weeks to moderate vapor concentrations of TCE. These changes generally appear to be reversible. Residual auditory loss resulting from losses of cochlear spiral ganglion and hair cells have been observed in rats inhaling high concentrations of TCE. Similar effects have been found in rodents exposed to PCE. In addition, studies of PCE have shown changes in behavior and neurochemical markers at lower levels. Some animal data suggest sensitive windows during development when organisms are more susceptible to PCE exposure, which results in alterations of neurologic development and behavior.

Immunologic Outcomes

Epidemiologic studies have provided some support of two immunologically mediated end points: chronic glomerulonephritis and scleroderma. There is limited/suggestive evidence of an association between mixed solvent exposure and both end points and some indication of a specific association between TCE and scleroderma. The toxicologic data provide strong evidence that TCE can act as a skin sensitizer, modulate existing asthma, produce immunosuppression, and influence autoimmune diseases. Data on PCE have only a suggestion of effects on allergic sensitization and immunosuppression.

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CONCLUSIONS

The committee did not find sufficient evidence to justify causal inference for any health effects it reviewed. However, some effects were identified from a review of the collective evidence from epidemiologic and toxicologic investigations as being relevant health outcomes to consider in future studies of exposures at Camp Lejeune, including kidney cancer, renal toxicity, hepatic toxicity, neurotoxicity, and autoimmune disease. Although other health end points with less support from the existing literature should not be excluded from consideration, such findings are more likely to reflect random error if not supported by additional contexts in the literature.

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8

Studies of the Camp Lejeune Population

This chapter summarizes research that directly addresses the potential impact of contaminated water supplies on the health of Camp Lejeune residents. Although there is indirect evidence on the chemicals of concern from laboratory research and epidemiologic studies of other populations (Chapters 4-7), such information must be extrapolated to the Camp Lejeune setting and population, and extrapolation carries the potential for incorrect inferences. To the extent that scientifically valid epidemiologic research has been conducted directly on Camp Lejeune residents, extrapolation is unnecessary. Thus far, the research on the Camp Lejeune population has been limited with respect to the scope of health outcomes considered and the quality of exposure assessment.

COMPLETED STUDIES

The Agency for Toxic Substances and Disease Registry (ATSDR) is the only agency to have performed epidemiologic studies of the Camp Lejeune population exposed to water supplies contaminated with volatile organic compounds (VOCs). In a public health assessment, ATSDR (1997a) judged that exposure to VOCs in drinking water did not pose health risks to adults but raised questions about risks to children who may have been exposed via their mothers while in utero. Thus, the first study was a case-control study of pregnancy outcomes. Two published analyses resulted from that effort: ATSDR (1998), which focused on trichloroethylene (TCE) and perchloroethylene (PCE) exposures at Tarawa Terrace; and Sonnenfeld et al. (2001), which considered only PCE exposure at Tarawa Terrace. Both analyses focused on pregnancy outcomes regarding live-born infants, including mean birth weight, small for gestational age (SGA), and preterm delivery. ATSDR initially planned to evaluate fetal deaths, also, but that plan was abandoned because of the small number (83) of fetal deaths identified with the computerized state database and because the cause of fetal death was missing from death certificates in most cases (ATSDR 1998). The study methods used in the two analyses will be presented here first, followed by the results of each.

Outcome Measures

Birth weight and pregnancy duration were derived from North Carolina birth records. Preterm birth was defined as a live birth occurring before completion of 37 weeks of gestation. SGA, defined as below the 10th percentile of weight for gestational age, was calculated by using published sex-specific growth curves for white newborns in California (Williams et al. 1982) because a standard birth-weight distribution for the military population was not available. According to Sonnenfeld et al. (2001), of the three standards considered for use, the California standard was the one that fit best when all races were included.

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The study considered a base population of 12,493 singleton live births delivered after at least 20 weeks gestation to women residing in base housing during the period 1968-1985 who were identified through birth records (ATSDR 1998). That population did not include births to mothers who resided on the base during pregnancy but were no longer residents of Onslow County at the time of delivery. Residential mobility may be substantial: according to ATSDR, "approximately one-third of the women who sought prenatal care at the Navy Regional Medical Center at Camp Lejeune moved or were transferred before they delivered" (ATSDR 1998, p. 16). Although exposures were presumed to have occurred before 1968, a starting date of January 1, 1968, was chosen because electronic files of North Carolina birth certificates began that year. The analyses assumed delivery of contaminated water via the water-distribution system through February 1985 (ATSDR 1998; Sonnenfeld et al. 2001).

ATSDR documented that 523 (4%) of the 12,493 live births were excluded because exposure to contaminated water supplies was for less than 1 week or exclusively before conception (44), or because data were missing, inconsistent, or insufficient (479), leaving 11,970 live births for the mean-birth-weight analyses. Of the11,970 live births, 6,117 (51%) were to women who resided at Tarawa Terrace at the time of birth, 31 (0.26%) were to women who resided at Hospital Point (which received water from Hadnot Point), 141 (1.2%) were to women who resided in housing units temporarily supplied by Hadnot Point during a fuel-pump failure, and 5,681 (47%) were to women who resided in housing supplied by the Holcomb Boulevard system, were considered to be unexposed, and served as a comparison group. Additional exclusions were made for the SGA analyses (eight births with gestational age under 22 weeks) and the preterm-birth analyses (the eight births excluded from the SGA analyses plus 101 births classified as implausibly heavy preterm births).

Exposure and Confounder Data

Exposure was defined by linking birth records to the base's family housing records according to the mother's address at delivery and the father's name. The housing records, which contained dates of residence, were used to estimate the dates when the mother resided in base housing units. The study "assumed that each family resided in only one base housing unit during pregnancy" (ATSDR 1998, p. 21). A residential-history substudy indicated that about 55% of mothers in the study moved during their pregnancies, and 3.5% of them moved between base housing units (ATSDR 1998).

The 1998 ATSDR study included all identified births regardless of exposure, whereas the 2001 Sonnenfeld et al. study limited the exposed population to residents of Tarawa Terrace. The Tarawa Terrace residents were considered exposed to PCE from water contaminated by an off-base dry-cleaning establishment (ABC One-Hour Cleaners). ATSDR's analysis also included births to two groups of residents who were exposed to TCE and other VOCs through the Hadnot Point water system on either a long-term or a transitory basis. Transitory exposure (called short-term in the ATSDR report) covered all births to residents who received drinking water from the Holcomb Boulevard water system and who were pregnant for at least 1 week of the 12-day period during January-February 1985 when Hadnot Point water served the Holcomb Boulevard system. In both studies, residents of the base trailer park were excluded because housing records were incomplete, and, as noted above, a few births to mothers residing on base for a very short time or during ambiguous exposure periods were excluded. The remaining births to mothers residing on the base were considered unexposed, including births to all residents of the Marine Corps Air Station, Rifle Range, and Courthouse Bay and the remaining residents of Berkeley Manor, Midway Park, Paradise Point, and Watkins Village.

Exposure was categorized further by length of residence as a proxy for duration of exposure. Duration of exposure was defined as length of time before the birth that the mother lived at the residence specified on the birth certificate. Because inclusion in the study was based on maternal residence at the time of birth, exposure duration was relative to the end of pregnancy. Duration-of-exposure analyses excluded births that occurred after exposure ended in 1985. In analyses, duration of exposure was categorized as never, 1-3 weeks, 4-10 weeks, 11-20 weeks, over 20 weeks and less than the entire pregnancy,

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the entire pregnancy and less than 1 year before the last menstrual period, and the entire pregnancy and at least 1 year before the last menstrual period.

The covariates available for analysis were limited to information that could be obtained from the birth certificates and military records. They included infant's sex, year of birth, and gestational age; maternal age, race, parity, education level, military pay grade, adequacy of prenatal care, marital status, and history of fetal death; and paternal age, education level, and military pay grade. Gestational age was calculated from the date of the last menstrual period reported on the birth certificate. Women with records showing a month and year of last menstrual period but missing information on the day had their day interpolated to 15. Women with records missing the month of the last menstrual period were excluded. In the remaining data, there was evidence of gestational-age misclassification in that 17% of preterm infants of gestational age less than 28 weeks had birth weight above the 90th percentile of the distribution for the standard population (ATSDR 1998). Preterm infants above the 90th percentile for birth weight at 36 weeks of gestation were excluded from the preterm-delivery analysis but not the birth-weight or SGA analysis.

Results of the Sonnenfeld et al. Study

Exposure was not equally distributed across various demographic groups. Exposed women were less likely to be white, less likely to live in officers' housing, less likely to be college-educated, and less likely to have a college-educated partner (Sonnenfeld et al. 2001). Those differences raise questions about whether any observed differences in reproductive outcomes by exposure status were confounded by sociodemographic factors because not all the variables were examined as potential confounders or included in the adjusted analyses that were reported.

The overall results of the study indicated that "long-term" PCE exposure from the Tarawa Terrace water system was not strongly associated with reduced birth weight, preterm birth, or SGA. The mean birth weight in the PCE-exposed group was 26 g less than that in the PCE-unexposed group (90% confidence interval [CI], -43 to -9) (note use of 90% CI rather than 95% CI). The unadjusted odds ratio (OR) for PCE exposure and preterm birth was 1.0 (90% CI, 0.9-1.1) and for PCE exposure and SGA 1.2 (90% CI, 1.0-1.3). It was noted that adjustment for potential confounders had little effect on the results. The authors reported no consistent patterns in the associations between PCE exposure and mean birth weight, preterm birth, or SGA by duration of exposure.

In subgroup analyses, Sonnenfeld et al. reported that long-term exposure to PCE from the Tarawa Terrace water system was marginally associated with lower mean birth weight and an increase in risk of SGA but only in newborns of mothers more than 35 years old and mothers who had already had more than two fetal losses. The birth-weight analysis was adjusted for mother's age, history of fetal loss, race, and residence in officers' housing and infant's gestational age, year of birth, and sex. The SGA analysis was adjusted for mother's age, history of fetal loss, parity, residence in officers' housing, and education and infant's year of birth. The authors noted that older PCE-exposed mothers were different from their unexposed counterparts in race, college education of husbands, and household income (defined by the father's rank). However, not all those variables were included in the analyses. Specific subgroups showed statistically significant effects, but no formal hypothesis test for the presence of interaction between subgroups defined by maternal age or history of fetal loss was mentioned.

The authors concluded that there was no association between PCE exposure and mean birth weight or preterm birth and that there was a weak association between PCE exposure and SGA in all groups. In subgroup analyses, they observed stronger associations between PCE exposure and low birth weight and SGA of infants of mothers who had a history of fetal death and mothers more than 35 years old.

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Results of the Agency for Toxic Substances and Disease Registry Study

This section focuses on aspects of the ATSDR results that are distinctive from the Sonnenfeld et al. results. ATSDR reported analyses of PCE exposure at Tarawa Terrace that were unadjusted, and this may have contributed to the slight differences from Sonnenfeld et al. in birth-weight results (-24 g; 90% CI, -41 to -7), but the SGA and preterm delivery results were identical. In spite of the reported difference, the birth-weight results were said to show no association, because the magnitude of the difference was viewed as clinically negligible. The duration-of-exposure analyses were identical, but the effect-modification results were slightly different because of different exclusion of data and more limited control for confounding. In particular, the OR for PCE exposure and SGA in women more than 34 years old was 4.0 (90% CI, 1.6-10.2) after adjustment only for officers' housing. No exposure-response patterns were observed for PCE exposure and mean birth weight or SGA in women who had had fetal deaths.

The much smaller population of TCE-exposed births was analyzed with stratification by residence. Births in the long-term TCE-exposed group were to mothers living in housing ordinarily served by the Hadnot Point water-distribution system. Overall, there was limited evidence of a reduction in mean birth weight (reduction by 108 g; 90% CI, -230 to 13) or of increased risk of SGA (OR, 1.5; 90% CI, 0.5-3.8), interpreted by ATSDR as modest associations. The reported results were unadjusted despite differences between the two groups in the distribution of infant sex; mother's age, pay grade, history of fetal death, and parity; and father's education. Few analyses of interaction were conducted because of the small sample. TCE effects were found to be modified by infant sex for both birth weight and SGA. The study reported an increased risk of SGA in TCE-exposed male infants (OR, 3.9; 90% CI, 1.1-11.9) on the basis of three exposed cases. According to a rate estimated from the female control group, one exposed SGA female infant was expected; none was observed. No risk of any of the outcomes was found in the temporarily exposed population with a maximum exposure duration of 12 days.

Review and Evaluation

Retrospective case-control studies can be extremely difficult to conduct when historical information on exposure, outcome, and covariates—challenges applicable to the study of birth outcomes at Camp Lejeune—is scarce. This section discusses limitations in identifying the study population, assignment of exposure, confounder control, and analytic approach.

Exposure misclassification is a major limitation of the ATSDR and Sonnenfeld et al. analyses. A number of exposed births were misclassified as unexposed because of incorrect assumptions about the water-delivery system, which ATSDR later identified. Both studies assumed that all mothers who resided in family housing in the Holcomb Boulevard system service area from 1968 through 1984 were unexposed. In the course of exposure reconstruction of the Tarawa Terrace system, it was learned that the Holcomb Boulevard plant came on line in June 1972 and that before then the housing now served by Holcomb Boulevard was served by the Hadnot Point water-supply system. Thus, any mothers who resided in family housing in the Holcomb Boulevard system service area in 1968-1972 were actually exposed. That is an important (and correctible) source of misclassification that has the potential to alter study results dramatically because a sizable number of pregnancies will be reclassified from unexposed to exposed.

Other limitations in exposure classification in these studies are more difficult to correct. Aspects of residential-history assignment would have caused exposure misclassification of unknown magnitude. First, all mothers were assumed to have had only one residence on the base and to have been unexposed at all other residences. The residence-history validation study estimated that a sizable proportion of mothers changed housing on the base during their pregnancies. Second, the contaminant exposure and its variation over time are impossible to quantify accurately. As reviewed in Chapter 2, water-supply measurements of contaminant concentrations are sparse, and the data were collected only in the 1980s. Third, there is no information about individual behaviors that affect exposure (such as water consumption and frequency

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and duration of bathing and showering). Fourth, exposure was determined exclusively by place of *residence*, excluding workplace and other locations in which exposure may have occurred.

The studies relied on North Carolina birth-certificate data from Onslow County linked to base housing records. That was a feasible and efficient approach to conducting a study, but the information-retrieval process and restricted data sources have implications for population selection, outcome definition and quality, and confounder control. In particular, the base population used in the studies does not represent the entire population of live births to all women who resided at Camp Lejeune in 1968-1985. Infants whose mothers were transferred or moved away from Camp Lejeune before giving birth were not included. In addition, because residence at birth determined inclusion, all exposure-duration analyses were relative to the end of pregnancy. For instance, nearly all infants who were exposed only during the first trimester were excluded. Beyond its obvious impact on interpretation of the exposure-duration analyses, the effect of a selection approach based on location at the time of delivery is unknown.

Outcome variables were based on information included on birth certificates, and there are known limitations in the quality of some items (Wingate et al. 2007). In particular, accurate estimates of the date of the last menstrual period are critical for defining SGA and preterm birth. The ATSDR study found a disproportionate number of heavy liveborn infants relative to a standard population of the same gestational age—a reminder of the fallibility of birth-certificate-based gestational-age estimates. Outcome-based exclusions varied among the three outcomes; preterm birth outcome was related to the largest number of exclusions.

Control for confounding is another challenge. Because of reliance on birth-certificate data on the period of the exposure episode, such key confounders as maternal smoking and alcohol use were not available. In addition, in reported analyses, control for confounding was not often done even for variables that were available. The ATSDR report gives unadjusted estimates of the primary results even though the exposed and unexposed populations differed in important respects and the study protocol (ATSDR 1994) stated that all analyses would be adjusted for race. The sensitivity of results to potential confounders should be examined more thoroughly.

The implications of the results of subgroup analyses are unclear. The interactions of exposure with maternal age, history of fetal loss, and infant sex do not appear to be based on strong assumptions but instead resulted from exploratory statistical analysis. Although such interactions cannot be discounted, they should not be taken as evidence of an important effect of exposure. But these results are often cited as the primary study findings (for example, ATSDR 2005a). It is well known that overinterpretation of subgroup analyses can be misleading; such analyses typically suffer from low power and higher than nominal probability of reporting false positive effects (for example, Stallones 1987; Brookes et al. 2004; Weiss 2008). In addition, the various subgroup analyses used different numbers of observations and different adjustment variables, depending on the report, outcome, and exposure variable. Subgroup membership should be described, and the sensitivity of results to data exclusions and more thorough confounder adjustment should be examined.

CURRENT STUDIES

Study Methods

ATSDR's 1997 public-health assessment for Camp Lejeune led to a recommendation that an epidemiologic study be performed to evaluate whether mothers exposed to chlorinated solvents in drinking water, particularly TCE and PCE, during pregnancy have a higher risk of giving birth to a child with a birth defect or cancer, given the recognition of the limited scientific information on how those chemicals might affect a fetus or child (ATSDR 1997a). (ATSDR withdrew this report on April 28, 2009.) ATSDR later began a multistep process to determine the appropriateness of such a study. First, the childhood health problems to study were identified. On the basis of its review of the scientific literature, ATSDR decided to focus on specific childhood cancers and birth defects: childhood leukemia, childhood non-Hodgkin lymphoma, spina bifida, anencephaly, cleft lip, and cleft palate (ATSDR 2005a). The rationale

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for focusing on those particular outcomes given the prior epidemiologic and toxicologic research and considerations of feasibility (specifically, statistical power) is discussed later in this chapter.

The second step was to identify the children eligible for the study by conducting a telephone survey. The survey, conducted from September 1999 to January 2002, built on the database initially constructed for the two case-control studies of preterm birth and fetal growth (ATSDR 1998; Sonnenfeld et al. 2001). The survey sought information on all children who were born in 1968-1985 to mothers who resided on the base at any time during their pregnancies. Births in Onslow County were included, as were births that occurred after mothers were transferred off the base. ATSDR attempted to locate and contact the parents of each eligible child to elicit information on the child's health, to confirm that the mother was a Camp Lejuene resident during the pregnancy, and to collect data on potential confounders. It identified eligible children in multiple ways. Initially, it used the birth-certificate information from the previous Camp Lejeune study of SGA (ATSDR 1998) that included only women who were residents on the base at the time of their deliveries. Next, children born in 1968-1985 to mothers whose pregnancies occurred while they lived in base housing but who delivered after moving off the base were identified by word of mouth (for example, in parent groups), by referrals from other parents during their interviews, or by public requests (via the mass media, e-mails from the Marine Corps, and notices) that parents contact ATSDR. ATSDR surveyed the parents of 12,598 eligible children of an estimated 16,000-17,000 eligible births, representing an overall participation rate of 74-79%, depending on the estimated number of births that occurred off the base (ATSDR 2003). Parents were asked if their children had had birth defects or childhood cancer. A total of 106 cases that fit the case definition of parent-reported birth defect or childhood cancer were reported in the survey: 35 neural-tube defects, 42 oral clefts, and 29 childhood cancers.

The third step was to confirm the children's health problems by reviewing their medical records. As of June 23, 2008 (Bove and Ruckart 2008), of the 35 reported or potential cases of neural-tube defects, 15 were confirmed (six anencephaly and nine spina bifida), 13 were ruled out, two had no medical records for confirmation, three were ineligible, and the parents of two potential cases refused to participate. For children who had parent-reported oral clefts without medical records, a dental examination was used to confirm that surgery was performed as a result of a cleft lip or palate. Of the 42 children who were reported to have oral clefts, 24 were confirmed (11 cleft palate and 13 cleft lip with or without cleft palate), 11 were ruled out, four had no medical records for confirmation and dental examinations could not confirm the conditions, and the parents of three potential cases refused to participate. Of the 29 reported childhood leukemia or non-Hodgkin lymphoma cases, 13 were confirmed (11 leukemia and two non-Hodgkin lymphoma), eight were ruled out, one had no medical records for confirmation, four were ineligible, and the parents of three potential cases refused to participate. The parents of 15 children with neural-tube defects, 23 children with oral clefts, and 13 children with leukemia or non-Hodgkin lymphoma were successfully interviewed.

The fourth and final step of the process is to conduct a case-control analysis that incorporates water-system modeling; that work is under way. The primary hypotheses concern the association between drinking TCE- or PCE-contaminated water during the first trimester and specific birth defects and the association between drinking TCE- or PCE-contaminated water during pregnancy and childhood cancers. The hypotheses are extended to incorporate contaminant concentration and personal exposure (taking into account the amount of water consumed by the mother or used in showering, hand-washing dishes, and so on).

The base population for the case-control study consists of all live births to mothers residing at Camp Lejuene in 1968-1985 who participated in the survey. Cases are confirmed birth defects (diagnosed by the age of 5 years) or childhood cancers (diagnosed by the age of 20 years). (Planned sensitivity analyses will also include unconfirmed cases.) Controls will be randomly selected from all other births included in the survey to attain a target of 10 controls for each case.

Exposure assessment will be based on the ATSDR water-distribution system modeling (see Chapter 2). That includes a protocol for modeling the present water-distribution system and then developing historical distribution-system models for the study period and generating estimates of contaminant concentrations in the water supply by year and housing complex. The stated exposure variables will be "ex-

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posure status, concentration level, and/or percent of water from a contaminated source during the specific time periods of interest in the 1-year period before the child's birth. TCE and PCE will be evaluated separately" (ATSDR 2005a, p. 29). Categorization of exposure is planned to be collapsed into ever vs never and into more refined exposure categories. Cut points will be determined from the contaminant-concentration distributions. Water use and consumption will be incorporated into the exposure metrics.

According to the ATSDR protocol (ATSDR 2005a, page 25), with alpha set at 0.10, 80% power, and an exposure prevalence of 40%, minimum detectable ORs are as follows: 4.3 for 15 cases and 2.9 for 28 cases of neural-tube defects, 3.6 for 20 cases and 2.5 for 36 cases of oral cleft, and 5.2 for 14 and 4.3 for 19 cases of childhood cancer. Even with the uncertainty about the total number of cases that will eventually be included in the analysis and even under the more optimistic scenario, statistical power is low.

Review and Evaluation

Owing to the paucity of measurements of PCE and TCE concentrations in contaminated water at Camp Lejeune during the period of interest, exposure assessment is a major limitation of the current birth-defect and childhood-cancer study. ATSDR has proposed to use water-system modeling as a way to improve the quantification of exposure. As indicated in Chapter 2, exposure estimates based on water-system modeling require a number of assumptions, and the validity of many of the assumptions is impossible to evaluate in light of the historical measurement data. Given the lack of information on which wells were used to supply water on any particular day, the quality of exposure estimates based on water-system modeling is highly uncertain, especially for the quantification of PCE and TCE concentrations over the short periods of interest for the study of birth defects. In addition, historical information about water behavior will be available in two pregnancy-related periods (the mother's questionnaire asks about only two periods: before and during the first trimester and during the second and third trimesters), and that information will be obtained only if the mother can be interviewed. Recall of such information over periods of decades is of questionable accuracy. Although the study-protocol data-analysis plan appropriately addresses exposure-assessment limitations by proposing that exposure be categorized in analysis, the proposed analytic approach calls into question the need for complex water-system modeling. To the extent that simple categories of exposure will be used in the final analysis, the rationale for waiting for complex water modeling to be completed is unclear.

Another major limitation of the study is the inadequate statistical power to detect associations in a plausible range. The selection of specific health end points is the primary reason that power is so limited, so the question arises as to whether they were the most informative outcomes to study. There is some basis for speculating that those outcomes are associated with the solvents of interest largely on the basis of prior epidemiologic studies of water-contamination episodes, but the evidence is not compelling, and there is no reason to believe that these are the "best" choices, given their rarity. The committee's review of the literature on the epidemiology of populations exposed to TCE and PCE (Chapter 5) and the toxicology of the compounds (Chapter 4) did not identify birth defects or childhood cancers as among the outcomes more plausibly related to exposure.

For each of the three outcomes (neural-tube defects, oral clefts, and childhood cancers), there is adequate power only for markedly increased odds ratios (larger than 3). Given current knowledge about the etiologies of these conditions, it is highly unlikely that the exposures that occurred at Camp Lejeune would have increased risk to that degree, regardless of uncertainty about exposure magnitudes. Furthermore, because the investigators also proposed to conduct multivariate analyses to control for the potential impact of other factors on the risk of the conditions, it is important to note that the power of a multivariate analysis will probably be even lower than the estimate for the unadjusted associations.

The data-analysis plan in the protocol is very general and leaves room for the possibility of a proliferation of analyses that will make it more difficult to assess the meaning of any associations that are identified. A detailed written analysis plan specifying primary exposure metrics and key confounders should be prepared in advance of the analysis and should consider alternative approaches to controlling

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confounders. The planned secondary and sensitivity analyses should be discussed more fully in the analysis plan. Because there is interest in multiple exposure periods (for various durations before, during, and after pregnancy), in different approaches to estimating exposure, and in different exposure categories, it is necessary to distinguish the primary exposure metric (such as peak exposure) from those to be evaluated in secondary and sensitivity analyses.

FUTURE STUDIES

An expert panel convened by ATSDR in 2005 judged that additional studies of the Camp Lejeune population would be challenging, perhaps requiring medical evaluation of hundreds of people from widely scattered locations. However, the panel concluded that it might be feasible to conduct a study of mortality outcomes and a study of cancer incidence. Before performing such studies, it recommended that their feasibility be assessed (ATSDR 2005b).

ATSDR has prepared a report on the feasibility of conducting epidemiologic studies to address exposures that occurred at Camp Lejeune (Bove and Ruckart 2008). The report proposed a study of all-cause mortality and a study of cancer incidence by using Department of Defense (DOD) personnel databases to identify a cohort of active-duty marines and Navy personnel who were assigned to Camp Lejeune at any time from June 1975 through December 1985 and a cohort of civilians who worked at the base at any time from June 1974 through December 1985. The agency also proposed to include as a comparison population a sample of active-duty marines and civilians stationed at Camp Pendleton at any time during 1975-1985 who started duty on or after June 1975 and were never stationed at Camp Lejeune during the period of drinking-water contamination. The three cohorts would be considered for inclusion in an all-cause mortality study and a cancer-incidence study, and the Camp Pendleton cohort would serve as an external comparison group for the analysis of civilian and military personnel at Camp Lejeune.

ATSDR proposed to link study participants' residence history on the base with housing records (family housing unit or barracks) to identify participants' drinking-water supply-system history. That would allow inclusion of monthly estimates of water contamination from the water-distribution system in individual-level exposure assessment. For civilian workers, the occupation code and information on the location of each occupation obtained from base staff (such as base industrial hygienists) would be used to link the workplace with the appropriate drinking-water system. Information on length of service on the base obtained from computerized personnel data would be used to estimate the duration of exposure. Marines and civilians assigned to Camp Pendleton would be considered unexposed.

ATSDR's feasibility assessment included a literature review of the health effects of VOCs, particularly TCE and PCE. The review concluded that previous studies supported evaluation of a variety of health effects, predominantly cancers, in future studies at Camp Lejeune. ATSDR's review relied on previous reports by the National Toxicology Program and the National Research Council, occupational studies, and community drinking-water exposure studies. The review identified more health outcomes than described in Chapter 7 of this report, and this suggested a lower threshold for inclusion than applied by the present committee. Both reviews identified kidney cancer, lung cancer, breast cancer, scleroderma, hepatic disease, renal disease, and spontaneous abortion as being of interest. The ATSDR review also suggested that the following outcomes may be important: liver cancer, leukemias, cervical cancer, bladder cancer, esophageal cancer, soft-tissue sarcoma, skin disorders, aplastic anemia, non-Hodgkin lymphoma, multiple myeloma, Hodgkin disease, pancreatic cancer, brain cancer, Parkinson disease, and lupus. The present committee and ATSDR took different approaches to assessing the epidemiologic literature. ATSDR focused on previous reviews and studies that yielded positive results, especially community studies of drinking-water contamination. The committee used an approach developed by the Institute of Medicine (IOM 2003) for reviewing the epidemiologic literature, including consideration of individual study characteristics and biases, synthesis of the available studies, and consideration of evidence from the toxicology literature. Only outcomes that were corroborated and single, very strong studies were flagged as deserving of consideration.

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Health Survey

In January 2008, Congress mandated a Navy-Marine Corps health survey to be conducted in 2009. The survey will be mailed to the active-duty and civilian cohorts at Camp Lejeune, the Camp Pendleton sample, the 12,598 respondents in the 1999-2002 ATSDR survey, and anyone who has registered with the Marine Corps or provided contact information to ATSDR. Items on the survey will include information about any cancer diagnoses (such as type of cancer, date of diagnosis, and state and hospital of diagnosis), residential history, residences on the base, occupational history, and several risk factors (such as socioeconomic status, demographics, smoking, and alcohol consumption). Permission to gain access to medical records will be requested from those reporting cancer diagnoses.

The health survey has the potential to improve future studies of Camp Lejeune residents. For example, the survey would enhance the collection of relevant covariates and expand the potential scope of nonfatal disease and disability beyond what can be addressed in a typical mortality study or in a cancer registry. The health survey would also demonstrate that the health concerns of Camp Lejeune residents are being investigated to the extent feasible. Nevertheless, the committee has several concerns about the health survey as a source of scientifically useful information for assessing the impact of water-supply contamination at Camp Lejeune. First, the statistical power for evaluating relevant outcomes appears to be low and incompletely addressed in the feasibility study. Second, there may be a bias in disease reporting and participation; a person who has a disease or disability may be more likely to participate. ATSDR has determined that for the health survey to be successful, and therefore useful for the proposed studies described below, a participation rate of at least 65% would be necessary. Even with that level of response, there is much potential for participation to be influenced by exposure or disease history. Third, the health survey would include only active-duty personnel and civilians who lived on the base after 1975, not those who were present and exposed before then. Fourth, as previously noted, the quality of exposure data would remain uncertain for the same reasons noted above in connection with the completed and current studies.

All-Cause Mortality Study

The purpose of the mortality study is to evaluate all causes of death in the three cohorts—Camp Lejeune military, Camp Lejeune civilian, and Camp Pendleton military. Followup would begin at the start of known assignment at Camp Lejeune or at the start of active duty for the Camp Pendleton cohort and continue to the end of the study period (December 31, 2007) or death.

Cause-specific mortality in the cohorts would be compared with national rates by using standardized mortality ratios and standardized mortality ORs. ATSDR also proposes to compare those exposed to contaminated drinking water at Camp Lejeune with those unexposed at Camp Pendleton to minimize bias due to the healthy-veteran effect caused by differences in underlying mortality between veterans and the general public (Bove and Ruckart 2008). ATSDR considered conducting internal comparisons between exposed and unexposed groups at Camp Lejeune but rejected such analysis because of the small number of subjects at Camp Lejeune who were free of exposure. Finally, the agency proposed to consider lagging exposures in the analyses to account for a latent period.

Because individual-level information on potential confounders is not available in the computerized databases used to identify study subjects, ATSDR proposes two approaches to consider potential confounders. If the Navy-Marine Corps health survey is deemed successful, it will use information from the survey participants to adjust for confounding in a two-stage approach, extrapolating the information from the health survey for application to the mortality study. If the survey does not generate an adequate response, consideration will be given to nested case-control sampling with interviews of decedents' next of kin to determine information on risk factors. Those are reasonable strategies but are of unknown feasibility.

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Cancer-Incidence Study

The cancer-incidence study would evaluate all confirmed cancers diagnosed in the active-duty and civilian worker cohorts at Camp Lejeune and Camp Pendleton and the cohort of survey participants. Because the number of women in the active-duty cohort is small, an additional 2,900 women who lived on the base and were identified through their participation in the birth-defects and childhood-leukemia study would be added to the Camp Lejeune active-duty cohort. To identify cancer cases, ATSDR proposed to match each cohort member's personal identification information to the available data on cancers in all 50 state cancer registries (or at least the cancer registries from the 25-30 states with the highest percentages of known retirees), the DOD, and Department of Veterans Affairs (VA) cancer registries, the Naval Health Research Center's Career History Archival Medical and Personnel System (CHAMPS), death certificates, and the National Death Index. Followup would begin with the start of each registry's operation or 1975, whichever is later, and continue until December 31, 2007. If the Navy-Marine Corps health survey is successful, the cancer-incidence study would also include participants in the survey. Personal identification information on the survey participants will be matched to available data on cancer in the state, DOD, and VA cancer registries. Therefore, like the mortality study, the incidence study will use a two-stage approach in which information on exposure and cancer would be available on everyone in the study who is not lost to followup, but information on individual-level potential confounders will be available only on those who complete the health survey. That information will be used to adjust for confounding in the analyses of the entire study population.

Because all state cancer registries have data available from 1997 on, cancer incidences in the Camp Lejeune and Camp Pendleton cohorts will be compared with national incidences for the period 1997-2007. Comparisons between the exposed and unexposed participants stationed at Camp Lejeune and comparisons between Camp Lejeune and Camp Pendleton would use all cancers identified from 1975 to 2007—the entire study period.

Other Future Studies

ATSDR will also consider studying nonfatal, noncancer diseases. The Navy-Marine Corps health survey would include questions on nonfatal diseases and symptoms that are known to be or suspected of being associated with solvent exposure. Such diseases as Parkinson disease, renal failure and other severe renal diseases, severe hepatic diseases, lupus, and scleroderma will be asked about directly, and space will be provided so that respondents can report other disease conditions. Symptom ascertainment may include questions on skin disorders and neurologic disorders. All those diseases and conditions can be confirmed by using medical records. The CHAMPS database can also be used to identify and confirm diseases occurring in marines on active duty from 1980 on. However, ATSDR states that a study using that database would probably have insufficient statistical power and therefore the study is of very low priority.

Review and Evaluation

ATSDR proposed to conduct morbidity and mortality studies that would address some of but not all the questions that have been raised by the affected community. The health end points to be considered would include fatal conditions that are sufficiently common for analysis (depending on the success of the mortality study), incident cancers (depending on the success of the cancer-incidence study), and nonfatal diseases of interest other than cancer, such as scleroderma and neurologic deficits (depending on the success of the health survey). The mortality study is very likely to be feasible, given the documentation of data sources in the ATSDR feasibility assessment, whereas it is not clear that the cancer-incidence study would be successful in engaging and linking with all 50 state registries. The health survey is subject to uncertain response, as noted by ATSDR, which may limit its value.

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ATSDR recognized that it is necessary to focus on health conditions that are sufficiently common to allow useful epidemiologic evaluation. It conducted a series of sample-size calculations to ensure that there would be sufficient statistical power to evaluate associations of exposure with prevalent cancers and all-cause mortality with a 10-year lag in exposure (Bove and Ruckart 2008). It is not clear whether there is sufficient power for comparisons of the Camp Lejeune and the Camp Pendleton cohorts, nor is it clear whether outcomes of particular interest to ATSDR and to the committee (such as kidney cancer) can be evaluated with adequate power. ATSDR has begun to consider the adequacy of statistical power, but the information and interpretation fall short of making a clear case that the study methods, even if successful, would generate adequate power for the comparisons of interest.

ATSDR recognized the potential for confounding due to unmeasured risk factors in both the mortality and cancer-incidence studies. With the exception of age, sex, and race, individual-level factors in the populations of Camp Lejeune and Camp Pendleton are not available. However, some information on the population that completes the health survey would be available. ATSDR proposes a two-stage approach, using the survey data to estimate the effects of confounding with reference to the cohort as a whole. How that would be performed is not described in detail (that is, on an individual basis or by applying patterns of confounding from the health survey to the mortality and cancer-incidence studies). It also is not clear whether the survey will be adequately designed to provide information on the Camp Pendleton cohort that is comparable with that on the Camp Lejeune residents. As ATSDR notes, the value of those data is contingent on generating an adequate response. The use of nested case-control studies of deaths from causes of interest with interviews of next of kin to assess confounding is an alternative approach that is feasible but quite demanding in that it will be necessary to locate, recruit, and interview the next of kin after identification of deaths or incident cancers.

ATSDR recognized the potential for bias in the assessment of exposures because of uncertainties in identifying locations on the base where cohort members were stationed and because of possible exposure to drinking-water contaminants at other than primary residences or work locations. The agency suggested that such bias would tend to underestimate the disease risk associated with exposure if exposure actually causes the disease. ATSDR was confident that the extensive water modeling that is being done at the base would reduce the effect of exposure-misclassification bias that might occur. The committee has less confidence in the certainty of the modeling efforts, given the small number of water-supply measurements available for validating the models (see Chapter 2). ATSDR has discussed basing the exposure assessment on the monthly concentrations of contaminants in the drinking water at either the residences or the workplace locations, as appropriate. However, there has been no discussion of the exposure metric that would be calculated and linked with outcomes. For example, it was unclear whether ATSDR would assess the effect of cumulative exposure or of peak exposure.

Advantages of the cancer-incidence study over the mortality study, as described by ATSDR, are the higher number of cancer cases and the ability to assess etiology independently of survival. Several female cancers (breast, ovarian, cervical, and uterine) could be evaluated with adequate statistical power (Bove and Ruckart 2008). However, there are concerns about the comparability of the women at Camp Lejeune, who include spouses of workers and women identified because of having given birth, compared with those identified at Camp Pendleton. The cancer-incidence study would also have greater power to detect associations with a broader array of cancers of interest (such as kidney, non-Hodgkin lymphoma, and leukemia) and would eliminate potential effects of differential survival. ATSDR discussed the possibility of missed cancers in the incidence study due to incomplete coverage of the study period by the individual state cancer registries. As it noted, there should be no bias in the internal comparisons, because missing cases are unlikely to be associated with exposure status. However, the comparison between Camp Lejeune and Camp Pendleton could be affected if there are differences between the bases in the percentage of retired marines migrating to states whose cancer registries are older, and there are broader concerns about the constitution of the study populations and the multiple ways in which the Camp Lejeune cohort would be assembled.

In summary, although the major issues bearing on the feasibility of the proposed studies have been considered by ATSDR and the approach has some strengths, notably inclusion of a comparable ma-

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rine base, there are serious unresolved questions about the feasibility and ultimate value of the studies. It is not clear that the cancer-incidence study or the health survey would be successful; success in the former would be contingent on the cooperation of many cancer registries, and success of the latter on generating an adequate response. The statistical power to compare groups of interest across the array of outcomes of interest was not provided. The ultimate ability to measure and adjust for potential confounding factors is not certain, nor is it clear how the information from the health survey would be applied to the study cohorts. With those concerns layered on the previously noted problems regarding the accuracy of exposure assessment, it is not clear what the scientific value of additional studies would be.

FINDINGS OF COMPLETED, CURRENT, AND FUTURE STUDIES

The committee considered the value of completed, current, and planned studies of the Camp Lejeune population in light of the information available on assessing exposure, health end points of primary concern, and what is known about the potentially affected population from previous studies and work in progress. Review of data and modeling efforts pertaining to exposure provided clear documentation that contaminants were present but provided little basis for suggesting that exposures of the population can be reconstructed with much precision. The literature on potential health effects of the agents of primary concern, TCE and PCE (see Chapters 4 and 5), indicates an array of possible health effects, including cancers, reproductive effects, neurobehavioral effects, immunologic effects, and renal and hepatic toxicity, possibly affecting both children and adults.

Completed and current research at Camp Lejeune has been limited to particular end points and focused on pregnancy outcomes—including fetal growth, preterm birth, and birth defects—and childhood cancers. Those studies have not distinguished and are unlikely to be able to distinguish between an absence of adverse effects and the presence of modest effects that fall below the limits of what can be identified in light of exposure misclassification and low statistical power. A broader consideration of health effects would be needed to provide scientific evidence to answer questions regarding the possible effects of water-supply contamination. For new studies to make a substantial contribution to evaluating whether exposure to contaminated water resulted in adverse health effects, an array of feasibility considerations needs to be addressed and resolved favorably. ATSDR has made a reasonable effort to evaluate those issues in the study of the feasibility of future work, but structural problems make it difficult to show that such research will be of high scientific merit. Key feasibility considerations that apply to all environmental epidemiology studies, including the evaluation of water contaminants and health at Camp Lejeune, are listed below.

- *Study population*. The residents of Camp Lejeune potentially exposed to the contaminated water supplies of concern need to be enumerated for study, with inclusion of exposed people and comparable unexposed people identified from elsewhere on the base, from periods beyond the years of contamination, or from other military bases.
- *Exposure*. The water serving the homes of the individual residents at specific times would need to be identified to assess potential exposure to specific toxicants. There would need to be an independent process of exposure assessment that allows estimation of concentrations of specific pollutants going from the source to the tap and related to specific time and places. It would then be necessary to reconstruct residential histories in Camp Lejeune to link people to estimated water concentrations of pollutants in their homes. Ideally, studies would consider water sources at the locations of work, day care, and schools and consider individual behavior, including water consumption and bathing.
- *Statistical power*. The health outcomes of interest vary greatly in frequency of occurrence. For research results to be informative, sufficient numbers of exposed and unexposed people are needed to generate stable estimates of rates of diseases and to make comparisons. Disease latency—the time between exposure and development and manifestation of disease—is important. The Camp Lejeune population was generally young, so even with the passage of 20 or more years since exposure onset, they are still not

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at the ages at which some of the specific diseases of concern are commonly observed. Given the size and age distribution of the population, it may be infeasible to focus on such end points as kidney cancer, although it is justified on the basis of independent research as reflected in the toxicology and epidemiology literature. Furthermore, given the brevity of many people's residence on the base, realistic effect sizes would need to be considered in assessing adequacy of statistical power.

- *Potential confounders*. The potential for confounding of the observed effects of water exposure by other factors that affect disease incidence would need to be addressed. Because residence or workplace on the base is a primary determinant of exposure and may be related to rank, seniority, or job duty, which themselves may be markers of disease risk, they would need to be measured and adjusted for in the analysis. More direct markers of disease risk—such as tobacco and alcohol use history, body-mass index, and diet—would also need to be addressed for selected health end points, including those of primary concern (such as renal disease).
- *Time and cost*. Realistic estimates of the time required to conduct the study are needed, particularly in light of the long history of concerns regarding contaminated water and health at Camp Lejeune. The financial cost is also a key consideration in that studies that require generating large volumes of new data through individual contact and advanced water modeling are expensive and time-consuming.
- *Credibility of findings*. It is important not only that the research be scientifically rigorous but that the results be fully and widely accepted. That issue would need to be addressed from the outset in framing the question, the mechanism of funding, the selection of the researchers, the conduct of the study, and the interpretation, evaluation, and dissemination of results.

For structural reasons, meeting the criteria above is problematic. One major problem is that the number of people available for the study may be too small to generate statistically meaningful results related to rare outcomes of greatest interest (such as kidney cancer). Historical contaminant-exposure estimates are difficult to construct and might be impossible to quantify with any confidence in the absence of contaminant measurements taken during the period of concern, no matter how elaborate the water models are. Many residents were exposed for relatively short periods; most lived in the affected areas for only a few years (2-3 years was typical for marines stationed at the base), and it is difficult to know what types of exposures they had before or after they lived at Camp Lejeune. We know that there were some highly contaminated wells for some periods, but their operations were cycled with those of uncontaminated wells, so exposure to water contaminants was intermittent and cannot be determined on an individual basis or for time frames of weeks as required to assess the occurrence of reproductive health end points. Even if all the information on the population, exposure, and health outcomes could be obtained, consideration should be given to whether the cost and time required to conduct more definitive studies justify the likely delay in or distraction from resolving the public-health concerns and the controversy that has developed around the issue. The costs and benefits of such efforts need to be reconciled. Finally, the long-standing controversy over this episode is apparent, and some question the objectivity of the Marine Corps in generating valid, objectively interpreted scientific data on the topic. Future research needs to be both scientifically informative and credible to the multiple target audiences.

CONCLUSIONS AND RECOMMENDATIONS

The scope of health outcomes addressed in completed and current studies of the Camp Lejeune population is limited and driven, to a large extent, by the types of diseases that are feasible to measure with available surveillance data and a health survey. They are not necessarily the conditions or diseases that would be considered of highest priority on the basis of the committee's review of the literature of epidemiology and toxicology. There are serious limitations in the quality of existing studies of the Camp Lejeune population. Consequently, those studies provide little information to assess directly whether the population exposed to water contaminants has suffered adverse health effects of them. Completion of the studies in progress will provide only a marginal improvement in understanding.

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Recommendations:

- The planned reanalyses of the preterm-birth and fetal-growth study should be completed as soon as possible, taking advantage of the corrected exposure information that is available but not awaiting more extensive water modeling. Reanalyses should include development of a detailed written analysis plan (for example, Sheppard 2008). Careful attention should be paid to confounding, given the associations between residence and indicators of risk. Given the inherent limitations of birth-certificate data, sensitivity analyses to address gestational-age misclassification, subgroup analyses, and confounding should be incorporated. Finally, future reports should provide full details of the approach, results, and sensitivity analyses; the STROBE (strengthening the reporting of observational studies in epidemiology) guidelines (Vandenbroucke et al. 2007) would be suitable for such documentation. Despite the limited scientific benefit of this effort, the modest cost justifies its prompt completion.
- The current case-control study of birth defects and childhood cancer should be completed, given the effort already invested, despite severely limited statistical power. The same recommendations noted for the study of preterm birth and fetal growth apply here as well, including careful planning of analytic methods and full documentation. Relative to the overall effort expended thus far, the committee recognizes the need for completion of this study.

It could be argued that additional studies of the potential health effects from the historical contamination of drinking water at Camp Lejeune could help guide decisions on how to resolve the claims of former residents. Beyond its scientific merit, a more thorough evaluation of health patterns of former Camp Lejeune residents could be seen as providing a valuable public-health service in providing documentation of the experience of former residents and perhaps characterizing the population better. However, on the basis of what is known about the contamination of water supplies at Camp Lejeune; the size, age, and residential mobility of the residents; and the availability of records, the committee concludes that it would be extremely difficult to conduct direct epidemiologic studies of sufficient quality and scope to make a substantial contribution to resolving the health concerns of former Camp Lejeune residents. Conduct of research that is deficient in those respects not only would waste resources but has the potential to do harm by generating misleading results that erroneously implicate or exonerate the exposures of concern.

Recommendations:

- New studies should be undertaken only if their feasibility and promise of providing substantially improved knowledge on whether health effects have resulted from water exposure at Camp Lejeune are established in advance.
- Decisions regarding the appropriate policy response to health concerns about exposure to contaminated water at Camp Lejeune should not be delayed or await the results of epidemiologic studies that are in progress or planned inasmuch as those studies are unlikely to provide definitive information on potential health effects.

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Appendix A

Biographic Information on the Committee on Contaminated Drinking Water at Camp Lejeune

David A. Savitz *(Chair)* is the Charles W. Bluhdorn Professor in the Department of Community and Preventive Medicine at the Mount Sinai School of Medicine. He also serves as director of the Disease Prevention and Public Health Institute. His research interests are in reproductive, environmental, and cancer epidemiology. Dr. Savitz was president of the Society for Epidemiologic Research and the Society for Pediatric and Perinatal Epidemiologic Research and was the North American regional councilor for the International Epidemiological Association. He has served on several Institute of Medicine (IOM) and National Research Council committees, including being chair of the Committee on Making Best Use of the Agent Orange Exposure Reconstruction Model. Past service includes the Committee on EPA's Exposure and Human Health Reassessment of TCDD and Related Compounds and the Committee on Understanding Premature Birth and Assuring Health Outcomes. He serves on the Committee to Reexamine IOM Pregnancy Weight Guidelines. Dr. Savitz received his MS in preventive medicine from Ohio State University and his PhD in epidemiology from the University of Pittsburgh. He was elected to membership in IOM in 2007.

Caroline L. Baier-Anderson is a health scientist with the Environmental Defense Fund and an assistant professor in the Department of Epidemiology and Preventive Medicine of the University of Maryland, Baltimore (UMB). Her research interests are in the use of science in risk assessment and environmental decision-making, exposure assessment, multistakeholder problem-solving for complex environmental issues, and risk communication. Past work has included providing technical outreach assistance to communities adjacent to hazardous-waste sites and working with the U.S. Environmental Protection Agency (EPA) and the U.S. Army on the cleanup of Superfund sites at Aberdeen Proving Ground. She has consulted on risk assessments of solvent-contaminated groundwater. Dr. Baier-Anderson received her PhD in toxicology from UMB.

James V. Bruckner is a professor in the Department of Pharmaceutical and Biomedical Sciences of the University of Georgia College of Pharmacy. His research interests are in the pharmacokinetics and toxicologic and carcinogenic potential of volatile organic compounds, including trichloroethylene (TCE) and tetrachloroethylene. His current efforts are directed toward developing physiologically based pharmacokinetic models of TCE and its interactions with alcohol. Dr. Bruckner has served on several National Research Council committees, including the Committee on Acute Exposure Guideline Levels and the Committee on Use of Third Party Toxicity Research with Human Test Subjects. He received his MS from the University of Texas at Austin and his PhD in toxicology from the University of Michigan.

Prabhakar Clement is a professor of environmental engineering and Arthur H. Feagin Chair of Civil Engineering at Auburn University. Before joining the university, he worked as a senior research engineer

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at the Pacific Northwest National Laboratory for 6 years and then as a senior lecturer in the Department of Environmental Engineering at the University of Western Australia for 3 years. His research interests are in modeling of water flow and reactive-contaminant transport in groundwater systems, bioremediation of contaminated aquifers, numerical modeling of environmental processes, water-quality modeling, and optimal design of treatment systems. He is a member of the Groundwater Quality Committee of the American Society of Civil Engineers (ASCE) and served as the associate editor of ASCE's *Journal of Hydrologic Engineering* and the *Journal of Contaminant Hydrology*. Dr. Clement received his MSc in physics from Madurai University, his MTech in environmental sciences and engineering from the Indian Institute of Technology, Bombay, and his PhD in civil engineering from Auburn University. He is a registered professional civil engineer.

Carole A. Kimmel is a consultant in toxicology and risk assessment, particularly in reproductive and developmental effects. She was a senior scientist for 20 years with the National Center for Environmental Assessment at the U.S, Environmental Protection Agency (EPA). She spent her career at EPA working on advances in risk assessment for noncancer health effects, including reproductive and developmental toxicity and neurotoxicity. Dr. Kimmel cochaired the Developmental Disorders Working Group of the President's Task Force on Environmental Health Risks and Safety Risks to Children and was a leader in an interagency effort to plan and implement the National Children's Study. She is a former president of the Teratology Society and of the Reproductive and Developmental Toxicology Specialty Section of the Society of Toxicology. Her current consulting work includes a part-time position with Exponent as a senior managing scientist and continued involvement in the National Children's Study. Dr. Kimmel received her PhD in anatomy and teratology from the University of Cincinnati.

Francine Laden is an assistant professor of environmental epidemiology at the Harvard School of Public Health and assistant professor of medicine at the Channing Laboratory of Brigham and Women's Hospital and Harvard Medical School. Her research interests are in the environmental epidemiology of cancer and respiratory disease. Her current research is focused on analyses of the relationship between organochlorines and non-Hodgkin lymphoma and Parkinson disease; lung cancer and cardiovascular mortality and diesel exhaust in the Trucking Industry Particle Study; ambient air pollution and cardiopulmonary disease in the Nurses' Health Study; and mortality followup in the Harvard Six Cities Study. Dr. Laden was a member of the Institute of Medicine Committee on Gulf War and Health: Review of the Medical Literature Relative to Gulf War Veterans' Health. She received her MS in environmental health management and her ScD in epidemiology from the Harvard School of Public Health.

Bruce P. Lanphear is a senior scientist at the Child & Family Research Institute and professor of Children's Environmental Health at Simon Fraser University, both in British Columbia, Canada. He is the principal investigator for a study of fetal and early-childhood exposure to prevalent environmental neurotoxins—including lead, alcohol, pesticides, mercury, polychlorinated biphenyls, and environmental tobacco smoke—funded by the National Institute of Environmental Health Sciences and the Environmental Protection Agency (EPA). Dr. Lanphear has conducted numerous epidemiologic studies and randomized controlled trials of environmental hazards, including the use of high-efficiency particulate air cleaners to reduce asthma symptoms and lead-hazard controls to prevent childhood lead exposure. His research also explores gene-environment interactions to enhance understanding of susceptibility to environmental pollutants. He recently served on EPA's Clean Air Scientific Advisory Committee for the national ambient air quality lead standard. He received his MD from the University of Missouri-Kansas City, and his MPH from the Tulane University School of Public Health and Tropical Medicine.

Xiaomei Ma is an assistant professor in the Department of Epidemiology of the Yale School of Public Health. Her research interests are in the epidemiology of malignancies of the human hematopoietic system. Specifically, she is interested in environmental and genetic factors in the etiology of childhood leukemia, the epidemiology of myeloproliferative disorders, and methodologic issues in the design of epi-

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demiologic studies. Dr. Ma received her MS from Shanghai Medical University and her PhD in epidemiology from the University of California, Berkeley.

John R. Nuckols is a professor in the Department of Environmental and Radiological Health Sciences of Colorado State University. He is also director of the Environmental Health Advanced Systems Laboratory. His research interests are in exposure assessment in population-based environmental health studies using computer simulation modeling and spatial information systems. Dr. Nuckols received his MS in civil engineering from Northwestern University and his PhD in engineering from the University of Kentucky.

Andrew F. Olshan is a professor in and chair of the Department of Epidemiology of the University of North Carolina School of Public Health. His research interests are in the etiology of birth defects and cancer in children. His recent work has focused on the role of paternal exposure and adverse health effects in children, risk factors for birth defects and Wilms tumor in children, and the effects of drinking-water disinfection byproducts on male reproductive health. He has served on several Institute of Medicine committees, most recently the Committee for Review of Evidence Regarding Link between Exposure to Agent Orange and Diabetes. Dr. Olshan received his MS and PhD in epidemiology from the University of Washington.

Lianne Sheppard is a professor in the Department of Biostatistics and the Department of Occupational and Environmental Health Sciences at the University of Washington School of Public Health. She is also an affiliate member of the Fred Hutchinson Cancer Research Center. She is an elected fellow of the American Statistical Association and serves as an expert panelist on the ozone, NO_x, and SO_x review panels the U.S. Environmental Protection Agency Clean Air Scientific Advisory Committee. Her scientific interests include estimating the health effects of occupational and environmental exposures, air-pollution health effects, observational-study design, and group information in observational studies. She is an active co-investigator in several occupational-health and environmental-health studies, particularly in air pollution and occupational noise exposure. Her statistical-methods research addresses the role of exposure and study design in estimating health effects in observational studies. Dr. Sheppard received her ScM in biostatistics from Johns Hopkins University and her PhD from the University of Washington.

Elaine Symanski is an associate professor in the Division of Epidemiology and Disease Control of the University of Texas School of Public Health. Her research interests are in the development and application of quantitatively based approaches for evaluating occupational and environmental exposure, retrospective exposure assessment, and investigation of health effects associated with exposure in workplace and community settings. Dr. Symanski received her MSPH and PhD in environmental sciences and engineering from the University of North Carolina at Chapel Hill.

Janice W. Yager is an adjunct professor in the Department of Internal Medicine, Division of Epidemiology and Statistics, of the University of New Mexico School of Medicine. Her current research interests are in application of biomarkers in epidemiology and the development and impact of increased knowledge in toxic modes of action on reducing uncertainties in risk assessment with specific interest in solvents and metals. Before joining the university, she initiated, managed, and provided scientific contributions to research programs and projects in environmental and occupational health sciences at the Electric Power Research Institute (EPRI). Before joining EPRI, Dr. Yager was associate research toxicologist and lecturer in the Department of Environmental Health Sciences of the School of Public Health of the University of California, Berkeley and was a National Institutes of Health visiting scientist to the Academy of Finland. She has served as president and member of the Executive Committee of the Genetic and Environmental Toxicology Association, on the Board of Councilors of the Environmental Mutagen Society, and on a number of scientific advisory committees, including the American Conference of Governmental Industrial Hygienists Biological Exposure Indices Committee and the U.S. Environmental Protection

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Agency (EPA) External Program Peer Review Committee Carcinogenesis Section. Dr. Yager was a member of the National Research Council Committee on Human Health Risks of Trichloroethylene and EPA's Scientific Advisory Board Arsenic Review Panel. She received her MPH and PhD in environmental health sciences from the University of California, Berkeley.

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Appendix B

Participants at Public Sessions

September 24, 2007, Washington, DC

Persons who made formal presentations

Major General (Select) Eugene G. Payne, Jr., Assistant Deputy Commandant Installations and Logistics (Facilities), Headquarters Marine Corps
Kelly Dreyer, Headquarters Marine Corps
Marcia Crosse, U.S. Government Accountability Office
Frank Bove, Agency for Toxic Substances and Disease Registry
Morris Maslia, Agency for Toxic Substances and Disease Registry
Jerry Ensminger

Persons who made comments at open-microphone session

Jeff Byron, The Few, the Proud, the Forgotten

Attendees

Brynn Ashton, U.S. Marine Corps
Cheryl Siegel Scott, U.S. Environmental Protection Agency
Chris Rennix, Navy Environmental Health Center
John Sludden
Ken Stier
Lita Hyland
Marie Roda, Roda Creative
Mary A Simmons, Navy Environmental Health Center
Paul Dugard, HSIA
Shannon Ensminger, Roda Creative
Steve Risotto, HSIA
Yvonne Walker, Navy Environmental Health Center

November 15, 2007, Camp Lejeune, NC

Persons who made formal presentations

Mary Hill, U.S. Geological Survey
Richard Clapp (via conference call)

Persons who made comments at open-microphone session

Cindy Cribb, Private citizen
Col. Michael E. Williams, USCG Training Center

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Curtisteen Hill, Private citizen
Eli Sharpless
Jeff Byron, The few, the proud, the forgotten (website coordinator)
Jerry W. Townsend, retired
Kris L. Thomas, Private citizen
Marilyn Wallace, retired civilian
Mary Walton Freshwater, USMC
Nellie Bell, retired civilian
Paula Lawrence, Dep
Terry Dyer, the Stand

Attendees

Angelo Inglisa
Ann G. Turner
Betty Reed
Brad I. Walker, Lighthouse Films
Catherine Maria Keener, WHQR Public Radio
Chelsea Donovan, WITN
Clifton Jones, Jr.,
David Steinberger, CBS news
Erika Maureen DuChien
Eugene Shelton, WCTI-TV
Frances Midgett Hollowell
Gareth J. McGrath, Wilmington Star-News
James H. Middleton
James Highsmith
Jennifer Elise Hlad, Jacksonville Daily News
Joy Barker
Louise Jigettes
Marilyn Mejarado
Michael Sean Partain
Mike Spencer, Wilmington Star-News
Morris Levi Maslia, Agency for Toxic Substances and Disease Registry
Rachel E Libert, Tied to the Tracks Films, Inc
Reginald Huff, CBS news cameraman
Robert Keven Thomas
Sandra H. Bridges, CAP member for ASTSDR
Steve Goyas
Vianna Witcher

September 12, 2008, Washington, DC

Persons who made formal presentations

Frank Bove, Agency for Toxic Substances and Disease Registry
Persons who made comments at open-microphone session

Jeff Byron, The Few, the Proud, the Forgotten (website coordinator)

Attendees

Harold Graef, U.S. Marine Corps
Mary Byron
Mike Tencate, U.S. Marine Corps
Scott Williams, U.S. Marine Corps

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Appendix C

Supplemental and Supporting Data for Chapter 2

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TABLE C-1 Characteristics of Remedial Investigation Sites Outside Tarawa Terrace and Hadnot Point Water-Supply Areas[a]

Water-Supply Area	Operable Unit, RI Site	Site Description	Nature of Waste or Contamination	Groundwater Contaminants Identified
Stone Bay Rifle Range	OU 14, site 69	Rifle range, chemical dump	Disposal of chemical wastes: PCBs, solvents, pesticides, tear gas or other training agents	VOCs in groundwater
Stone Bay Rifle Range	Pre-RI site 68	Rifle range, dump	Disposal of mixed wastes: garbage, building debris, waste treatment sludge, solvents	Low concentrations of organics in groundwater
Camp Geiger/MCAS	OU 3, site 48	MCAS mercury dump	No contaminants identified	No groundwater contamination
Camp Geiger/MCAS	OU 4, site 41	Camp Geiger dump near former trailer park	Mixed-waste dump containing solvents, batteries, ordnance and chemical training materials, construction waste, petroleum waste, pesticides	Metals (chromium, iron, lead, manganese) in groundwater
Camp Geiger/MCAS	OU 6, site 36	Camp Geiger dump area	Mixed industrial waste	VOCs in groundwater
Camp Geiger/MCAS	OU 6, site 43	Agan Street dump	Construction debris, sewage sludge, semivolatiles, pesticides	No significant groundwater contamination
Camp Geiger/MCAS	OU 6, site 44	Jones Street dump	Construction debris, paint, pesticides	Contaminated groundwater (VOCs) traced to other sites (OU 16)
Camp Geiger/MCAS	OU 6, site 54	Fire training-burn pit for airport	Unlined pit used until 1975 for burning VOCs	VOCs, SVOCs
Camp Geiger/MCAS	OU 10, site 35	Camp Geiger fuel farm	Fuel storage-tank releases	Multiple fuel, solvent plumes
Camp Geiger/MCAS	OU 16, 89	Camp Geiger area UST	Fuel storage-tank releases	Fuel contamination
Camp Geiger/MCAS	OU 16, 93	Camp Geiger area UST	Fuel storage-tank releases	Fuel contamination
Camp Geiger/MCAS	OU 20, site 86	Tank area, storage for petroleum products	Fuel storage-tank releases	VOC, SVOC contamination
Camp Geiger/MCAS	Pre-RI, site 75	MCAS basketball-court site	Reported drum burial—never found	No contamination
Camp Geiger/MCAS	Pre-RI, site 76	MCAS Curtis Road site	Reported drum burial—never found	No contamination
Camp Geiger/MCAS	Pre-RI, site 87	MCAS officer housing area dump	Hospital wastes eroding from bank	No groundwater contamination
Camp Johnson	OU 8, site 16	Monford Point burn dump	Housing trash, vehicle staging area	No significant groundwater contamination
Camp Johnson	Pre-RI, site 85	Camp Johnson battery dump	Battery disposal, metals in soils	No significant groundwater contamination
Holcomb Blvd.	OU 4, site 74	Mess hall grease-disposal area	Disposal area for pesticides, chemical-warfare materiel	Low concentrations of pesticides in one monitoring well

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Holcomb Blvd.	OU 5, site 2	Former nursery, day-care center	Former pesticide storage area with soil contamination	Low concentrations of toluene, ethylbenzene
Holcomb Blvd.	OU 11, site 80	Paradise Point golf maintenance area	Pesticides in soil	No significant groundwater contamination
Holcomb Blvd.	OU 12, site 3	Old creosote plant	Residual creosote contamination	VOCs, PAHs in groundwater
Holcomb Blvd.	OU 19, site 84	Building with PCBs, petroleum wastes	Building, soil contamination	No significant groundwater contamination
Courthouse Bay	OU 9, site 65	Engineer dump	Battery-acid, petroleum-product disposal	No significant groundwater contamination
Courthouse Bay	OU 17, sites 90, 91, 92	Courthouse Bay UST storage area	Fuel-storage tank releases	Fuel, solvent contamination from site 90 only
Courthouse Bay	OU 21, site 73	Courthouse Bay liquid-disposal area	Waste-oil , battery-acid disposal	VOCs in groundwater

[a]Data abstracted from Baker Environmental, Inc (1999), CH2M Hill and Baker Environmental, Inc (2005).
Abbreviations: MCAS = Marine Corps Air Station, OU = operable unit, PAH = polycyclic aromatic hydrocarbon, RI = remedial investigation, SVOC = semi-volatile organic compound, UST = underground storage tank, VOC = volatile organic compound.

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TABLE C-2 Documents That Contain Water-Quality Testing Information

CLW Documents				JTC Reports Not in CLW Documents		CMC Panel Summary
ALL	Hadnot Point	Tarawa Terrace	Holcomb Blvd.	Report	JTC Report	Document References
14RDENR300490	CLW0436	14RDENR300490	CLW1054	226	86-072	14 R DENR 300490
21RDENR000992	CLW0438	21RDENR000992	CLW1426	229	86-088	21 R DENR 000992
57MDENR050686	CLW0441	57MDENR050686	CLW1650	231	86-092	57 M DENR 050686
CLW 0430	CLW0443	CLW0592	CLW4512	237	86-094	
CLW 0436	CLW0444	CLW0606	CLW4513	243	86-112	
CLW 0438	CLW0446	CLW0694	CLW4516	251	86-122	
CLW 0441	CLW0543	CLW0952	CLW4533	253	86-140	
CLW 0443	CLW0566	CLW1124	CLW4546	259	86-142	
CLW 0444	CLW0580	CLW1182	CLW4558	261	86-143	
CLW 0446	CLW0592	CLW1183	CLW4708	273	86-211	
CLW 0487	CLW0596	CLW1232	CLW4709	275	86-212	
CLW 0495	CLW0606	CLW1244	CLW4787	275	86-212	
CLW 0498	CLW0694	CLW1283	CLW5369	286	86-265	
CLW 0500	CLW0952	CLW1355	CLW5371	289	86-278	
CLW 0503	CLW1051	CLW1426	CLW5484	298	86-276	
CLW 0508	CLW1054	CLW1475	CLW5509	302	86-323	
CLW 0511	CLW1089	CLW1557	CLW5594	308	86-324	
CLW 0514	CLW1093	CLW2979		316	86-329	
CLW 0543	CLW1283	CLW4513		320	86-347	
CLW 0566	CLW1426	CLW4546		333	86-381	
CLW 0580	CLW1647	CLW4558		341	86-398	
CLW 0592	CLW1650	CLW4707		345	86-410	
CLW 0596	CLW1652	CLW4787		346	86-411	
CLW 0606	CLW1796	CLW4806		353	86-422	
CLW 0694	CLW1917	CLW5082		358	86-453	
CLW 0952	CLW3256	CLW5094		363	86-464	
CLW 1051	CLW4512	CLW5102		493	87-001	
CLW 1054	CLW4513	CLW5131				
CLW 1089	CLW4516	CLW5362				
CLW 1093	CLW4533	CLW5452				
CLW 1124	CLW4546	CLW5478				
CLW 1182	CLW4558	CLW5484				
CLW 1183	CLW4708	CLW5509				
CLW 1232	CLW4709	CLW5529				
CLW 1244	CLW4787	CLW5565				
CLW 1283	CLW4976	CLW5570				
CLW 1355	CLW5102	CLW5839				

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CLW 1426
CLW 1475
CLW 1557
CLW 1647
CLW 1650
CLW 1652
CLW 1796
CLW 1917
CLW 2979
CLW 3256
CLW 3679
CLW 3689
CLW 3736
CLW 3745
CLW 4512
CLW 4513
CLW 4516
CLW 4533
CLW 4546
CLW 4558
CLW 4707
CLW 4708
CLW 4709
CLW 4787
CLW 4806
CLW 4976
CLW 5082
CLW 5094
CLW 5102
CLW 5112
CLW 5123
CLW 5131
CLW 5146
CLW 5156
CLW 5169
CLW 5362
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CLW5658
CLW5664
CLW5669
CLW5839
CLW5849
CLW5868
CLW5881
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CLW6339

CLW5849
CLW5868
CLW5881
CLW5892
CLW6339

(Continued)

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TABLE C-2 Continued

CLW Documents				JTC Reports Not in CLW Documents		CMC Panel Summary
ALL	Hadnot Point	Tarawa Terrace	Holcomb Blvd.	Report	JTC Report	Document References
CLW 5478						
CLW 5484						
CLW 5509						
CLW 5529						
CLW 5539						
CLW 5565						
CLW 5570						
CLW 5594						
CLW 5632						
CLW 5644						
CLW 5658						
CLW 5664						
CLW 5669						
CLW 5839						
CLW 5845						
CLW 5849						
CLW 5861						
CLW 5868						
CLW 5877						
CLW 5881						
CLW 5888						
CLW 5892						
CLW 6039						
CLW 6075						
CLW 6124						
CLW 6285						
CLW 6339						

Abbreviation: CLW = Camp Lejeune water.
Source: U.S. Marine Corps, personal commun., September 15, 2008.

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WATER-SAMPLING DATA IN TABLES C-3 AND C4

The committee reviewed Camp Lejeune water (CLW) documents for water-quality sample information relevant to Hadnot Point. The Marine Corps provided guidance on which CLW documents contained water-sampling data (Table C-2). CLW documents are publicly available from the Agency for Toxic Substances and Disease Registry (CD accompanying Maslia et al. [2007]). They are indexed by the first page number of a file; often, specific information abstracted from the files by the committee came from later pages in files. The committee reviewed at least one CLW for each sample listed in the table, even if sample information was summarized in multiple CLWs. For each sample, the committee reviewed at least the primary CLW, defined as the original laboratory report of the water-sample analysis results. If the committee looked at other CLWs in addition to the primary laboratory report, they are listed in the "Secondary CLW" column. Additional review was most commonly needed to determine the field sampling date.

Tables C-3 and C-4 summarize all samples abstracted by the committee for the Hadnot Point water-supply system. The universe of possible samples was restricted to those taken in the period from the earliest known water-sampling date in October 1980 through February 7, 1985. Because of removal of contaminated wells from the water-supply system, the committee believes that February 7, 1985, is the last date when samples were taken that would potentially reflect the contaminated water supply. All later samples were believed to have been taken after any measurable residual contamination would have remained in the water-supply system. Results of measurements in distinct samples were included in the table for each unique laboratory report. (See additional comments on this topic below.) There is a separate table of analytic results from mixed water samples taken from the water-distribution system (either before or after treatment; Table C-3) and a table of results from potable-water well samples (Table C-4). The two tables record concentrations of trichloroethylene (TCE), tetrachloroethylene (PCE), benzene, 1,1,1-trichloroethane (TCA), 1,1-dichloroethylene (1,1-DCE), *trans*-1,2-dichloroethylene (1,2-DCE; this compound was assumed if only "DCE" was listed in primary or secondary CLWs), methylene chloride (MC), toluene, and vinyl chloride (VC). Units are micrograms per liter (parts per billion), and the concentrations that appear on the laboratory sheets are recorded directly in the table. "ND" means not detected and appears when it was recorded by the laboratory. Occasionally, a laboratory used other indications for "not detected," such as "<1.0" or "<2.0"; in such cases, these values appear in the table. A dash, "—", appears when the document format suggests that a compound was not analyzed for. When the primary laboratory sheet listed the method detection limit, this value was recorded in the "DL" column of the table. That column was left blank when the information was not explicitly available. Additional sample information is contained in the "sample date" and "sample location" columns. The sample date is intended to be the date on which the sample was collected in the field. Because many of the primary laboratory sheets list the date on which a sample was received by the laboratory, secondary information was needed to make a judgment about the field collection date. This is one example of when "secondary CLWs" were consulted. "Sample location" is a description of the base location where the sample was obtained.

Separate samples were defined on the basis of the presence of a unique laboratory report, so there are distinct entries in the table for samples that were collected at the same location on the same day. The committee does not have information to determine definitively whether those are pure duplicates (one sample split into two vials for laboratory analysis) or separately collected samples. Regardless, measurements on samples collected at the same location on the same day are bound to be more similar than other samples because of their proximity in space and time. In particular, the data include a pair of measurements collected on the same day from well 651. It is unclear from the source documents whether those are measurements on a split sample or measurements on two samples collected on the same day. In addition, there are several instances of multiple samples from the same location in the mixed water samples; in these cases, the sample descriptions have minor distinctions (such as cold-water tap vs hot-water tap or filter 1 vs filter 2) to suggest that the samples were not split.

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TABLE C-3 Concentrations of Contaminants in Hadnot Point Mixed and Finished Water Samples Collected in October 1980–February 7, 1985

		Contaminants, µg/L											
Sample Date	Sample Location	TCE	PCE	1,2-DCE	1,1-DCE	Benzene	MC	TCA	Toluene	VC	DL[a]	Primary CLW[b]	Secondary CLWs[b]
Oct 21,1980	5 locations[c]	D[d]	D[d]	—	—	—	—	—	—	—		0436	
Dec 18, 1980	5 locations[c]	D[d]	D[d]	—	—	—	—	—	—	—		0438	
Jan 29, 1981	5 locations[c]	D[d]	D[d]	—	—	—	—	—	—	—		0441	
Feb 26, 1981	5 locations[c]	D[d]	D[d]	—	—	—	—	—	—	—		0443	
May 27, 1982	NH-1	1,400	15	—	—	—	—	—	—	—		0592	0606
June 1, 1982	Multiple locations	D[d]	D[d]	—	—	—	—	—	—	—		0566	
July 27, 1982	HP WTP raw	19	<1	—	—	—	—	—	—	—		0592	0606
July 27, 1982	Treated water at HP plant	21	<1	—	—	—	—	—	—	—		0592	0606
July 28, 1982	FC-530	—	1	—	—	—	—	—	—	—		0592	0606
Dec 2, 1982	Multiple locations	D[d]	D[d]	—	—	—	—	—	—	—		0694	
Aug 29, 1983	Multiple locations	D[d]	D[d]	—	—	—	—	—	—	—		0952	
Dec 4, 1984	20-raw	46	ND	15	ND	ND	ND	ND	ND	ND	10	5632	1051, 1054, 4546
Dec 4, 1984	20-treated	200	3.9	83	ND	ND	ND	ND	ND	ND	10	5632	1051, 1054, 4546
Dec 10, 1984	HP-treated	2.3	ND	2.3	ND	ND	ND	ND	ND	ND	10	5644	1054, 4546
Dec 13, 1984	20-untreated	ND	ND	ND	ND	ND	54	ND	ND	ND	10	5644	1054, 4546
Dec 14, 1984	HP WTP-raw	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5658	1054, 4546
Dec 15, 1984	HP WTP-raw	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5658	1054, 4546
Dec 16, 1984	HP WTP-raw	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5658	1054, 4546
Dec 17, 1984	HP WTP-raw	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5658	1054, 4546
Dec 18, 1984	HP WTP-raw	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5664	1054, 4546
Dec 19, 1984	20	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5664	1054, 4546
Dec 19, 1984	FC-540	1.2	ND	ND	ND	ND	ND	ND	ND	ND	10	5664	1054, 4546
Jan 29, 1985	670-reservoir	8.2	—	—	—	—	—	—	—	—		1426	4546
Jan 29, 1985	670-treated before reservoir	339.8	—	—	—	—	—	—	—	—		1426	4546
Jan 29, 1985	MOQ PP-2212	1,040.9	—	—	—	—	—	—	—	—		1426	4546
Jan 31, 1985	20-treated	900	—	321.3	—	—	—	—	—	—		4546	5371
Jan 31, 1985	670-bottom	24.1	—	7.4	—	—	—	—	—	—		4546	5371
Jan 31, 1985	670-middle	25.8	—	7.8	—	—	—	—	—	—		4546	5371
Jan 31, 1985	670-top	26.8	—	7.6	—	—	—	—	—	—		4546	5371
Jan 31, 1985	BM-5531	905.5	—	335	—	—	—	—	—	—		4546	5371

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Jan 31, 1985	BM-5677	981.3	—	368.7	—	—	—	—	—	—		4546	5371
Jan 31, 1985	Hydrant MOQ 2204	839.7	—	307.6	—	—	—	—	—	—		4546	5371
Jan 31, 1985	Hydrant tank S830	849	—	340	—	—	—	—	—	—		4546	5371
Jan 31, 1985	MOQ 2212 (cold water)	724.6	—	249.4	—	—	—	—	—	—		4546	5371
Jan 31, 1985	MOQ 2212 (hot water)	612.9	—	201.2	—	—	—	—	—	—		4546	5371
Jan 31, 1985	PP-2600 (fire department)	890.9	—	332.4	—	—	—	—	—	—		4546	5371
Jan 31, 1985	Tank S-2323	407.1	—	159	—	—	—	—	—	—		4546	5371
Jan 31, 1985	Tank SLCH-4004	318.3	—	107.5	—	—	—	—	—	—		4546	5371
Feb 5, 1985	20	429	7.5	150	ND	ND	ND	ND	ND	2.9	10	5509	4708, 4709
Feb 5, 1985	HB filter #1	2.8	ND	ND	ND	ND	ND	ND	ND	ND	10	5509	4708, 4709
Feb 5, 1985	HB filter #2	1.5	ND	ND	ND	ND	ND	ND	ND	ND	10	5509	4708, 4709
Feb 7, 1985	20-filter #1	<2.0	—	<2.0	—	—	—	—	—	—		1426	4546
Feb 7, 1985	20-filter #2	3.4	—	<2.0	—	—	—	—	—	—		1426	4546
Feb 7, 1985	20-influent	<2.0	—	<2.0	—	—	—	—	—	—		1426	4546
Feb 7, 1985	20-reservoir finished water	16.8	—	5.3	—	—	—	—	—	—		1426	4546
Feb 7, 1985	5400-Berkley Manor School	135.1	—	44.8	—	—	—	—	—	—		1426	4546
Feb 7, 1985	670-filter #1	<2.0	—	<2.0	—	—	—	—	—	—		1426	4546
Feb 7, 1985	670-filter #2	<2.0	—	<2.0	—	—	—	—	—	—		1426	4546
Feb 7, 1985	670-influent	<2.0	—	<2.0	—	—	—	—	—	—		1426	4546
Feb 7, 1985	670-reservoir finished water	<2.0	—	<2.0	—	—	—	—	—	—		1426	4546
Feb 7, 1985	MOQ 2204, hydrant system	32.4	—	9	—	—	—	—	—	—		1426	4546

[a]Analysis detection limit.
[b]Documents available on CD accompanying Maslia et al. (2007).
[c]Including locations designated as WTP, NH-1, 1202, 65, and FC-530.
[d]Samples were assumed to be detected on the basis of notes on the laboratory reports and inferences from later laboratory reports.
Abbreviations: D = detected, ND = not detected, — = no data available.

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TABLE C-4 Concentrations of Contaminants in Hadnot Point Supply Well Water Samples Collected in October 1980–February 7, 1985

		Contaminants, µg/L											
Sample Date	Supply Well	TCE	PCE	1,2-DCE	1,1-DCE	Benzene	MC	TCA	Toluene	VC	DL[a]	Primary CLW[b]	Secondary CLWs[b]
Dec 4, 1984	601	210	5	88	ND	ND	ND	ND	ND	ND	10	5632	4546
Dec 10, 1984	601	230	4.4	99	ND	ND	10	ND	ND	ND	10	5644	4546
Jan 16, 1985	601	26	ND	8.8	ND	ND	ND	ND	ND	ND	10	5594	4546
Nov 30, 1984	602	1,600	24	630	2.4	120	ND	ND	5.4	18	10	5632	4546
Dec 10, 1984	602	540	ND	380	ND	720	ND	ND	ND	ND	10	5644	4546
Dec 14, 1984	602	340	ND	230	ND	230	ND	ND	12	ND	10	5644	
Feb 4, 1985	602	38	1.5	74	ND	ND	ND	ND	ND	ND	10	5509	4546
Dec 4, 1984	603	4.6	ND	ND	ND	ND	ND	ND	ND	ND	10	5632	4546
Dec 10, 1984	603	ND	ND	ND	ND	ND	7	ND	ND	ND	10	5644	4546
Jan 16, 1985	603	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Jan 16, 1985	606	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Dec 4, 1984	608	110	ND	5.4	ND	3.7	ND	ND	ND	ND	10	5632	4546
Dec 10, 1984	608	13	ND	2.4	ND	4	14	ND	ND	ND	10	5644	4546
Feb 4, 1985	608	9	ND	ND	ND	1.6	ND	ND	ND	ND	10	5509	4546
Jan 16, 1985	609	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Feb 4, 1985	610	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5509	4546
Jan 16, 1985	611	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Jan 16, 1985	613	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Jan 16, 1985	614	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Jan 16, 1985	616	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Jan 16, 1985	620	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Jan 16, 1985	621	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Jan 16, 1985	627	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Jan 16, 1985	632	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Jan 16, 1985	633	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Dec 4, 1984	634	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5632	4546
Dec 10, 1984	634	ND	ND	2.3	ND	ND	130	ND	ND	ND	10	5644	4546
Jan 16, 1985	634	1,300	10	700	ND	ND	ND	ND	ND	6.8	10	5594	4546
Jan 16, 1985	635	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Jan 16, 1985	636	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Dec 4, 1984	637	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5632	4546
Dec 10, 1984	637	ND	ND	ND	ND	ND	270	ND	ND	ND	10	5644	4546

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Jan 16, 1985	637	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Jan 16, 1985	638	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Jan 16, 1985	640	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Jan 16, 1985	641	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Dec 4, 1984	642	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5632	4546
Dec 10, 1984	642	ND	ND	ND	ND	ND	38	ND	ND	ND	10	5644	4546
Jan 16, 1985	642	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Jan 16, 1985	643	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Jan 16, 1985	644	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Jan 16, 1985	646	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Jan 16, 1985	647	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Jan 16, 1985	648	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Jan 16, 1985	650	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Jan 16, 1985	651	3,200	386	3,400	187	ND	ND	ND	ND	655	10	5594	4546
Feb 4, 1985[c]	651	18,900	400	7,580	ND	ND	ND	ND	ND	168	200	5509	4546
Feb 4, 1985[c]	651	17,600	397	8,070	ND	ND	ND	ND	ND	179	200	5509	4546
Jan 16, 1985	652	9	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Jan 16, 1985	653	5.5	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Feb 4, 1985	654	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5509	4546
Jan 16, 1985	655	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Jan 16, 1985	639 new	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Jan 16, 1985	639 old	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5594	4546
Feb 4, 1985	645-5	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5509	4546
Feb 4, 1985	649-3	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	5509	4546

[a]Analysis detection limit.
[b]Documents available on CD accompanying Maslia et al. (2007).
[c]Water taken from supply well 651 on February 4, 1985, was reported on two laboratory reports; this resulted in two sets of contaminant concentrations. CLW 4546 reports these values in a table as "duplicates."
Abbreviation: ND = not detected.
Source: Maslia et al. 2007.

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TABLE C-5 Positive Detection Summary, Deep Monitoring Wells, Hadnot Point Installation Restoration Sites 78, 6, 9, and 82,[a] Remedial Investigation Sampling Efforts, 1992-1993

				Concentrations (µg/L), Sampling Year and Round[b]		
Well	Depth, ft	Nearest PWS Well	Contaminant	1992	1993 Round 1	1993 Round 2
78-GW04-3	153	608	Benzene	30	Not sampled	Not sampled
			cis-1,2-DCE	3		
			Phenol	5		
			Arsenic	118		
			Cadmium	21		
			Manganese	591		
78-GW09-3	150	608	Alpha chlordane	0.11	Not sampled	Not sampled
			Bis(2-ethylhexyl) phthalate	18		
			Phenol	8		
78-GW24-3	148	634	Benzene	35	Not sampled	Not sampled
			cis-1,2-DCE	3		
			trans-1,2-DCE	1		
			Naphthalene	2		
			Phenol	5		
			Cadmium	5		
78-GW30-3	153	634	[c]	ND	Not sampled	Not sampled
78-GW31-3	153	601	Benzene	15.3	Not sampled	Not sampled
			cis -1,2-DCE	1		
			Phenol	4		
78-GW32-3	153	601, 602, 630	1,2-DCA	1	Not sampled	Not sampled
			2-Methylphenol	2		
			Phenol	2		
			TCE	6		
6-GW01-DW	112.5	651	Benzene		Not sampled	6.7
			Chlorobenzene			13
			Chloromethane			1.4
			1,4-Dichlorobenzene			17
			1,2-DCA			30
			1,1-DCE			51
			trans-1,2-DCE	5,600		26,000
			Ethylbenzene	48		52
			Methylene Chloride	790		
			PCE	630		920
			Phenol	3		
			1,1,2-TCA			5.8
			TCE	58,000		50,000
			Toluene			1.4

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			Vinyl chloride			800
			Xylenes			2.1
			Barium	71.5		
			Manganese	21.6		
6-GW01-DA	230	651	TCE base/top	Not sampled	83/160	Not sampled
			Total 1,2-DCE base/top		38/100	
			PCE base/top		1.3/2.9	
6-GW02-DW	119	651	Phenol	3	Not sampled	ND
			TCE	1.4		
			Arsenic	3.8		
6-GW07-DW	100.5	651	1,1-DCE	0.6	Not sampled	
			Phenol	3		
			TCE	1.2		2.1
			Aluminum	336		
			Manganese	33.5		
6-GW15-DW	155	651	TCE	Not sampled	34	Not sampled
			Total 1,2-DCE		9.1	
			PCE		1	
6-GW27-DW	110	651	Bis(2-ethylhexyl)phthalate	5	Not sampled	
			Chlorobenzene			3.6
			1,2-DCA			16
			1,1-DCE			55
			trans-1,2-DCE	5,800		30,000
			PCE			18
			Phenol	22		
			TCE	18,000		22,000
			Vinyl chloride			250
			Antimony	15.3		
			Manganese	14.2		
6-GW28-DW	114.5	651	Bis(2-ethylhexyl)phthalate	22	Not sampled	
			Chlorobenzene			18
			1,2-DCA			7.5
			1,1-DCE			12
			trans-1,2-DCE	500		5,800
			Ethylbenzene			2
			PCE			42
			Phenol	2		
			TCE	3,600		9,100
			Vinyl chloride			100
			Manganese	14.2		

(Continued)

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TABLE C-5 Continued

Well	Depth, ft	Nearest PWS Well	Contaminant	Concentrations (µg/L), Sampling Year and Round[b]		
				1992	1993 Round 1	1993 Round 2
6-GW36-DW	95	651	TCE	Not sampled	6.4	Not sampled
			Total 1,2-DCE		3.4	
6-GW37-DW	95	651	TCE	Not sampled	60	Not sampled
			Total 1,2-DCE		120	
			1,2-Dichlorobenzene		2.6	
9-GW07-DW	110	635	Bis(2-ethylhexyl)phthalate	2	62	
			Dimethyl phthalate	1		
			Phenol	7	5	
			TCE			1.2
			Aluminum	207	1,360	
			Barium	34.9	356	
			Manganese	14.8	49.3	
			Selenium		2.1	

[a]Monitoring wells for site 82 are labeled "6"; sites 6 and 82 are adjacent.
[b]Data for this table copied from tables in remedial investigation reports. Blanks appear as in original tables. The committee interprets blanks as representing analyses that registered "below the detection limit."
[c]None of the chemicals test for were detected.
Abbreviation: ND = not detected.
Note: Data abstracted from Remedial Investigation Report, Operable Unit 1, sites 21, 24, and 78, Marine Corps Base, Camp Lejeune, NC, Undated Report. Tables 4-6 (Organic Chemicals) and 4-7 (TAL Total Metals and Cyanide).
Data abstracted from Remedial Investigation Report, Operable Unit 2, sites 6, 9, and 82, Marine Corps Base, Camp Lejeune, NC, Contract Task Order 0133, prepared by Baker Environmental, August 20, 1993.
Depths: Tables 1-1, 2-8, 2-9, 2-18, and 2-21.
Concentrations: Chapter 4 and Tables 4-5 (Phase I Organic Chemicals) and 4-6 (Phase I TAL Total Metals and Cyanide).
Tables 4-23 (Phase II Round 1 Organic Chemicals), 4-24 (Phase II Round 1 TAL Total Metals and Cyanide), and 4-10 (Comparison of Organic Chemicals, Round I and Round II).

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TABLE C-6 Estimated Number of Residences by Water-Treatment Plant, 1941-2000

Water Treatment Plant and Distribution System	Years of Operation	Housing Areas
Courthouse Bay water system	1942-2000	Courthouse Bay housing—8 homes
		Courthouse Bay barracks
Camp Johnson water system	1941-1946	Camp Johnson barracks
Camp Geiger water system	1941-1976	Camp Geiger barracks
Rifle range water system	1942-1993	Rifle range housing—5 homes
		Rifle range barracks
Onslow County water system	1994-2000	Rifle range housing—5 homes
		Rifle range barracks
Hadnot Point water system	1943-1971	Midway Park housing—699 homes
		Paradise Point general officer housing—4 homes
		Paradise Point two-story housing—216 homes
	1947-1971 Added	Hospital Point housing—24 homes
		Paradise Point cracker box housing—100 homes
	1948-1971 Added	Paradise Point Cape Cod housing—67 homes
	1961-1971 Added	Berkeley Manor housing—677 homes
	1962-1971 Added	Paradise Point Capehart housing—123 homes
Hadnot Point water system	1943-2000	French Creek barracks
		Hadnot Point barracks
Tarawa Terrace water system	1952 - 1986	Tarawa Terrace I & II housing—1,843 homes
		Knox trailer park—112 spaces
Marine Corps Air Station water system	1958 - 2000	Marine Corps Air Station housing—435 homes
	1977-2000 Added	Camp Geiger barracks
Holcomb Boulevard water system	1972-2000	Midway Park housing—699 homes
		Paradise Point general officer housing—4 homes
		Paradise Point two-story housing—216 homes
		Paradise Point cracker box housing—100 homes
		Paradise Point Cape Cod housing—67 homes
		Berkeley Manor housing—677 homes
		Paradise Point Capehart housing—123 homes
	1978-2000 Added	Watkins Village housing—250 homes
	1987-2000 Added	Tarawa Terrace I & II housing—1,843 homes
		Knox trailer park—112 spaces
		Camp Johnson barracks
	1989-2000 Added	Knox trailer park expanded by—75 spaces

Source: U.S. Marine Corps.

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Appendix D

Review of Other Chemical Contaminants of Concern

Chapter 2 identified seven contaminants of the water supply at Camp Lejeune that the committee judged as warranting further attention in addition to trichloroethylene and perchloroethylene: 1,2-dichloroethylene (1,2-DCE; *cis*- and *trans*-forms), 1,1-dichloroethylene (1, 1-DCE), benzene, methylene chloride (MC), toluene, and vinyl chloride (VC). (Information about the detection of these chemicals is presented in Chapter 2 and Appendix C.) The committee used comprehensive reviews performed by other organizations and agencies to compile the following overview of the potential health effects of those contaminants.

1,2-DICHLOROETHYLENE

The health effects of 1,2-DCE were reviewed by ATSDR (1996). 1,2-DCE is used to produce solvents and in chemical mixtures. There are two forms (isomers) of 1,2-DCE: *cis*-1,2-DCE, and *trans*-1,2-DCE. The two forms are sometimes present as a mixture. 1,2-DCE evaporates rapidly into air. Most 1,2-DCE in the soil surface or bodies of water will evaporate into air, and it can travel through soil or dissolve in water in soil. It is possible that it can contaminate groundwater. There is a slight chance that 1,2-DCE will break down into VC, which is believed to be more toxic than 1,2-DCE. One can be exposed by breathing 1,2-DCE that has leaked from hazardous-waste sites and landfills; by drinking contaminated tap water or breathing vapors from contaminated water while cooking, bathing, or washing dishes; by breathing it; by touching it; or by touching contaminated materials in the workplace. The most important effects of 1,2-DCE exposure are hematologic (such as a decrease in the number of red blood cells) and hepatic. Clinical symptoms that have been reported in humans exposed to 1,2-DCE at high concentration in air include nausea, drowsiness, fatigue, intracranial pressure, and ocular irritation. One fatality has been reported. No information is available on oral toxicity of 1,2-DCE in humans. No information is available on the relative toxicities of *cis*- and *trans*-1,2-DCE in humans. A variety of genotoxicity tests have been performed on 1,2-DCE. The predominant results are negative, and no carcinogenicity studies were found in the literature. EPA has determined that *cis*-1,2-DCE is not classifiable as to human carcinogenicity. No EPA cancer classification of *trans*-1,2-DCE is available. Specific effects of 1,2-DCE in animals are discussed below.

Hepatic Toxicity

Subchronic exposure to *trans*-1,2-DCE in drinking water (17-452 mg/kg per day) has caused biochemical changes in the livers of mice (Barnes et al. 1985). Both sexes had increased glucose concentrations, and females had decreased serum glutamic-pyruvic transaminase, serum glutamic-oxaloacetic

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transaminase, and aniline hydroxylase activity at all doses. Males had significantly decreased glutathione at the highest dose. In studies with rats, increased relative hepatic weights were observed with *cis*-1,2-DCE at 32 mg/kg per day and higher (McCauley et al. 1995). Variable changes in hepatic enzyme concentrations were seen, but no histopathologic lesions of the liver. A study of *trans*-1,2-DCE administered to rats in microcapsules for 14 weeks reported increased hepatic weights in females but not males at 395 mg/kg per day (NTP 2002c). No significant alterations in clinical-chemistry measures were found.

In an inhalation study, fatty degeneration of liver lobules was observed in female rats exposed to *trans*-1,2-DCE at 200 ppm for 8 or 16 weeks (Freundt et al. 1977).

Renal Toxicity

There is little clinical or histologic evidence of renal toxicity in experimental studies of 1,2-DCE (ATSDR 1996). A recent 14-week study of *trans*-1,2-DCE reported significantly reduced absolute renal weights in male rats at 1,540 mg/kg per day (NTP 2002c) but no gross or microscopic lesions.

Pulmonary Toxicity

With the exception of some effects on the lungs after lethal doses of *trans*-1,2-DCE, experimental studies of DCE isomers have yielded little clinical or histologic evidence of pulmonary toxicity (ATSDR 1996).

Reproductive Toxicity

One study of pregnant rats exposed by inhalation to *trans*-1,2-DCE at 6,000 or 12,000 ppm found a significant increase in the mean number of resorptions per litter (Hurtt et al. 1993), but the authors noted that the value was within the range of historical control values; maternal toxicity was observed. The National Toxicology Program (NTP 2002c) reported no significant changes in sperm motility or vaginal cytology in rats or mice fed microencapsulated *trans*-1,2-DCE at doses as high as 8,065 mg/kg per day for 14 weeks.

Developmental Toxicity

Hurtt et al. (1993) reported significantly reduced mean combined and female fetal weights in rats exposed to *trans*-1,2-DCE by inhalation during pregnancy at 12,000 ppm. The dams had frank maternal toxicity, as evidenced by reduced food consumption and reduced weight gain.

Neurotoxicity

Several studies have reported central nervous system (CNS) depression in rats after exposure to *cis*-1,2-DCE at 878 mg/kg per day (McCauley et al. 1995) or to either isomer of 1,2-DCE at lethal doses (Barnes et al. 1985; McCauley et al. 1995). After inhalation exposure, experimental animals have exhibited lethargy, behavioral changes, and other neurologic effects (ATSDR 1996), but the significance of the changes is unclear. A functional observational battery performed on mice and rats given microencapsulated *trans*-1,2-DCE in their feed at up to 8,065 mg/kg per day for 14 weeks found no evidence of CNS depression (NTP 2002c).

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Immunotoxicity

In studies of mice given *trans*-1,2-DCE orally at 224 mg/kg per day, an increase in leukocyte counts and a decrease in relative thymus weight were found in females, but no changes in cell-mediated or humoral immunity were observed (Barnes et al. 1985; Shopp et al. 1985). However, in one study, male mice treated with *trans*-1,2-DCE at 17-387 mg/kg per day exhibited decreased spleen-cell production of antibody against sheep erythrocytes, which did not result in a functional effect on the humoral immune system (Shopp et al. 1985). An inhalation-exposure study of *trans*-1,2-DCE by Freundt et al. (1977) reported fatty degeneration of Kupffer cells, decreased leukocyte counts, and pulmonary infiltration at 200 ppm and greater.

Hematopoietic Toxicity

Female rats exposed to *cis*-1,2-DCE exhibited decreased hemoglobin concentrations, red blood cell counts, and hematocrit values at 98 mg/kg per day for 90 days (McCauley et al. 1995) but not at lower doses, and no statistically significant effects were observed in male rats. Other studies have reported no hematologic effects in rats or mice after oral exposure to *trans*-1,2-DCE at up to 3,114 mg/kg per day for 90 days (Barnes et al. 1985; Hayes et al. 1987).

In a more recent 14-week study, the NTP (2002c) reported mild decreases in hematocrit values, hemoglobin concentrations, and red blood cell counts in rats fed microcapsules containing *trans*-1,2-DCE at 380 mg/kg per day for males and 1,580 mg/kg per day for females. Mice similarly exposed did not have those changes.

Genotoxicity

Genotoxicity studies of 1,2-DCE have had predominantly negative results (ATSDR 1996; NTP 2002c). Both isomers were negative in mutagenicity assays with bacteria and chromosomal-aberration tests with Chinese hamster cells. Mixed results have been reported with respect to chromosomal effects in mammalian systems (ATSDR 1996; NTP 2002c). Negative results were reported in a peripheral-blood micronucleus test performed with mice fed microencapsulated *trans*-1,2-DCE for 14 weeks (NTP 2002c).

Cancer

No cancer bioassays of either isomer of 1,2-DCE have been performed.

1,1-DICHLOROETHYLENE

The health effects of 1,1-DCE, also known as vinylidene chloride, were reviewed by the Agency for Toxic Substances and Disease Registry (ATSDR 1994), the International Agency for Research on Cancer (IARC 1999a), and the U.S. Environment Protection Agency (EPA 2002). 1,1-DCE is an industrial chemical not found naturally in the environment. It is used to make plastics (such as flexible films for wrapping food and packaging materials), to make flame-retardant coatings for fiber and carpet backings, and in piping, coating for steel pipes, and adhesives. 1,1-DCE evaporates quickly from water and soil, breaks down slowly in water, and is slowly transformed to other, less harmful chemicals in soil. One may be exposed to 1,1-DCE through employment in industries that make or use 1,1-DCE, through food that is wrapped in plastic that contains 1,1-DCE, through drinking water from the small percentage of supplies that contain 1,1-DCE, and through air near factories or hazardous-waste sites. It has been used in the past

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as a gaseous anesthetic agent; its use as an anesthetic agent was discontinued after it was discovered that it induced cardiac arrhythmia at anesthetic doses. Inhalation of high concentrations of 1,1-DCE is known to cause reversible nervous system impairment. Workers exposed to 1,1-DCE have reported a loss in hepatic function, but other chemicals were present. Specific effects of 1,1-DCE in animals are discussed briefly below.

Hepatic Toxicity

Acute doses of 1,1-DCE administered orally to rats at 25-100 mg/kg per day induced hepatic toxicity, including alterations in hepatic enzymes indicative of damage or dysfunction and histopathologic evidence of damage (ATSDR 1994). Gavage studies of more prolonged exposure to 1,1-DCE (13 weeks) reported hepatic necrosis in male mice exposed at 250 mg/kg per day and in female mice at 5 mg/kg per day (NTP 1982). Similarly exposed rats had chronic hepatic inflammation at a dose of 250 mg/kg per day. Drinking-water and feed studies have reported little or milder evidence of hepatic toxicity. For example, Quast et al. (1983) reported no histopathologic changes in the livers of dogs exposed to 1,1-DCE in drinking water at 25 mg/kg per day for 97 days. In 2-year exposure studies with rats, only mild hepatocellular changes were observed at doses of 6-30 mg/kg per day (Rampy et al. 1977; Quast et al. 1983).

Inhalation-exposure studies have reported similar evidence of hepatic toxicity in rats and mice (ATSDR 1994). After some of the longer exposures, changes observed at 25 ppm included cytoplasmic vacuolation (ATSDR 1994) and fatty infiltration of the liver (Quast et al. 1986), and at 125 ppm, centrilobular fatty degeneration and hepatic necrosis (ATSDR 1994). Food intake appears to affect the hepatic toxicity of 1,1-DCE: greater effects have been observed in fasted rats in both oral and inhalation studies (ATSDR 1994).

Renal Toxicity

Several types of renal effect have been reported in experimental animals exposed to 1,1-DCE orally and by inhalation. For example, single oral doses of 1,1-DCE at 200 mg/kg or greater caused histopathologic changes in the kidneys of rats (ATSDR 1994). However, no renal effects were observed in experimental animals exposed at 30 mg/kg per day or less in chronic-exposure studies (Rampy et al. 1977; Quast et al. 1983).

In acute-inhalation studies, renal effects have included enzyme changes, hemoglobinuria, increased kidney weight, and tubular swelling, degeneration, and necrosis at concentrations as low as 50 ppm in rats and 10 ppm in mice (ATSDR 1994). In toxicity studies of longer duration (52 weeks), severe renal effects have been observed in mice at 10-25 ppm (Maltoni et al. 1985) but not in rats (Maltoni et al. 1985; Quast et al. 1986).

The renal toxicity of 1,1-DCE appears to be related to sex-specific expression of CYP2E1 in male mice (EPA 2002). One proposed mechanism of renal toxicity is the formation of cytotoxic intermediates from CYP2E1 activity in the kidneys. Another possible mechanism is the formation of *S*-conjugates that are metabolized by β-lyase in the proximal renal tubules and yield products that interact with macromolecules (ATSDR 1994; EPA 2002).

Pulmonary Toxicity

Acute inhalation exposure to 1,1-DCE has produced swelling, edema, and congestion of the lungs of rodents at 500-15,000 ppm and in some species at concentrations as low as 20 ppm (ATSDR 1994). One acute oral study of 1,1-DCE (100 mg/kg) found pulmonary injury in mice (Forkert and Reynolds 1982). Clara cells are especially targeted in the lungs of mice (Forkert et al. 1986). In longer-term inhala-

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tion-exposure studies, no histopathologic changes in the lungs or respiratory system were observed in several test species at 100 ppm (Prendergast et al. 1967; Quast et al. 1986).

Reproductive Toxicity

No evidence of reproductive toxicity was found in a three-generation study of rats exposed to 1,1-DCE in drinking water at up to 200 ppm (Nitschke et al. 1983). Similarly, no effects were found in reproductive studies in male rats exposed to 1,1-DCE by inhalation at up to 50 ppm (Anderson et al. 1977; ATSDR 1994).

Developmental Toxicity

Murray et al. (1979) studied the effects of inhaled 1,1-DCE on pregnant rats. Maternal and embryo toxicity was observed in rats exposed during gestation at 80 ppm or greater and in rabbits at 160 ppm, but there was no evidence of teratogenicity in either species. A study of 1,1-DCE administered in the drinking water of pregnant rats at 200 ppm found no evidence of maternal or fetal toxicity or teratogenicity (Murray et al. 1979).

In another study, 1,1-DCE was administered to rats in drinking water before mating and/or during gestation (Dawson et al. 1993). A significant increase in congenital cardiac malformations was observed in the fetuses of rats treated before mating and during gestation at a drinking-water concentration of 0.15 or 100 ppm, but a dose-response relationship was not demonstrated. However, a three-generation study of rats exposed to 1,1-DCE in drinking water at up to 200 ppm did not find cardiac changes (Nitschke et al. 1983). One study reported a significant increase in the mean number of mouse fetuses with an unossified incus and with incompletely ossified sternebrae at a drinking-water concentration of 15 ppm (EPA 2002). Other evidence of developmental toxicity was observed at higher concentrations, but frank maternal toxicity was also observed at those concentrations.

Neurotoxicity

Like other organic solvents, 1,1-DCE at high concentrations has a narcotic effect on experimental animals (ATSDR 1994). In general toxicology studies, there have been no reports of neurologic effects of 1,1-DCE after oral or inhalation exposure, but these studies were not designed specifically to evaluate neurologic effects.

Immunotoxicity

Ban et al. (2003) exposed mice to 1,1-DCE by inhalation at 5-15 ppm and tested systemic and local immune response. IgM response in the lymph nodes to challenge with sheep red blood cells was increased, and the highest exposure provoked a similar response in the spleen. A significant increase in the release of interferon-gamma was found in lymph node cultures but the increase in spleen cell cultures was smaller. The investigators concluded that lung-associated lymph nodes could be sensitive targets for inhaled 1,1-DCE.

Hematopoietic Toxicity

No significant hematologic changes have been reported in drinking-water studies of 1,1-DCE in

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dogs exposed at 25 mg/kg per day for 97 days (Quast et al. 1983) or in rats exposed at 30 mg/kg per day for 2 years (Rampy et al. 1977; Quast et al. 1983). No evidence of hematotoxicity was observed in inhalation studies with rats and mice exposed at 55-75 ppm for 1 year or more (Lee et al. 1977; Quast et al. 1986).

Genotoxicity

1,1-DCE has been shown to be mutagenic, to induce chromosomal aberrations and sister-chromatid exchanges in vitro, and to cause DNA damage in vivo (ATSDR 1994; EPA 2002). In most cases, metabolic activation was required to produce the results.

Cancer

A number of chronic bioassays of oral and inhaled 1,1-DCE have been performed in rodents (ATSDR 1994; EPA 2002; Roberts et al. 2002). Only one inhalation study has shown evidence of carcinogenicity (Maltoni et al. 1985); male mice exposed at 25 ppm had an increased incidence of renal adenocarcinomas. IARC judges 1,1-DCE as not classifiable with respect to human carcinogenicity (IARC 1987, 1999a).

BENZENE

Benzene, also known as benzol, has industrial and natural sources. First discovered and isolated from coal tar in the 1800s, benzene is made mostly from petroleum today and ranks in the top 20 in production volume among chemicals produced in the United States. Other sources of benzene include gas emissions from volcanoes, forest fires, gasoline, and cigarette smoke. Benzene is widely distributed in the environment, and low-level inhalation over long periods is of most concern. People employed in industries that make or use benzene or products that contain it are probably exposed to the highest concentrations of atmospheric benzene. People with benzene-contaminated tap water can be exposed from drinking the water or eating foods prepared with it; by inhalation during showering, bathing, and cooking; and through dermal contact during showering and bathing.

Benzene is a well-studied chemical and has been the subject of several comprehensive reviews and risk assessments (IARC 1982, 1987; EPA 1998b, 2002; ATSDR 2007). It is well established in those reviews that benzene is associated with effects on the hematologic, immune, and nervous systems. Evidence of the effects is found in reports of controlled animal experiments (Gill et al. 1980; Rozen et al. 1984; Cronkite et al. 1985, 1989; Rosenthal and Snyder 1985; Molnar et al. 1986) and in the epidemiologic literature, especially reports of occupational studies of benzene exposure (Srbova et al. 1950; Yin et al. 1987a; Kraut et al. 1988; Rothman et al. 1996; Lan et al. 2004).

There is agreement in the scientific community that benzene is a human carcinogen (IARC 1987; EPA 1998b; NTP 2005; ATSDR 2007). Inhalation studies of rodents show that benzene causes cancer in multiple tissues, and there is strong evidence of lymphoid tumors in mice (Snyder et al. 1980, 1984, 1988; Cronkite et al. 1984, 1985, 1989; Maltoni et al. 1989; Farris et al. 1993). Acute myelogenous leukemia is the predominant cancer found in humans exposed to benzene and has been documented in studies of workers exposed to benzene in rubber hydrochloride manufacturing plants (Rinsky et al. 1981, 1987) and in factories in China (Yin et al. 1987b, 1989, 1996; Hayes et al. 1996, 1997). Most epidemiologic studies have also found an increased risk of leukemia in general, total lymphatic and hematopoietic cancers, and other specific types of leukemia, such as chronic lymphocytic leukemia (Savitz and Andrews 1997; NTP 2005). The health effects of benzene were most recently reviewed by ATSDR (2007). The central conclusions of that review are summarized below.

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The carcinogenicity of benzene in exposed workers is well documented. Epidemiologic studies of occupational cohorts provide clear evidence of a causal relationship between occupational exposure to benzene and benzene-containing solvents and acute myelogenous leukemia. All leukemias and myelodysplastic syndromes have been linked to occupational exposure to benzene at high concentrations, and there appears to be a dose-response relationship. Other cancer outcomes associated with occupational exposure to benzene in some studies are non-Hodgkin lymphoma and multiple myeloma; however, these associations have not been consistently observed among studies.

Benzene has been shown to have adverse hematologic and immunologic effects. All the major types of blood cells are susceptible (erythrocytes, leukocytes, and platelets). Severe toxicity may result in hypercellular bone marrow that exhibits ineffective hematopoiesis and pancytopenia (reduced numbers of all types of blood cells). Severe damage to the bone marrow involving cellular aplasia is known as aplastic anemia and can lead to leukemia. Early studies of benzene-exposed workers demonstrated that chronic exposure to benzene at air concentrations of 10 ppm or more had adverse hematologic effects, which increased in severity with increasing benzene concentration. More recent epidemiologic studies have observed hematologic effects (including significant reductions in the numbers of various types of blood cells) in workers chronically exposed to benzene at less than 10 ppm and even at 1 ppm or less. After inhalation exposure for intermediate and chronic durations, benzene has had adverse immunologic effects, including decreases in concentrations of antibodies and leukocytes in benzene-exposed workers.

The current literature suggests that humans exposed to benzene in an occupational setting for acute, intermediate, or chronic durations by inhalation and orally are at risk for neurologic effects. However, benzene concentrations in ambient air, in drinking water, and at hazardous-waste sites are lower and not likely to be of concern. Limited information is available on other systemic effects in humans and is associated with high exposure. Respiratory effects, dermal effects (skin irritation and burns), ocular effects (irritation), and cardiovascular effects (particularly ventricular fibrillation) have been suggested after exposure to benzene vapors. Gastrointestinal effects have been noted after fatal inhalation exposure (congestive gastritis) or ingestion (toxic gastritis and pyloric stenosis). Reports of renal effects refer to renal congestion after fatal inhalation exposure.

The evidence of effects of benzene exposure on human reproduction is not sufficient to demonstrate a causal association. Epidemiologic studies implicating benzene as a developmental toxicant have many limitations, and it is not possible to assess the effect of benzene on the human fetus.

METHYLENE CHLORIDE

MC is used in various industrial processes, including paint stripping, pharmaceutical manufacturing, paint-remover manufacturing, and metal cleaning and degreasing. It may also be found in some aerosol and pesticide products and is used in the manufacture of photographic film. MC is a toxic chemical that is known to cause death in humans at high doses (ATSDR 2000a). Human fatalities are most often associated with effects on the nervous system. In general, people can be exposed through air, water, food, or such products as paint thinner (ATSDR 2000a). ATSDR (2000a) reviewed the scientific literature for toxicologic profile. The Office of Environmental Health Hazard Assessment of the California Environmental Protection Agency also reviewed the available studies to develop a public-health goal for MC in drinking water (CalEPA 2000b).

In addition, three organizations reviewed the scientific literature to determine whether MC causes cancer. The NTP concluded that MC is "reasonably anticipated" to be a human carcinogen on the basis of evidence of carcinogenicity in mice. In 1999, IARC concluded that MC was "possibly carcinogenic to humans." In 1991, EPA classified it as a "probable human carcinogen" on the basis of sufficient evidence of hepatic and lung cancer and mammary tumors in experimental animals (EPA 1991). EPA announced that it had begun a reassessment of MC, but no findings have been posted.

In 1992, EPA adopted a maximum contaminant level (MCL) in drinking water of 5 ppb and an MCL goal of 0 ppb, citing concerns about hepatic effects and cancer (EPA 2003). The MCLs reflected

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consideration of the potential for health effects and of the feasibility and cost of treatment technologies and so may not represent health-based standards. California adopted a public-health goal in drinking water of 4 ppb on the basis solely of health concerns. The California drinking-water standard, like the federal standard, is 5 ppb and was adopted in 1994 (CalEPA 2000b).

IOM (2003) reviewed the human health effects of chronic exposure to MC, including results of several occupational studies, such as those of aircraft-maintenance workers (Blair et al. 1998), cellulose-fiber production-plant workers (Lanes et al. 1993; Gibbs et al. 1996), photographic-film base-manufacturing workers (Hearne and Pifer 1999), cellulose triacetate film workers (Tomenson et al. 1997), and lamp-manufacturing workers (Shannon et al. 1988). No consistent pattern of increased risk of any health effect was found. The present committee performed an updated literature review to identify new studies since the IOM (2003) review. No new studies in which exposure to MC could be specifically evaluated were found. IOM concluded that there was inadequate/insufficient evidence to determine whether there is an association between MC and cancer or neurologic, reproductive, developmental, or other health effects. The committee supports IOM's conclusions.

We also surveyed reports published since the earlier reviews were performed. Little testing has been done for additional health end points. Most of the published research focuses on the interpretation of data from studies in animals and addresses such issues as differences between mice and humans (e.g., Jonsson and Johanson 2001; Sherratt et al. 2002; Slikker et al. 2004), development of physiologically based pharmacokinetic models (e.g., Sweeney et al. 2004), and application of findings to cancer risk assessment (e.g., David et al. 2006; Marino et al. 2006; Starr et al. 2006). One study reported that ingestion of acetaminophen, a commonly used analgesic, increased the activation of MC in rats (Kim et al. 2007). With regard to additional studies of end points of concern, the committee found one new investigation of the immunotoxicity of MC, which is discussed below.

Hepatic Toxicity

Studies of animals exposed to MC in drinking water have reported effects on the liver. Kirschman et al. (1986) reported changes in hepatic cells (including centrilobular necrosis, granulomatous foci, and cytoplasmic cosinophilic bodies) in male rats after 90 days of exposure to MC in drinking water at 1,200 mg/kg per day. Less serious effects were observed at the lowest dose, 166 mg/kg per day, in males and a slightly higher dose in females. MC was reported to alter the distribution of lipids among tissues. The study also reported changes in blood chemistry characteristics, such as fasting glucose, cholesterol, and triglyceride values, at all doses, at 1 and 3 mo. The same authors reported subtle centrilobular fatty changes in male $B6C3F_1$ mice exposed for 90 days at 587 mg/kg per day.

Serota et al. (1986a,b) reported hepatic changes, including cellular alterations in Fischer rats exposed to MC for 78-104 weeks at 55 mg/kg per day and increased hepatic fat in $B6C3F_1$ mice exposed for 2 years at 236 mg/kg per day.

EPA reported a NOAEL of 5.8 and 6.5 mg/kg per day for histologic alterations of the liver in male and female rats, respectively, exposed during a 2-year bioassay of exposure in drinking water (EPA 1988). The lowest observed-adverse-effects levels (LOAELs) reported were 52.6 and 58 mg/kg per day in male and female rats, respectively (National Coffee Association [1982], as cited by EPA 1988). EPA used those values to set a reference dose for exposure in drinking water of 0.06 mg/kg per day. EPA has not set a reference dose for inhalation exposure.

Kjellstrand et al. (1986) reported increased hepatic weight in mice exposed at 75 ppm for 90 days. No NOAEL was reported. Burek et al. (1984) reported hepatocellular vacuolization and multinucleated hepatocytes in Sprague-Dawley rats after exposure at 500 ppm for 2 years 5 days/week and 6 h/day but did not report a NOAEL. Nitschke et al. (1988a,b) reported multinucleated hepatocytes in females of the same species after inhalation exposure at 200 ppm for the same duration, with a NOAEL of 50 ppm. Those data were used by ATSDR to derive a chronic inhalation minimal risk level of 0.3 ppm. In 2-year MC bioassays with rats, hepatocellular vacuolization and multinucleate hepatocytes were found at a con-

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centration of 500 ppm (NTP 1986d; Nitschke et al. 1988a). NTP (1986d) also reported hepatic hemosiderosis, cytomegaly, necrosis, granulomatous inflammation, and bile duct fibrosis.

Reproductive Toxicity

The NTP (1986d) exposed mice and rats to MC by inhalation at up to 1,500 ppm for 2 years. Mice exhibited atrophy of the uterus, ovary, and testes. In a dominant lethal study, no microscopic effects on the testes were found in mice exposed to MC at vapor concentrations up to 200 ppm (Raje et al. 1988). In a two-generation reproductive-toxicity study, no effects on fertility, litter size, neonatal growth, or survival were found in rats exposed by inhalation at up to 1,500 ppm (Nitschke et al. 1988a).

Developmental Toxicity

Schwetz et al. (1975) reported an extra ossification in the sternum or delayed ossification of sternebrae in rats and mice exposed to MC by inhalation at 1,250 ppm. An increased incidence of dilated renal pelvis was also observed in rats. In another study, no teratogenic effects were reported after rats were exposed at 4,500 ppm before mating or during gestation (Hardin and Manson 1980), but a followup study of the offspring found alterations in rates of behavioral habituation to novel environments. Several other studies of exposure to MC during reproduction or development found no significant effects on survival, viability, growth, or development (ATSDR 2000a).

Neurotoxicity

Two studies reported neurologic effects. Briving et al. (1986b) reported alterations in the amino acids present in the brain in gerbils exposed by inhalation at 210 ppm for 3 mo. Rosengren et al. (1986b) reported decreased DNA concentrations in the hippocampus in Mongolian gerbils exposed by inhalation at 210 ppm for 7-16 weeks. Negative findings in some neurologic tests in rats after exposure at 2,000 ppm for 13 weeks have been reported (Mattsson et al. 1990).

Immunotoxicity

One study has looked at immune system effects. Warbrick et al. (2003) exposed Sprague-Dawley rats to MC by inhalation at 5,000 ppm by inhalation for 6 h/day 5 days/week for 28 days. Immune response was evaluated by the capacity of the rats to mount an antibody response to sheep red blood cells. The study reported that relative spleen weight was reduced in females but not in males. The authors reported no significant differences in antibody production between treated rats and controls.

Hematologic Effects

MC can contribute to an increase in concentrations of carbon monoxide in the blood, as first documented in a 1993 case report (ATSDR 2000a). That can cause hypoxia. Recent results suggest that the effect can be enhanced by coexposure to acetaminophen, a widely used medication (Kim et al. 2007). The significance of the report for chronic exposure does not appear to have been assessed. Similar effects may be of concern in connection with other solvents that are metabolized through pathways similar to that of MC, including others included in this report. The issue may warrant additional attention.

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Genotoxicity

Mixed results have been found in genotoxicity assays of MC. In vitro studies with human cells have reported that MC induced sister-chromatid exchanges, chromosomal breaks, and chromosomal loss, but studies with rodent cells have not. Single-strand breaks in DNA have been observed in studies with mammalian cells, but there has been no evidence of mutations (IARC 1999b). There is some evidence of tissue-specific genotoxic effects (Sasaki et al. 1998), which could be related to the differential expression of metabolizing enzymes.

Cancer

Three studies reported cancer in experimental animals after inhalation exposure. Mennear et al. (1988) exposed Fischer 344 rats to MC at 1,000-4,000 ppm 6 h/day 5 days/week for 102 weeks and reported an increase in mammary tumors in males at 4,000 ppm and in females at all doses. The NTP (1986d) reported the same results. That strain of rat is known to have a high background incidence of tumors. Nitschke et al. (1988b) exposed rats at lower doses (0, 50, 200, and 500 ppm) in another 2-year study and reported increases in numbers of tumors per animal in females in the 500-ppm group; no effects were reported in males.

Mennear et al. (1988) exposed $B6C3F_1$ mice to MC at 2,000 or 4,000 ppm 6 h/day 5 days/week for 102 weeks and reported increases in hepatic and lung tumors in mice exposed at 2,000 ppm or higher. The NTP (1986d) reported the same result.

Maltoni et al. (1988b) reported a statistically significant increase in pulmonary tumors in male mice treated with MC by gavage at 500 mg/kg per day for 64 weeks. Supporting evidence of lung-tumor development in mice after inhalation exposure to MC is found in studies by Kari et al. (1993) and Maronpot et al. (1995).

A 2-year drinking-water study with MC up to 250 mg/kg per day found an increase in the incidence of combined hepatocellular carcinomas and neoplastic nodules in female rats and male mice compared with concurrent controls (Serota et al. 1986a,b). However, the incidence was within the range for historical controls, and there was no dose-response relationship.

Other Effects

Other effects of MC reported in experimental animal studies include alterations in urinary pH and renal weights in rats and renal tubular changes in dogs, rats, and mice after inhalation exposure (ATSDR 2000a; CalEPA 2000b).

TOLUENE

The health effects of toluene have recently been reviewed by ATSDR (2000b). This section will first summarize the central conclusions of the ATSDR review pertaining to human studies and then summarize the toxicologic evidence. The existing information on human health effects comes from studies of acute, intermediate, and chronic exposure primarily by inhalation. The nervous system appears to be particularly susceptible to the effects of toluene. Effects range from reversible acute effects (fatigue, headaches, decrease in manual dexterity, and narcosis) to persistent neurologic impairment in people who abused solvents or inhaled toluene at high concentrations. Subtle alterations in neurologic functions (cognitive functions, hearing, and color discrimination) have been found in workers chronically exposed at lower concentrations.

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Animal and human evidence—alterations in concentrations of hormones (follicle-stimulating hormone, leutenizing hormone, and testosterone) and decreased sperm counts—suggests that toluene may have endocrine-disrupting effects in males and females. However, there are few epidemiologic studies of adverse reproductive effects in humans. Finnish studies of occupational toluene exposure of women or of wives of occupationally exposed men suggested an increased risk of miscarriage, but the studies had a number of limitations. There have been a series of case reports of birth defects in the offspring of women who intentionally inhaled large amounts of toluene or organic solvents during pregnancy. One small Finnish study reported that the opffspring of women occupationally exposed to a mixture of solvents had increases in CNS anomalies.

The ATSDR review included 11 epidemiologic studies of toluene and cancer risk. In general, toluene was not associated with an increased risk of cancer at most sites. Three cohort studies included workers exposed to toluene. They suggested an association with several cancers—including lung cancer, gastric cancer, and colon cancer—but consistent patterns of association with measures of cumulative exposure were not found. Those and other studies also could not rule out confounding by other chemicals, such as benzene.

With regard to other health effects, case reports of solvent abusers have shown some association with cardiac arrhythmia. Other health effects—hematologic, hepatic, or renal—have not been consistently reported.

The toxicology, pharmacokinetics, epidemiology, and health risks associated with exposure have been well documented (EPA 1983a,b, 1990; IARC 1988, 1989; ATSDR 2000b; ACGIH 2007). Chronic exposure to toluene at 50-200 ppm in air can produce neurobehavioral impairments, including impairments in cognitive and neuromuscular performance, hearing, and color discrimination. At higher concentrations, exposure can produce CNS effects, including encephalopathy, headache, fatigue, impairment in coordination, transient memory loss, and impairment in reaction time. Evidence of those effects is found in reports of controlled animal experiments (Dyer et al. 1988; NTP 1990b; von Euler et al. 1993, 2000; Mehta et al. 1998; ATSDR 2000b) and in the epidemiologic literature, especially reports of occupational studies of toluene (Iregren 1982; Orbaek and Nise 1989; Vrca et al. 1997a,b; Cavalleri et al. 2000; Campagna et al. 2001; ACGIH 2007). Results of dosimetric studies of acute behavioral effects of toluene in rats have been used for quantitative comparison of the effects in humans (Benignus et al. 2007; Boyes et al. 2007; Bushnell et al. 2007). There is agreement in the scientific community that toluene is not carcinogenic at lifetime exposures up to 1,200 ppm (NTP 1990b; ATSDR 2000b; Huff 2003). Toluene has had negative results for mutagenicity in a number of test systems (Nestmann et al. 1980; McCarroll et al. 1981). Results of animal studies indicate that toluene is not a teratogenic agent but can retard fetal growth, skeletal development, and behavior of offspring at 1,500 ppm, at which maternal weight gain is also affected (Saillenfait et al. 2007). Another recent study of developmental and reproductive toxicity in rats indicated a NOAEL for maternal toxicity of 750 ppm and a LOAEL of 1,500 ppm for maternal and developmental toxicity (Roberts et al. 2007).

In summary, chronic inhalation exposure to toluene at 50-200 ppm can produce neurobehavioral impairment. Both maternal toxicity and developmental toxicity are observed at the relatively high exposure concentration of 1,500 ppm. Information from well-conducted studies indicates that toluene is not carcinogenic or mutagenic.

VINYL CHLORIDE

The health effects of VC have recently been reviewed by ATSDR (2006). VC is produced primarily (98% of total production) for use in the manufacture of polyvinyl chloride (PVC). PVC materials are used in a variety of products, including automotive parts, packaging products, pipes, and construction material. The primary route of exposure to VC is through ambient air around VC production facilities. It can also be present in groundwater or drinking water because of microbial degradation of other chlorinated

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solvents. However, its rapid volatilization decreases the probability of such exposure of the general population.

The liver appears to be particularly susceptible to the effects of exposure to VC by inhalation. Hepatic damage—such as hepatomegaly, hyperplasia and hypertrophy of hepatocytes and sinusoidal cells, and cirrhosis (independent of alchohol consumption—has been observed. The association between VC and angiosarcoma of the liver (a very rare cancer in humans) has been demonstrated in numerous occupational and animal studies. Other cancer outcomes associated with VC exposure in some studies include hepatocellular carcinoma, cholangiocellular carcinoma, and cancers of the lung and respiratory tract, the lymphatic-hematopoietic system, and the CNS. However, those associations have not been consistent among studies. VC has been classified as "carcinogenic to humans" by IARC (1979, 1987), a "known human carcinogen by the inhalation route of exposure" by EPA (2000), and "known to be a human carcinogen" by the NTP (2005) on the basis of the findings of epidemiologic and animal studies. The key animal data and findings from those reviews are discussed briefly below and are updated with studies published since the reviews were performed.

Additional outcomes have been assessed in epidemiologic studies of workers exposed to VC. Reversible CNS effects—such as dizziness, drowsiness, and headache—have been reported after acute inhalation of high concentrations of VC. Peripheral neuropathy has been reported in workers. Adverse respiratory effects have been observed in some studies but not others. Many of the studies may be confounded by smoking and exposure to PVC resin dust. Development of Raynaud phenomenon (a condition in which the fingers blanch and become numb with discomfort on exposure to cold) has been associated with current occupational exposure. A condition labeled vinyl chloride disease—consisting of Raynaud phenomenon, acroosteolysis, joint and muscle pain, enhanced collagen deposition, stiffness of the hands, and scleroderma-like skin changes—has been identified in some VC workers. In some cases, there has been a correlation with immunologic abnormalities. Occupational exposure to VC has also been implicated in alterations in the immune system, including increased percentages of lymphocytes and increased circulating immune complexes (for example, cryoglobulinemia). There is evidence of increased risk of hypertension associated with VC exposurebut no conclusive evidence of an association with coronary heart disease.

Reproductive and developmental effects have also been observed. Case studies have reported sexual impotence and loss of libido in male workers. An increase in pre-eclampsia has been observed. Studies have reported an excess of fetal loss in wives of men exposed to VC. Increases in birth defects—including clubfoot and malformations of the CNS, upper alimentary tract, and genital organs—have been reported in populations exposed to emissions from PVC polymerization facilities.

VC is considered a known human carcinogen mainly on the basis of the consistent observation of excess rates of angiosarcoma of the liver in workers exposed via inhalation.

According to the review by ATSDR, there is limited/suggestive evidence of associations between VC and Raynaud phenomenon, scleroderma-like skin changes, and other immunologic effects. There is inadequate/insufficient evidence to support a conclusion about associations between chronic exposure to VC and reproductive and developmental effects. Specific health effects of VC in animals is discussed below.

Hepatic Toxicity

Hepatic lesions were found in rats exposed chronically to VC in their feed (1.3 mg/kg per day) (Feron et al. 1981; Til et al. 1991). The nonneoplastic lesions included hepatic-cell polymorphism and hepatic cysts. When exposed by inhalation, rats have developed hepatocellular degeneration, hepatic swelling with compression of sinusoids, altered enzyme activity, proliferation of reticulocytes, and increased ratio of liver weight to bodyweight (EPA 2000; ATSDR 2006). Hepatic toxicity is thought to be due to the reactive metabolites of VC that bind to hepatic proteins, DNA, and RNA (ATSDR 2006).

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Renal Toxicity

At high concentrations (300,000 ppm), VC caused renal congestion and degenerative changes. At lower concentrations (3,000 ppm) for longer durations, VC has been reported to increase ratios of renal weight to bodyweight, but this was an inconsistent finding (ATSDR 2006).

Pulmonary Toxicity

At high concentrations, VC is irritating to the respiratory tracts of experimental animals (ATSDR 2006). Chronic-exposure studies have reported a slightly higher incidence of hyperplasia of the olfactory epithelium, increased cellularity of the interalveolar septa, and pulmonary hemorrhage in rats exposed at 5,000 ppm (Feron and Kroes 1979).

Reproductive Toxicity

Some inhalation studies of VC have found effects on male reproduction in rats, including damage to the seminiferous tubules and spermatogenic epithelium, depletion of spermatocytes, disorders of spermatogenesis, and decreases in the ratio of pregnant to mated females at concentrations as low as 100 ppm (Sokal et al. 1980; Bi et al. 1985). Other studies, including a two-generation toxicity study of rats exposed to VC at up to 1,100 ppm (Thornton et al. 2002), did not find such effects. Questions have been raised about the methodology of some studies that reported positive effects (ATSDR 2006). EPA (2000) identified the no-observed-adverse-effect level (NOAEL) for reproductive effects as over 1,100 ppm.

Developmental Toxicity

John et al. (1977, 1981) evaluated the effects of VC on the embryonal and fetal development of mice, rats, and rabbits. Developmental effects were found in mice after in utero exposure to VC. At an inhalation concentration of 500 ppm, the effects included increased fetotoxicity and fetal resorptions, decreased fetal bodyweight, smaller litters, and retarded cranial and sternal ossification. In rats exposed at higher concentrations, an increased incidence of dilated ureters was found in offspring. In both mice and rats, the effects on offspring were observed at concentrations that produced maternal toxicity, as evidenced by increased mortality, reduced bodyweight, and reduced absolute hepatic weight in the dams. No effects were found in rabbits.

No embryo-fetal developmental toxicity was found in a two-generation reproductive-toxicity study of rats exposed to VC at inhalation concentrations up to 1,100 ppm (Thornton et al. 2002).

Neurotoxicity

Like other solvents, VC at high concentrations had neurotoxic effects, such as ataxia, unconsciousness, incoordination, and tremors. After chronic exposure by inhalation (30,000 ppm), rats had decreased responses to external stimuli, surrounding and infiltration of peripheral nerve ends with fibrous tissue, and brain lesions (CalEPA 2000a; ATSDR 2006).

Immunotoxicity

A few studies have reported that VC has an immune-stimulating effect on mice and causes splenomegaly in them (ATSDR 2006). Stimulation of spontaneous lymphocyte transformation was ob-

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served after 2 weeks of exposure at 1,000 ppm and then after 4-8 weeks of exposure at concentrations as low as 10 ppm (Sharma and Gehring 1979).

Genotoxicity

VC is a well-established genotoxicant, having been investigated in a variety of test systems, including in vitro studies of bacteria, fungi, and mammalian cells and in vitro studies of rodents and humans (ATSDR 2006). It has been shown to be mutagenic, and its mutagenicity is enhanced with metabolic activation; this suggests that one of its metabolites is more mutagenic than VC (CalEPA 2000a; ATSDR 2006).

Cancer

VC has been shown to cause cancer in multiple organs and multiple species when inhaled or ingested (IARC 1979; EPA 2000; ATSDR 2006). The association between VC and hepatic angiosarcomas in the epidemiologic literature is supported by similar findings in mice (e.g., Drew et al. 1983), rats (e.g., Feron et al. 1981; Maltoni et al. 1981; Drew et al. 1983; Bi et al. 1985), and hamsters (e.g., Drew et al. 1983). Tumors in rats were found after oral exposure at concentrations as low as 1.7 mg/kg per day.

Other cancers found in rats were Zymbal-gland tumors, mammary-gland tumors, neuroblastomas, and lung tumors (Feron et al. 1981; Maltoni et al. 1981; Drew et al. 1983; Til et al. 1991). Mice exposed by inhalation developed lung tumors, mammary-gland tumors, and angiosarcomas and adenocarcinomas in various sites (Drew et al. 1983). Hamsters also developed hemangiosarcomas, mammary-gland carcinomas, gastric adenocarcinomas, and skin carcinomas (Drew et al. 1983). Some studies have shown that younger rats are more susceptible to the carcinogenicity of VC (Drew et al. 1983; Maltoni and Cotti 1988).

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Appendix E

Details of Epidemiologic Studies on Trichloroethylene and Perchloroethylene

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TABLE E-1 Exposure Information on Epidemiologic Studies Involving Exposure to TCE or PCE

Reference	Study Design, Exposure, Outcomes	Exposure Assessment	Exposure Metrics	Comments
Aschengrau et al. 2003	Population-based case-control Cape Cod, MA PCE from inner vinyl liner in cement pipes distributing tap water Breast cancer	Relative dose of PCE estimated by algorithm with variables for residential history, water flow (geometry, load on water-distribution system), pipe characteristics (such as pipe diameter, age); inputs determined from maps from local water suppliers or state DEPs	Ever vs never exposed (served by private well for entire Cape Cod residence) Cumulative exposure for each latency period: sum of RDDs for each residence (mass of TCE entering home in tap water over time at each address); categorized as never, low (up to and including median RDD), high RDD (above 50th, 75th, or 99th percentile)	Nine latency periods examined (0, 5, 7, 9, 11, 13, 15, 17, 19 years)
Blair et al. 2003	Cohort study of dry cleaners PCE used as solvent in dry cleaning Cancers, other causes of death	Exposure score for jobs based on published monitoring studies of dry-cleaning industry; scores increased with proximity	Exposure score assigned on basis of jobs held (cleaners, high, score of 40; pressers, sewers, counter workers, score of 7; pickup workers, low, score of 0) Little or no exposure (score of 0) vs medium-high exposure (score of 7 or 40)	Adjustment for age, sex, calendar time
Boice et al. 2006	Cohort of rocket-engine testing-facility workers Hydrazine, TCE All causes of death	All Rocketdyne workers employed on or after Jan. 1, 1948, for 6+ mo at SSFL, nearby facilities (for comparison group); identified from personnel files, work history cards; exposed were test-stand mechanics, inspectors, test-stand engineers, research engineers; personnel listings used to place test-stand mechanics at specific stands in calendar years; descriptive industrial-hygiene information to classify potential exposure to hydrazine, TCE, other chemicals; discussions with workers	Duration of employment (years) (SMR) Potential for exposure (flush engine parts or utility solvent use) (SMR) Duration of employment (RR) 4 decades of employment (RR) Years worked as test-stand mechanic (RR) Years worked with any potential TCE exposure (less than 4 years vs at least 4 years) (RR) Years worked with potential TCE exposure via engine cleaning, weighted by number of engine tests (less than 4 test-years vs at least 4 test-years)	Adjustment for year of birth, year of hire

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TABLE E-1 Continued

Reference	Study Design, Exposure, Outcomes	Exposure Assessment	Exposure Metrics	Comments
Brüning et al. 2003	Hospital-based case-control West Germany (site of metal, paper, wood-processing industries) TCE, PCE Renal-cell cancer	Telephone interview, occupational questionnaire devoted to screw-cutting industry and general for other jobs; TCE, PCE exposure for at least one job period (1+ year), cumulative of TCE in ppm per job per year in job, peaks; assessment semiquantitative for exposure to TCE, PCE; qualitative for other occupational exposures; confidence score (certain, probable, possible) used for each exposure assessed; assessed industry and job-title codes	Ever employed in specific occupations Longest job held Ever worked in tasks, occupations, or industries with TCE or PCE exposure Cumulative exposure assessed with JEM (Pannet et al. 1985): none, low, high (dichotomized at median) Self-reported exposure to TCE, PCE (separately) Occurrence of narcotic symptoms (any, nondaily, or daily) (TCE) Duration of exposure to TCE (none, less than 10 years, 10 to less than 20 years, 20+ years), PCE (none, less than 10 years, 10+ years)	
Chang et al. 2003	Cohort-mortality study of electronics factory workers Taiwan TCE, PCE Cancers	Employment histories at different factories, changes in insurance status from Bureau of Labor Insurance computer database for 1978-1997; confirmed, supplemented with list of names of patients in labor-insurance hospitalization dataset, United Labor Association; duration of employment calculated from insurance records, operation history of index electronics factory (1968-1992); EPA in Taiwan verified pollution of wells with TCE, PCE	Duration of employment (SMR) categorized as 1 year or less, more than 1 year but less than or equal to 5 yrs, more than 5 years) Year of death from cancer (1985-1990, 1991-1997)	
Charbotel et al. 2006	Case-control Arve Valley (France) TCE used as degreasing agent in screw-cutting industry in Arve Valley	Information from occupational questionnaires, task-exposure matrix for screw-cutting tasks; employee's activity, job title encoded; assessed for exposure to solvents, oils, welding fumes, etc.; semiquantitative assessment for exposure to TCE, qualitative (low, medium, high) for other exposures	By industry (NACE codes) (OR) By Job title (ILO 68 codes) (OR) Ever vs never exposed (OR) Cumulative exposure (ppm-years); task-exposure matrix used to estimate cumulative	Adjustment for tobacco-smoking, BMI

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	Other exposures (chlorinated solvents, oxygenated solvents, white-spirit and petroleum solvents), oils, welding fumes, lead, cadmium, asbestos Renal-cell cancer		dose for each job period (OR) (categorized into tertiles) Cumulative exposure with assessment for peaks (low-medium without peaks, low-medium with peaks, high without peaks, high with peaks) (OR) Cumulative exposure with assessment for peaks (low-medium without peaks, low-medium with peaks, high without peaks, high with peaks) with only exposures scored certain or probable summed in cumulative-exposure score (OR)	
Costas et al. 2002	Case-control Woburn, MA TCE-contaminated groundwater wells in Woburn, MA (site of tannery, chemical manufacturing wastes) TCE (primary), PCE Childhood leukemia	Exposure assessed based on potential for residence to receive water from contaminated wells G and H, not on actual contaminant concentration in wells; water-distribution model used, validated; cumulative exposure based on exposure periods, operation of wells	With water-distribution model, exposure index developed for each hydraulic area and month (exposure index: fraction of month when contaminated water reached hydraulic area multiplied by fraction of water supplied by contaminated wells) Average, cumulative exposure scores (for seven etiologic windows) categorized as never vs some or never, least, most (median of some exposure used to define least, most) Etiologic windows: entire etiologic period (2 years before conception to date of case diagnosis); preconception period, duration of pregnancy; 1st, 2nd, 3nd trimester of pregnancy; period from time of birth to case diagnosis	
De Roos et al. 2001	Case-control (cases identified from hospitals participating in two pediatric collaborative clinical trials) Occupational exposure to five categories of chemicals Neuroblastoma	Self-reported occupational exposures to solvents obtained by telephone interview; industrial-hygienist review of self-reported exposures	Self-reported parental exposure to five categories of chemicals (halogenated hydrocarbons; nonvolatile hydrocarbons; volatile hydrocarbons; paints, inks, pigments; metals, alloys, solders (any vs none) Industrial hygienist reviewed assessment of exposure on basis of questionnaire data (probable exposure assigned yes, otherwise no)	Adjustment for child's age, maternal race, maternal age, maternal education

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TABLE E-1 Continued

Reference	Study Design, Exposure, Outcomes	Exposure Assessment	Exposure Metrics	Comments
Diot et al. 2002	Hospital-based case-control Central region of France Occupational exposures to silica, organic solvents (including TCE) Systemic sclerosis	Employment periods of over 6 mo recorded from interview, but only employment corresponding to period before patient's diagnosis was included; exposure to various occupational hazards asked; expert committee (occupational physicians, epidemiologists, industrial hygienists) assessed exposure	Ever vs never exposed High cumulative exposure score vs those without high cumulative exposure score Cumulative exposure score: sum of exposure scores for each employment Exposure score: probability x intensity x frequency x duration; probability of exposure: 0 = nonexposure, 0.25 = possible exposure, 0.75 = probable exposure, 1 = certain exposure; intensity of exposure: 0 for nonexposure to 1 for highest level of exposure; length of time worked daily: <10% = 0.05, 10-50% = 0.30, >50% = 0.75; number of years worked	
Fabbro-Peray et al. 2001	Population-based case-control Languedoc-Roussillon, France Occupational exposure to benzene, rubber, coal tar, paints, waste oil, dry-cleaning solvents, petroleum products, pesticides Non-Hodgkin lymphoma	Cohort interviewed about occupational exposures, including chemicals, pesticides, electromagnetic radiation; asked about smoking; subjects considered exposed if exposure lasted more than 1 year	Self-reported exposure (yes vs no) Age at first exposure Duration of exposure (never, up to 15 years, over 15 years) Cumulative exposure (lifetime-days of exposure) (never-erratic, up to 810 days, over 810 days) Time since first exposure (never, up to 10 years, over 10 years) Further classifications for benzene, pesticides	Lag time of 5 years before diagnosis (or interview for controls) Adjustment for age, sex, urban setting, education
Garabrant et al. 2003	Case-control Michigan, Ohio Occupational or hobby-related exposure to hydrocarbons, chlorinated solvents Systemic sclerosis	Women asked whether ever worked at least once a week for 3 mo or more in any of 16 jobs or hobbies that commonly involve solvents; information obtained on job title, years, specific tasks, nine specific solvents (paint thinners and removers, mineral spirits naphtha or white spirits, gasoline, toluene, xylene, benzene, TCE, PCE, trichloroethane), other solvents), safety precautions; reviewed by expert	Self-reported exposure to specific, all solvents Expert-reviewed exposure to specific, all solvents Self-reported jobs, hobbies	Adjustment for age, year of birth

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Hansen et al. 2001	Cohort Denmark TCE Cancer	Historical files of individual air, urinary measurements of TCE exposure (from Labor Inspection Services of Denmark); job information reconstructed from national pension fund	Period of first employment (1947-1964, 1965-1989) Duration of employment (less than 75 mo vs at least 75 mo) Average personal TCE exposure (less than 19 mg/m^3 vs at least 19 mg/m^3) Cumulative TCE exposure (less than 1,080 months-mg/m^3 vs at least 1,080 months-mg/m^3)	Sensitivity analyses: 10-year, 20-year lag periods (data not shown; no change in results)
Infante-Rivard et al. 2005	Population-based case-control Quebec, Canada Maternal occupational exposure to solvents, solvent mixtures Childhood ALL	Maternal occupational exposures to solvents before and during pregnancy estimated by coding by job for specific contaminants (also called expert method); coded for 21 solvents; home exposure to solvents evaluated on basis of activities, including hobbies, furniture stripping, electronic and motor-vehicle repair, home painting	Jobs held during 2 years before, during pregnancy coded as "possible," "probable," "definite"; level assigned (low = 1, medium = 2, high = 3) Any vs no exposure Any vs no exposure (none and "possible" vs "probable" and "definite") Level of exposure (0 = baseline, 1 = some exposure (concentration x frequency less than 4), 2 = greater exposure (concentration x frequency at least 4)	Adjustment for age, education
Krishnadasan et al. 2007	Nested case-control Nuclear-energy, rocket-engine development, testing facility in Southern California PAHs, TCE, hydrazine, mineral oil, benzene Prostatic cancer	Workers employed 1950-1992 at nuclear-energy, rocket-engine-testing facility; company records used to construct JEM for exposures to hydrazine, TCE, PAHs, benzene, mineral oil; from job-description manuals, walk-throughs, interviews; industrial hygienist created estimate of likelihood, intensity of exposures during three periods (1950s-1960s, 1970s, 1980s-1990s); duration of employment of longest-held job (and others)	Industry-based JEM (for all jobs held) For each job and by chemical, likelihood (none, low, high), intensity (low, medium, high) for three periods (1950-1969, 1970-1979, 1989-1999) Cumulative-exposure score for each worker for all jobs held (none, low, moderate, high); cumulative-exposure score = sum of duration of employment x estimated intensity for each job Cumulative-exposure scores categorized by quartiles: unexposed vs low-moderate vs high	20-year (and zero lag) exposure estimates Adjustment for occupational physical activity, SES, other chemical exposures

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TABLE E-1 Continued

Reference	Study Design, Exposure, Outcomes	Exposure Assessment	Exposure Metrics	Comments
Lee et al. 2003	Case-control; residents of two villages in vicinity of electronics factory Chlorinated hydrocarbons in groundwater contaminated by hazardous-waste site (formerly electronics factory) Hepatic-cancer mortality	Groundwater sampling from off-site residential wells in nearby communities October 1999-May 2000; exposed were downstream residents; stratified on calendar periods based on establishment of factory (allowing 10 years to detect health effects of exposure)	Upstream (referent) vs downstream village (validated by groundwater well samples—detectable vinyl chloride, TCE, PCE, 1,1-dichloroethylene, 1,1,1,-trichloroethane, *cis*-1,2-dichloroethylene, 1,1-dichloroethane) Period of death: 1966-1979 (referent), 1980-1989, 1990-1997	
Lynge et al. 2006	Nested case-control; cohort of laundry, dry-cleaning workers Denmark, Finland, Norway, Sweden Occupational exposure to dry-cleaning solvents (predominantly PCE) Cancer	Occupation code "laundry and dry-cleaning worker" or industry code "laundry and dry cleaning"; categorized on basis of fewer than 10 workers in shop, laundry workers and other workers in dry-cleaning shops; length of employment in shop where worked in 1970 (only the period of 1964-1979 was included); interviews with next of kin; detailed history of dry cleaning in Nordic countries	Exposure categories: unexposed, dry cleaner and other exposed, other in dry cleaning, unclassifiable Dry cleaner length of employment (0-1 years, 2-4 years, 5-9 years, at least 10 years, unknown)	
Miligi et al. 2006	Population-based case-control study Italy Occupational solvent use in manufacturing industries or agriculture Lymphoma	Job-exposure matrix of most frequent job titles and sectors to assign probability- and intensity-weighted scales of exposure to solvents, five specific categories of chemical classes, eight individual chemicals; occupational history questionnaires	Unexposed vs very low, low and medium, high intensity levels and duration of exposure (15 yr or less vs 15 yr)	Adjustment for sex, age, education, area
Morgan and Cassady 2002	Cohort study of residents with contaminated drinking water San Bernardino County, CA (13 census tracts) PCE, chlorate, TCE Cancers	Residence in census tracts near Redlands, CA (where concerns about contamination of groundwater, drinking water with TCE, ammonium perchlorate; 1980 assessment of TCE in Redlands wells ranged from 0.09 to 97 ppb; since 1991, wells either treated or removed to maintain TCE under 5 ppb	None (SIRs—indirect standardization)	

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Perrin et al. 2007	Cohort study; offspring of dry cleaners Jerusalem, Israel Maternal or paternal occupational (dry-cleaning) exposure to TCE Schizophrenia in offspring	Occupations of parents obtained from birth certificate	Mother and/or father dry cleaner(s) at time of birth (yes vs no)	
Raaschou-Nielsen et al. 2003	Cohort Denmark TCE Cancers, including non-Hodgkin lymphoma, renal-cell carcinoma, esophageal adenocarcinoma	Employment based on companies classified by air TCE measurements in workplace 1947-1989 by Danish Labor Inspection Service, area and personal measurements (after 1974);included companies determined by size; iron and metal, electronics, painting, printing, chemical, dry cleaning, other; workers identified by Pension Fund or Central Population Registry (most recent job title)	Duration of employment (less than 1 year, 1-4.9 years, *at least* 5 years) Year of first employment (before 1970, 1970-1979, 1980-) Lag time (none, 20 years) Number of employees (fewer than 50, 50-99, 100-200)	Stratified analysis by sex
Radican et al. 2006	Retrospective cohort; aircraft workers TCE, 1,1,1-trichloroethane, methylene chloride, carbon tetrachloride, JP4 gasoline, Freon, isopropyl alcohol, acetone, toluene, methyl ethyl ketone, *o*-dichlorobenzene, PCE, chloroform, stoddard solvent, styrene, xylene End-stage renal disease	Subjects identified from database of former civilian employees of Hill Air Force Base I, Utah; semiquantitative estimate of TCE exposure obtained from comprehensive exposure assessment; cumulative exposure score computed for each subject	Cumulative-exposure score: frequency (times/day), duration (min/day), calendar period of use, years of exposure; categorized into tertiles	

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TABLE E-1 Continued

Reference	Study Design, Exposure, Outcomes	Exposure Assessment	Exposure Metrics	Comments
Ruder et al. 2001 (in IOM report)	Cohort study; dry-cleaning workers San Francisco, Oakland, CA; Chicago, IL; Detroit, MI; New York, NY Occupational exposure to PCE Cancer deaths	Dry-cleaning union records , people not known to ever have been exposed to carbon tetrachloride who had worked 1+ year before 1960 in shop using PCE; shops visited to verify solvent use history; PCE-only subcohort, PCE-plus cohort (records inadequate to confirm PCE use or another solvent, mostly Stoddard solvent or other petroleum solvents)	Time since first employment (less than 20 years, at least 20 years), duration of employment in dry-cleaning shops (1-5 years, 5+ years) PCE only solvent, PCE and other solvents used in dry-cleaning shops	
Schreiber et al. 2002	Cross-sectional; residents above dry-cleaning shops, day-care workers sharing building with dry cleaner compared with NY State Department of Health controls, matched by age (within 2 years), sex PCE Visual contrast sensitivity	Apartment residents above dry cleaner; air sampling of PCE in apartments; day-care workers sharing building with dry cleaner	Personal monitoring of PCE with passive monitors (3M organic vapor monitors) for exposed persons Creatinine-adjusted urinary PCE, trichloroacetic acid, trichloroethanol for exposed persons Exposed vs control groups	
Seidler et al. 2007	Population-based case-control Germany Occupational exposure to chlorinated, organic solvents Lymphoma	Complete occupational history obtained by interview: dates, job title, industry, job tasks, job-task-specific supplementary questions; industrial physician assessed intensity, frequency of exposure to specific chlorinated hydrocarbons (including TCE, PCE), aromatic hydrocarbons	Intensity of exposure (low, medium, high—assigned in ppm depending on chemical); frequency of exposure based on 40-h workweek (low = 1-5%, medium = over 5 to 30%, high = over 30%); confidence (possible but not probable, probable, certain) Cumulative exposure (ppm x years): sum of intensity x frequency x duration for all jobs held; categorized among controls at 50th, 90th percentiles	
Sonnefeld et al. 2001	Case-control Camp Lejeune, NC Contaminated drinking-water TCE, other compounds Birthweight, small for gestational age, preterm birth	Residents of Tarawa Terrace were considered exposed; exposure magnitude determined by length of residence	Duration of exposure (never exposed, 1-3 weeks, 4-10 weeks, 11-20 weeks, over 20 weeks and less than entire pregnancy, entire pregnancy and less than 1 year before LMP, entire pregnancy and at least 1 year before LMP	

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Sung et al. 2007	Retrospective cohort; female workers at electronics factory Taoyuan, Taiwan Occupational exposure to solvents Cancer	Female workers of former electronics factory identified through Bureau of labor Insurance 1973-1997; duration of employment	Duration of employment (less than 1 mo, 1-11 mo, 1-4 years, 5-9 years, at least 10 years)	Latency accounted for in assessing person-years at risk (5 years, cancer of thyroid, leukemia; 15 years, breast cancer; 10 years, other cancers) Stratified by calendar year (in which regulations were enacted on use of organic solvents in factories): before and after June 20, 1974
Vieira et al. 2005	Population-based case-control Cape Cod, MA PCE from inner vinyl liner leaching from cement pipes distributing tap water Breast cancer	Used personal delivered-dose model that included personal data on tap-water consumption, bathing habits from subjects or next of kin	PDD: sum of PCE from inhalation, dermal absorption, ingestion based on RDD; categorized into four groups based on distribution among exposed controls: at least 50th percentile, over 50th percentile, over 75th percentile, over 90th percentile; ever vs never exposed Inhalation exposure: function of temperature, frequency, duration of baths, showers, concentration of PCE volatilized in air from water Dermal absorption: function of surface area, Fick's law Ingestion: function of volume of tap water consumed	Nine latency periods examined (0, 5, 7, 9, 11, 13, 15, 17, 19 years) Adjustment for age at diagnosis or index year, family history of breast cancer, personal history of breast cancer, age at first live birth or stillbirth, occupational exposure to PCE
Yauck et al. 2004	Case-control Milwaukee,WI TCE-emitting sites in Milwaukee, surrounding areas, 1996-1999 Congenital heart defects	GIS used to calculate distances between maternal residence, TCE sites; classification tree analysis used to determine distance for dichotomizing exposure: within or outside 1.32 miles of at least one TCE site	Proximity measure using classification-tree method: distance from maternal residence to TCE-emitting facility dichotomized into exposed (residence within 1.32 miles of at least one site), nonexposed (residence more than 1.32 miles of at least one site	

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TABLE E-1 Continued

Reference	Study Design, Exposure, Outcomes	Exposure Assessment	Exposure Metrics	Comments
Zhao et al. 2005	Retrospective cohort; Rockwell/Rocketdyne (now Boeing) aerospace male workers employed before 1980 Los Angeles, CA Hydrazine, TCE, PAHs, mineral oil, benzene Cancer mortality, incidence	California aerospace workers 1950-1993 at several Boeing North America facilities in LA, employed before 1980 in aerospace division of SSFL, worked 2− years and never monitored for radiation exposure; extensive industrial-hygienist review interested in exposure to rocket fuel hydrazine, TCE, PAHs, mineral oil, benzene	JEM used to assess exposure in each job group: Intensity (0-3) (1950-1969, 1970-1979, 1980-1989) × duration Cumulative-exposure score: low (up to 3), medium (over 3 up to 12), high (over 12)	Adjustment for time since first employment, SES, age at diagnosis

Abbreviations: ALL = acute lymphocytic leukemia, BMI = body-mass index, DEP = Department of Environmental Protection, EPA = U.S. Environmental Protection Agency, GIS = geographic information system, ILO = International Labor Organization, IOM = Institute of Medicine, JEB = job-exposure matrix, LMP = last menstrual period, OR = odds ratio, PAH = polycyclic aromatic hydrocarbon, PCE = perchloroethylene, PDD = personal delivered dose, RDD = relative delivered dose, RR = relative risk, SES = socioeconomic status, SIR = standardized incidence ratio, SMR = standardized mortality ratio, SSFL = Santa Susana Field Laboratory, TCE = trichloroethylene

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TABLE E-2 Studies of Cancer End Points and Exposure to TCE

Reference	Study Population	No. Exposed Persons	MOR, OR, SIR, or SMR (95% CI)
BUCCAL CAVITY AND PHARYNGEAL CANCER			
Cohort Studies—Incidence			
Hansen et al. 2001[a]	Danish workers:		
	Men	7	2.3 (0.9-4.7) SIR
	Women	0	—
Raaschou-Nielsen et al. 2003	Danish workers:		
	Men employed at least 3 mo	95	1.1 (0.90-1.36) SIR
	Women employed at least 3 mo	10	1.8 (0.84-3.24) SIR
Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	19	0.55 (0.33-0.86) SIR
	Women	42	0.96 (0.69-1.29) SIR
Sung et al. 2007	Female electronics workers in Taoyuan, Taiwan	10[b]	0.74 (0.35-1.36) SIR
Cohort Studies—Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	6	0.65 (0.50-0.83) SMR
	Women	10	0.71 (0.34-1.30) SMR
Boice et al. 2006	Male workers at rocket-engine testing facility	4	1.25 (0.34-3.21) SMR
ESOPIIAGEAL CANCER			
Cohort Studies—Incidence			
Raaschou-Nielsen et al. 2003	Danish workers:		
	Men:		
	All employed at least 3 mo	23	1.8 (1.5-2.73) SIR
	Employed <1 year	6	1.7 (0.6-3.6) SIR
	Employed 1-4.9 years	9	1.9 (0.9-3.6) SIR
	Employed ≥5 years	8	1.9 (0.8-3.7) SIR
	Women:		
	All employed at least 3 mo	0	0 (0.00-8.32) SIR
Zhao et al. 2005	Aerospace workers (men)		
	Cumulative-exposure score, lag 0:		
	Low (0-3)	9	1.00 SIR
	Medium (>3-15)	8	1.66 (0.62-4.41) SIR
	High (>15)	2	0.82 (0.17-3.95) SIR
Sung et al. 2007	Female electronics workers in Taoyuan, Taiwan	2	1.16 (0.14-4.20) SIR

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Contaminated Water Supplies at Camp Lejeune: Assessing Potential Health Effects

TABLE E-2 Continued

Reference	Study Population	No. Exposed Persons	MOR, OR, SIR, or SMR (95% CI)
Cohort Studies—Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	0	—
	Women	0	—
Zhao et al. 2005	Aerospace workers (men)		
	Cumulative-exposure score, lag 0:		
	Low (0-3)	18	1.00 SMR
	Medium (>3-15)	15	1.40 (0.70-2.82) SMR
	High (>15)	7	1.27 (0.52-3.13) SMR
Boice et al. 2006	Male workers at rocket-engine testing facility	3	0.88 (0.18-2.58) SMR
STOMACH CANCER			
Cohort Studies—Incidence			
Raaschou-Nielsen et al. 2003	Danish workers:		
	Men employed at least 3 mo	77	1.0 (0.80-1.27) SIR
	Women employed at least 3 mo	9	1.3 (0.59-2.46) SIR
Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	56[c]	0.73 (0.55-0.95) SIR
	Women	135[c]	0.93 (0.78-1.09) SIR
Sung et al. 2007	Female electronics workers in Taoyuan, Taiwan	42	0.88 (0.64-1.19) SIR
Cohort Studies—Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	7	0.93 (0.37-1.91) SMR
	Women	24	1.11 (0.71-1.65) SMR
Boice et al. 2006	Male workers at rocket-engine testing facility	6	1.37 (0.50-2.99) SMR
Case-Control Studies			
Lee et al. 2003	Community downstream of electronics factory in Taiwan (chlorinated hydrocarbons; males)	39	2.18 (0.97-4.89) MOR
COLON CANCER			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	327[d]	0.86 (99%CI 0.74-0.99) SIR
Raaschou-Nielsen et al. 2003	Danish workers:		
	Men employed at least 3 mo	142	0.9 (0.77-1.08) SIR
	Women employed at least 3 mo	35	1.2 (0.85-1.70) SIR

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Zhao et al. 2005	Aerospace workers (men)		
	Cumulative-exposure score, lag 0:		
	Low (0-3)	49	1.00 SIR
	Medium (>3-15)	28	0.93 (0.58-1.50) SIR
	High (>15)	13	0.92 (0.49-1.72) SIR
Sung et al. 2007	Female electronics workers in Taoyuan, Taiwan	98[d]	1.10 (0.89-1.34) SIR
	Employed before June 1974[e]	21[d]	1.02 (0.63-1.56) SIR
	Employed after June 1974[e]	77[d]	1.12 (0.88-1.40) SIR
Cohort Studies—Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	3	0.65 (0.13-1.91) SMR
	Women	19	1.36 (0.82-2.13) SMR
	Employed <1 year (men and women)	12	1.33 SMR
	Employed 1-5 years (men and women)	3	0.85 SMR
	Employed >5 years (men and women)	4	2.94 SMR
Zhao et al. 2005	Aerospace workers (men)		
	Cumulative-exposure score, lag 0:		
	Low (0-3)	36[d]	1.00 SMR
	Medium (>3-15)	18[d]	0.90 (0.51-1.60) SMR
	High (>15)	8[d]	0.76 (0.35-1.68) SMR
Boice et al. 2006	Male workers at rocket-engine testing facility	13[d]	1.08 (0.58-1.85) SMR
Case-Control Studies			
Lee et al. 2003	Community downstream of electronics factory in Taiwan (chlorinated hydrocarbons; males)	26[d]	0.83 (0.24-2.89) MOR
RECTAL CANCER			
Cohort Studies—Incidence			
Raaschou-Nielsen et al. 2003	Danish workers:		
	Men employed at least 3 mo	128	1.1 (0.95-1.35) SIR
	Women employed at least 3 mo	15	1.1 (0.62-1.84) SIR
Cohort Studies—Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	2	0.73 (0.08-2.65) SMR
	Women	13	1.67 (0.89-2.85) SMR
	Employed <1 year (men and women)	9	1.81 SMR
	Employed 1-5 years (men and women)	2	1.01 SMR
	Employed >5 years (men and women)	2	2.50 SMR

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TABLE E-2 Continued

Reference	Study Population	No. Exposed Persons	MOR, OR, SIR, or SMR (95% CI)
HEPATIC CANCER			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	28[f]	1.29 (99%CI 0.74-2.05) SIR
Raaschou-Nielsen et al. 2003	Danish workers:		
	Men:		
	All employed at least 3 mo	27	1.1 (0.74-1.64) SIR
	Employed <1 year	9	1.3 (0.6-2.5) SIR
	Employed 1-4.9 years	9	1.0 (0.5-1.9) SIR
	Employed ≥5 years	9	1.1 (0.5-2.1) SIR
	Women:		
	All employed at least 3 mo	7	2.8 (1.13-5.80) SIR
	Employed <1 year	2	2.8 (0.3-10.0) SIR
	Employed 1-4.9 years	4	4.1 (1.1-10.5) SIR
	Employed ≥5 years	1	1.3 (0.0-7.1) SIR
Sung et al. 2007	Female electronics workers in Taoyuan, Taiwan	36[f]	0.79 (0.55-1.10) SIR
Cohort Studies—Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	0	—
	Women	0	—
Boice et al. 2006	Male workers at rocket-engine testing facility	4[f]	1.28 (0.35-3.27) SMR
Case-Control Studies			
Lee et al. 2003	Community downstream of electronics factory in Taiwan (chlorinated hydrocarbons; males)	53	2.57 (1.21-5.46) MOR
PANCREATIC CANCER			
Cohort Studies—Incidence			
Raaschou-Nielsen et al. 2003	Danish workers:		
	Men employed at least 3 mo	66	1.1 (0.85-1.39) SIR
	Women employed at least 3 mo	9	1.0 (0.47-1.96) SIR
Zhao et al. 2005	Aerospace workers (men)		
	Cumulative-exposure score, lag 0:		
	Low (0-3)	13	1.00 SIR
	Medium (>3-15)	7	0.85 (0.33-2.17) SIR
	High (>15)	1	0.28 (0.04-2.14) SIR
Sung et al. 2007	Female electronics workers in Taoyuan, Taiwan	11	1.64 (0.82-2.94) SIR

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Cohort Studies—Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	1	0.49 (0.01-2.73) SMR
	Women	5	1.39 (0.45-3.25) SMR
	Employed <1 year (men and women)	2	0.91 SMR
	Employed 1-5 years (men and women)	2	2.15 SMR
	Employed >5 years (men and women)	1	2.22 SMR
Zhao et al. 2005	Aerospace workers (men)		
	Cumulative-exposure score, lag 0:		
	Low (0-3)	22	1.00 SMR
	Medium (>3-15)	15	1.13 (0.58-2.21) SMR
	High (>15)	2	0.35 (0.08-1.50) SMR
Boice et al. 2006	Male workers at rocket-engine testing facility	2	0.32 (0.04-1.14) SMR
LARYNGEAL CANCER			
Cohort Studies—Incidence			
Hansen et al. 2001[a]	Danish workers:		
	Men	2	1.1 (0.1-3.9) SIR
	Women	0	—
Raaschou-Nielsen et al. 2003	Danish workers:		
	Men employed at least 3 mo	53	1.2 (0.87-1.52) SIR
	Women employed at least 3 mo	3	1.7 (0.33-4.82) SIR
Cohort Studies—Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	0	—
	Women	0	—
Boice et al. 2006	Male workers at rocket-engine testing facility	2	1.45 (0.18-5.25) SMR
LUNG CANCER			
Cohort Studies—Incidence			
Hansen et al. 2001[a]	Danish workers:		
	Men	16	0.8 (0.5-1.3) SIR
	Women	1	0.7 (0.01-3.8) SIR
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	356[g]	0.71 (99%CI 0.61-0.81) SIR

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TABLE E-2 Continued

Reference	Study Population	No. Exposed Persons	MOR, OR, SIR, or SMR (95% CI)
Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	20	0.94 (0.57-1.45) SIR
	Women	34	0.95 (0.66-1.33) SIR
Raaschou-Nielsen et al. 2003	Danish workers:		
	Men:		
	All employed at least 3 mo	559	1.4 (1.28-1.51) SIR
	Employed <1 year	181	1.6 (1.4-1.9) SIR
	Employed 1-4.9 years	193	1.3 (1.1-1.5) SIR
	Employed ≥5 years	185	1.4 (1.2-1.6) SIR
	Women:		
	All employed at least 3 mo	73	1.9 (1.48-2.35) SIR
	Employed <1 year	28	2.5 (1.6-3.6) SIR
	Employed 1-4.9 years	25	1.6 (1.1-2.4) SIR
	Employed ≥5 years	20	1.6 (1.0-2.5) SIR
Zhao et al. 2005	Aerospace workers (men)		
	Cumulative-exposure score, lag 0:		
	Low (0-3)	43	1.00 SIR
	Medium (>3-15)	35	1.36 (0.86-2.14) SIR
	High (>15)	14	1.11 (0.60-2.06) SIR
Sung et al. 2007	Female electronics workers in Taoyuan, Taiwan	46[h]	0.92 (0.67-1.23)
Cohort Studies—Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	13[h]	0.90 (0.48-1.53) SMR
	Women	25[h]	1.01 (0.65-1.49) SMR
Zhao et al. 2005	Aerospace workers (men)		
	Cumulative-exposure score, lag 0:		
	Low (0-3)	99	1.00 SMR
	Medium (>3-15)	62	1.05 (0.76-1.44) SMR
	High (>15)	33	1.02 (0.68-1.53) SMR
Boice et al. 2006	Male workers at rocket-engine testing facility	51[h]	1.24 (0.92-1.63) SMR
Case-Control Studies			
Lee et al. 2003	Community downstream of electronics factory in Taiwan (chlorinated hydrocarbons; males)	41	1.75 (0.79-2.39) MOR
BONE CANCER			
Cohort Studies—Incidence			

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Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	1	0.61 (0.01-3.39) SIR
	Women	6	1.28 (0.47-2.78) SIR
Sung et al. 2007	Female electronics workers in Taoyuan, Taiwan	3	0.92 (0.19-2.70) SIR
Cohort Studies—Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	0[i]	—
	Women	4[i]	1.63 (0.44-4.18) SMR
	Employed <1 year (men and women)	2[i]	1.25 SMR
	Employed 1-5 years (men and women)	2[i]	3.23 SMR
	Employed >5 years (men and women)	0[i]	—
Boice et al. 2006	Male workers at rocket-engine testing facility	0	0 (0.00-13.8) SMR
SOFT-TISSUE SARCOMA			
Cohort Study—Incidence			
Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	3	1.4 (0.3-4.2) SIR
	Women	8	1.0 (0.4-2.0) SIR
Cohort Study—Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	0	—
	Women	0	—
BREAST CANCER			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water (women only)	536	1.09 (99%CI 0.97-1.21) SIR
Raaschou-Nielsen et al. 2003	Danish workers:		
	Men employed at least 3 mo	2	0.5 (0.06-1.90) SIR
	Women employed at least 3 mo	145	1.1 (0.89-1.24) SIR
Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	0	0.00 (0.00-33.54) SIR
	Women	215	1.19 (1.03-1.36) SIR

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TABLE E-2 Continued

Reference	Study Population	No. Exposed Persons	MOR, OR, SIR, or SMR (95% CI)
Sung et al. 2007	Female electronics workers in Taoyuan, Taiwan	286	1.09 (0.96-1.22) SIR
	Employed before June 1974[e]	90	1.38 (1.11-1.70) SIR
	Employed after June 1974[e]	196	0.99 (0.85-1.14) SIR
Cohort Studies—Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	0	—
	Women	51	1.14 (0.85-1.51) SMR
	Employed <1 year (women)	31	1.08 SMR
	Employed 1-5 years (women)	14	1.25 SMR
	Employed >5 years (women)	6	1.32 SMR
CERVICAL CANCER			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	29	0.65 (99%CI 0.38-1.02) SIR
Raaschou-Nielsen et al. 2003	Danish workers (women employed for at least 3 mo)	62	1.9 (1.42-2.37) SIR
	Employed <1 year	30	2.5 (1.7-3.5) SIR
	Employed 1-4.9 years	22	1.6 (1.0-2.4) SIR
	Employed ≥5 years	10	1.3 (0.6-2.4) SIR
Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE (women):		
	Employed <1 year	177	1.1 (0.9-1.2) SIR
	Employed 1-5 years	69	1.1 (0.8-1.3) SIR
	Employed 5-10 years	26	1.6 (1.1-2.4) SIR
	Employed >10 years	1	0.1 (0.0-0.8) SIR
Sung et al. 2007	Female electronics workers in Taoyuan, Taiwan	337	0.96 (0.86-1.06) SIR
	Employed before June 1974[e]	72	0.84 (0.66-1.06) SIR
	Employed after June 1974[e]	265	0.99 (0.88-1.12) SIR
Cohort Studies—Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE and PCE (women)	21	0.80 (0.49-1.22) SMR
	Employed <1 year	14	0.84 SMR
	Employed 1-5 years	6	0.89 SMR
	Employed >5 years	1	0.34 SMR
UTERINE CANCER			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	124	1.35 (99%CI 1.06-1.70) SIR

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Raaschou-Nielsen et al. 2003	Danish workers (women employed at least 3 mo)	24	1.0 (0.66-1.53) SIR
Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE	337[j]	1.06 (0.95-1.18) SIR
Sung et al. 2007	Female electronics workers in Taoyuan, Taiwan	25	0.96 (0.62-1.42) SIR
Cohort Studies—Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE (women):	5	0.91 (0.29-2.13) SMR
	Employed <1 year	3	0.88 SMR
	Employed 1-5 years	2	1.42 SMR
	Employed >5 years	0	—
OVARIAN CANCER			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	81	1.16 (99%CI 0.85-1.53) SIR
Raaschou-Nielsen et al. 2003	Danish workers (w omen employed at least 3 mo)	22	0.9 (0.55-1.32) SIR
Sung et al. 2007	Female electronics workers in Taoyuan, Taiwan	36[k]	0.83 (0.58-1.15) SIR
Cohort Studies—Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE (women):	7	0.80 (0.32-1.64) SMR
	Employed <1 year	1	0.18 SMR
	Employed 1-5 years	3	1.36 SMR
	Employed >5 years	3	3.45 SMR
PROSTATIC CANCER			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	483	1.11 (99%CI 0.98-1.25) SIR
Raaschou-Nielsen et al. 2003	Danish workers (men employed at least 3 mo)	163	0.9 (0.79-1.08) SIR
Cohort Studies—Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE (men)	0	—
Boice et al. 2006	Male workers at rocket-engine testing facility	8	0.82 (0.36-1.62) SMR
Case-Control Studies			
Krishnadasan et al. 2007	Workers at nuclear energy and rocket-engine testing facility:		
	Low-moderate exposure, lag 0	90	1.3 (0.81-2.1) OR
	High exposure, lag 0	45	2.1 (1.2-3.9) OR
TESTICULAR CANCER			
Cohort Studies—Incidence			
Hansen et al. 2001[a]	Danish workers (men)	1	0.7 (0.01-4.0) SIR

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TABLE E-2 Continued

Reference	Study Population	No. Exposed Persons	MOR, OR, SIR, or SMR (95% CI)
Raaschou-Nielsen et al. 2003	Danish workers (men employed at least 3 months)	93	1.1 (0.92-1.40) SIR
Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE	1[l]	0.14 (0.00-0.76) SIR
Cohort Studies Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE (men)	0	—
Boice et al. 2006	Male workers at rocket-engine testing facility	0[l]	0 (0.00-8.53) SMR
RENAL CANCER			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	54	0.80 (99%CI 0.54-1.12) SIR
Raaschou-Nielsen et al. 2003	Danish workers:		
	Men		
	All employed at least 3 mo	93	1.2 (0.97-1.48) SIR
	Employed <1 year	14	0.8 (0.5-1.4) SIR
	Employed 1-4.9 years	25	1.2 (0.8-1.7) SIR
	Employed ≥5 years	29	1.6 (1.1-2.3) SIR
	Women:		
	All employed at least 3 mo	10	1.2 (0.55-2.11) SIR
	Employed <1 year	2	1.1 (0.1-3.8) SIR
	Employed 1-4.9 years	3	1.2 (0.2-3.4) SIR
	Employed ≥5 years	3	1.5 (0.3-4.3) SIR
Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	8[m]	1.06 (0.45-2.08) SIR
	Women	12[m]	1.09 (0.56-1.91) SIR
Zhao et al. 2005	Aerospace workers (men)		
	Cumulative-exposure score, lag 0:		
	Low (0-3)	6	1 SIR
	Medium (>3-15)	6	1.87 (0.56-6.20) SIR
	High (>15)	4	4.90 (1.23-19.6) SIR
Sung et al. 2007	Female electronics workers in Taoyuan, Taiwan	15[m]	1.10 (0.62-1.82) SIR
Cohort Studies—Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	0[m]	—
	Women	3[m]	1.18 (0.24-3.44) SMR
	Employed <1 year	1[m]	0.62 SMR

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	Employed 1-5 years	2[m]	3.08 SMR
	Employed >5 years	0[m]	—
Zhao et al. 2005	Aerospace workers (men)		
	Cumulative-exposure score, lag 0:		
	Low (0-3)	7	1 SMR
	Medium (>3-15)	7	1.43 (0.49-4.16) SMR
	High (>15)	3	2.03 (0.50-8.32) SMR
Boice et al. 2006	Male workers at rocket-engine testing facility	7	2.22 (0.89-4.57) SMR
Case-Control Studies			
Brüning et al. 2003	Hospital-based study in Arnsberg, Germany:		
	Longest-held job (men and women)	117	1.80 (1.01-3.20) OR
	Ever employed in:		
	Metal greasing, degreasing	15	5.57 (2.33-13.32) OR
	Metal processing	30	1.34 (0.81-2.23) OR
	Metalworking	9	2.33 (0.91-5.94) OR
	Pannett job-exposure matrix:		
	Degreasing agents:		
	Low	9	2.11 (0.86-5.18) OR
	High	7	1.01 (0.40-2.54) OR
	Solvents:		
	Low	8	1.80 (0.70-4.59) OR
	High	8	1.45 (0.59-3.58)OR
	Self-reported exposure	25	2.47 (1.36-4.49) OR
	Self-reported narcotic symptoms	19	3.71 (1.80-7.54) OR
	Duration of self-reported exposure:		
	None	109	1 OR
	<10 years	11	3.78 (1.54-9.28) OR
	10-20 years	7	1.80 (0.67-4.79) OR
	>20 years	6	2.69 (0.84-8.66) OR
Charbotel et al. 2006	Cases in Arve Valley, France:		
	Exposed during at least one job period:		
	Nonexposed	49	1 OR
	Exposed	37	1.64 (0.95-2.84) OR
	Cumulative dose:		
	Low	12	1.62 (0.75-3.47) OR
	Medium	9	1.15 (0.47-2.77) OR
	High	16	2.16 (1.02-4.60) OR
	Cumulative dose peaks:		

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TABLE E-2 Continued

Reference	Study Population	No. Exposed Persons	MOR, OR, SIR, or SMR (95% CI)
	Low-medium, no peaks	18	1.35 (0.69-2.63) OR
	Low-medium, with peaks	3	1.61 (0.36-7.30) OR
	High, no peaks	8	1.76 (0.65-4.73) OR
	High, with peaks	8	2.73 (1.06-7.07) OR
BLADDER CANCER			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	82	0.98 (99%CI 0.71-1.29) SIR
Raaschou-Nielsen et al. 2003	Danish workers:		
	Men employed at least 3 mo	203	1.0 (0.89-1.18) SIR
	Women employed at least 3 mo	17	1.6 (0.93-2.57) SIR
Zhao et al. 2005	Aerospace workers (men)		
	Cumulative-exposure score, lag 0:		
	Low (0-3)	20	1.00 SIR
	Medium (>3-15)	19	1.54 (0.81-2.92) SIR
	High (>15)	11	1.98 (0.93-4.22) SIR
Sung et al. 2007	Female electronics workers in Taoyuan, Taiwan	3	0.34 (0.07-1.00) SIR
Cohort Studies Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	1	0.96 (0.01-5.36) SIR
	Women	1	0.96 (0.01-5.33) SIR
Zhao et al. 2005	Aerospace workers (men)		
	Cumulative exposure score, lag 0:		
	Low (0-3)	8	1.00 SMR
	Medium (>3-15)	6	1.27 (0.43-3.73) SMR
	High (>15)	3	1.15 (0.29-4.51) SMR
Boice et al. 2006	Male workers at rocket-engine testing facility	5[n]	1.66 (0.54-3.87) SMR
SKIN MELANOMAS			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	137	1.42 (99%CI 1.13-1.77) SIR
Raaschou-Nielsen et al. 2003	Danish workers:		
	Men:		
	All employed at least 3 mo	56	0.7 (0.55-0.94) SIR
	Employed <1 year	17	0.6 (0.4-1.0) SIR
	Employed 1-4.9 years	26	0.9 (0.6-1.3) SIR
	Employed ≥5 years	13	0.6 (0.3-1.0) SIR

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	Women:		
	All employed at least 3 mo	16	0.8 (0.44-1.24) SIR
	Employed <1 year	9	1.2 (0.6-2.3) SIR
	Employed 1-4.9 years	3	0.4 (0.1-1.0) SIR
	E mployed ≥5 years	4	0.8 (0.2-2.1) SIR
Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	2	0.48 (0.05-1.73) SIR
	Women	13	0.99 (0.53-1.69) SIR
Zhao et al. 2005	Aerospace workers (men)		
	Cumulative-exposure score, lag 0:		
	Low (0-3)	17	1.00 SIR
	Medium (>3-15)	15	1.44 (0.71-2.92) SIR
	High (>15)	4	0.87 (0.29-2.64) SIR
Sung et al. 2007	Female electronics workers in Taoyuan, Taiwan	22	1.03 (0.65-1.56) SIR
Cohort Studies—Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	0	—
	Women	0	—
Boice et al. 2006	Male workers at rocket-engine testing facility	0	0 (0.00-1.51) SMR
CENTRAL NERVOUS SYSTEM CANCER			
Cohort Studie—-Incidence			
Hansen et al. 2001[a]	Danish workers:		
	Men	1	0.4 (0.01-2.1) SIR
	Women	0	—
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	37	1.54 (99%CI 0.96-2.31) SIR
Raaschou-Nielsen et al. 2003	Danish workers:		
	Men employed at least 3 mo	85	1.0 (0.76-1.18) SIR
	Women employed at least 3 mo	19	1.1 (0.67-1.74) SIR
Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	2	0.40 (0.05-1.46) SIR
	Women	15	0.97 (0.54-1.61) SIR
Zhao et al. 2005	Aerospace workers (men)		
	Cumulative-exposure score, lag 0:		
	Low (0-3)	7[o]	1.00 SIR

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TABLE E-2 Continued

Reference	Study Population	No. Exposed Persons	MOR, OR, SIR, or SMR (95% CI)
	Medium (>3-15)	2[a]	0.46 (0.09-2.25) SIR
	High (>15)	1[a]	0.47 (0.06-3.95) SIR
Sung et al. 2007	Female electronics workers in Taoyuan, Taiwan:		
	Brain	14	1.07 (0.59-1.80) SIR
	Other parts of nervous system	2	1.43 (0.17-5.17) SIR
Cohort Studies—Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	1	0.48 (0.01-2.66) SMR
	Women	6	0.91 (0.33-1.99) SMR
Zhao et al. 2005	Aerospace workers (men)		
	Cumulative-exposure score, lag 0:		
	Low (0-3)	12[a]	1.00 SMR
	Medium (>3-15)	3[a]	0.42 (0.12-1.50) SMR
	High (>15)	3[a]	0.83 (0.23-3.08) SMR
Boice et al. 2006	Male workers at rocket-engine testing facility	3	0.81 (0.17-2.36) SMR
CENTRAL NERVOUS SYSTEM CANCER IN CHILDREN			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	6	1.05 (99%CI 0.24-2.70) SIR
LYMPHATIC AND HEMATOPOIETIC CANCER			
Cohort Studies—Incidence			
Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	6	0.73 (0.27-1.60) SIR
	Women	16	0.65 (0.37-1.05) SIR
MALIGNANT LYMPHOMA			
Case-Control Studies			
Seidler et al. 2007	Cases with occupational exposure in Germany:		
	>0 to ≤4.4 ppm-year	40	0.7 (0.4-1.1) OR
	>4.4 to ≤35 ppm-year	32	0.7 (0.5-1.2) OR
	>35 ppm-year	21	2.1 (1.0-4.8) OR
NON-HODGKIN LYMPHOMA			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	111	1.09 (99%CI 0.84-1.38) SIR
Raaschou-Nielsen et al. 2003	Danish workers:		

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	Men:		
	All employed at least 3 mo	83	1.2 (0.98-1.52) SIR
	Employed <1 year	23	1.1 (0.7-1.6) SIR
	Employed 1-4.9 years	33	1.3 (0.9-1.8) SIR
	Employed ≥5 years	27	1.4 (0.9-2.0) SIR
	Women:		
	All employed at least 3 mo	13	1.4 (0.73-2.34) SIR
	Employed <1 year	2	0.7 (0.1-2.4) SIR
	Employed 1-4.9 years	6	1.6 (0.6-3.5) SIR
	Employed ≥5 years	5	1.8 (0.6-4.3) SIR
Zhao et al. 2005	Aerospace workers (men)		
	Cumulative-exposure score, lag 0:		
	Low (0-3)	28	1.00 SIR
	Medium (>3-15)	16	0.88 (0.47-1.65) SIR
	High (>15)	1	0.20 (0.03-1.46) SIR
Cohort Studies—Mortality			
Zhao et al. 2005	Aerospace workers (men)		
	Cumulative-exposure score, lag 0:		
	Low (0-3)	27	1.00 SMR
	Medium (>3-15)	27	1.49 (0.86-2.57) SMR
	High (>15)	6	1.30 (0.52-3.23) SMR
Boice et al. 2006	Male workers at rocket-engine testing facility	1	0.21 (0.01-1.18) SMR
Case-Control Studies			
Miligi et al. 2006	Cases with occupational exposure in Italy:		
	Very low-low	35	0.8 (0.5-1.3) OR
	Medium-high	35	1.2 (0.7-2.0) OR
	≤15 years	22	1.1 (0.6-2.1) OR
	>15 years	12	1.0 (0.5-2.6) OR
Seidler et al. 2007	Cases with occupational exposure in Germany:		
	B-non-Hodgkin lymphoma:		
	>0 to ≤4.4 ppm-years	32	0.7 (0.5-1.2) OR
	>4.4 to ≤35 ppm-years	27	0.8 (0.5-1.3) OR
	>35 ppm-years	17	2.3 (1.0-5.3) OR
	T-non-Hodgkin lymphoma:		
	>0 to ≤4.4 ppm-years	2	0.7 (0.2-3.3) OR
	>4.4 to ≤35 ppm-years	2	1.1 (0.2-5.1) OR
	>35 ppm-years	2	4.7 (0.8-26.1) OR

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TABLE E-2 Continued

Reference	Study Population	No. Exposed Persons	MOR, OR, SIR, or SMR (95% CI)
HODGKIN DISEASE			
Cohort Studies—Incidence			
Hansen et al. 2001[a]	Danish workers:		
	Men	0	—
	Women	0	—
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	17	0.93 (99%CI 0.44-1.67) SIR
Raaschou-Nielsen et al. 2003	Danish workers:		
	Men employed at least 3 mo	18	0.9 (0.51-1.37) SIR
	Women employed at least 3 mo	2	0.8 (0.09-3.00) SIR
Cohort Studies—Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	0	—
	Women	1	2.23 (0.03-12.40) SMR
Boice et al. 2006	Male workers at rocket-engine testing facility	2	2.86 (0.35-10.3) SMR
Case-Control Studies			
Seidler et al. 2007	Cases with occupational exposure in Germany:		
	>0 to ≤4.4 ppm-years	6	0.4 (0.2-1.1) OR
	>4.4 to ≤35 ppm-years	3	0.4 (0.1-1.4) OR
	>35 ppm-years	2	2.0 (0.4-10.5) OR
MULTIPLE MYELOMA			
Cohort Studies—Incidence			
Raaschou-Nielsen et al. 2003	Danish workers:		
	Men employed at least 3 mo	28	1.1 (0.70-1.52) SIR
	Women employed at least 3 mo	3	0.9 (0.18-2.56) SIR
Cohort Studies—Mortality			
Boice et al. 2006	Male workers at rocket-engine testing facility	1	0.50 (0.01-2.77) SMR
Case-Control Studies			
Seidler et al. 2007	Cases with occupational exposure in Germany:		
	>0 to ≤4.4 ppm-years	3	0.5 (0.2-1.9) OR
	>4.4 to ≤35 ppm-years	6	1.0 (0.4-2.7) OR
	>35 ppm-years	1	0.7 (0.1-5.5) OR
LEUKEMIA			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	77[p]	1.02 (99%CI 0.74-1.35) SIR

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Raaschou-Nielsen et al. 2003	Danish workers:		
	Men employed at least 3 mo	69	1.1 (0.84-1.37) SIR
	Women employed at least 3 mo	13	1.7 (0.89-2.86) SIR
Sung et al. 2007	Female electronics workers in Taoyuan, Taiwan	23	0.78 (0.49-1.17) SIR
Cohort Studies—Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	2	0.44 (0.05-1.59) SMR
	Women	8	0.54 (0.23-1.07) SMR
Boice et al. 2006	Male workers at rocket-engine testing facility	5[q]	1.08 (0.35-2.53) SMR
CHRONIC LYMPHOCYTIC LEUKEMIA			
Cohort Studies—Mortality			
Boice et al. 2006	Male workers at rocket-engine testing facility	1	1.19 (0.03-6.61) SMR
Case-Control Studies			
Seidler et al. 2007	Cases with occupational exposure in Germany:		
	>0 to ≤4.4 ppm-years	10	1.1 (0.5-2.4) OR
	>4.4 to ≤35 ppm-years	6	0.7 (0.3-1.7) OR
	>35 ppm-years	2	0.9 (0.2-4.5) OR
LEUKEMIA OTHER THAN CHRONIC LYMPHOCYTIC LEUKEMIA			
Cohort Studies—Mortality			
Boice et al. 2006	Male workers at rocket-engine testing facility	4	1.05 (0.29-2.69) SMR
DIFFUSE LARGE B-CELL LYMPHOMA			
Case-Control Studies			
Seidler et al. 2007	Cases with occupational exposure in Germany:		
	>0 to ≤4.4 ppm-years	6	0.5 (0.2-1.2) OR
	>4.4 to ≤35 ppm-years	7	0.8 (0.3-1.8) OR
	>35 ppm-years	4	2.6 (0.7-3.0) OR
FOLLICULAR LYMPHOMA			
Seidler et al. 2007	Cases with occupational exposure in Germany:		
	>0 to ≤4.4 ppm-years	7	1.3 (0.5-3.2) OR
	>4.4 to ≤35 ppm-years	3	0.7 (0.2-2.6) OR
	>35 ppm-years	3	3.2 (0.8-12.9) OR
MARGINAL ZONE LYMPHOMA			
Case-Control Studies			
Seidler et al. 2007	Cases with occupational exposure in Germany:		
	>0 to ≤4.4 ppm-years	2	0.9 (1.2-4.3) OR

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TABLE E-2 Continued

Reference	Study Population	No. Exposed Persons	MOR, OR, SIR, or SMR (95% CI)
	>4.4 to ≤35 ppm-years	2	4.2 (0.8-23.9) OR
	>35 ppm-years	2	4.2 (0.8-23.9)
CHILDHOOD LEUKEMIA			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	10	1.09 (99%CI 0.38-2.31) SIR
Case-Control Studies			
Costas et al. 2002	Cases in Woburn, MA (drinking water contaminated with TCE, PCE, other chemicals):		
	Ever exposed:		
	From 2 years before conception to case diagnosis	16	2.39 (0.54-10.59) OR
	During 2 years before conception	8	2.61 (0.47-14.37) OR
	During pregnancy	10	8.33 (0.73-94.67) OR
	From birth to diagnosis	12	1.18 (0.28-5.05) OR
	Cumulative exposure:		
	From 2 years before conception to case diagnosis		
	Least exposed	9	5.00 (0.75-33.50) OR
	Most exposed	7	3.56 (0.51-24.78) OR
	During 2 years before conception		
	Least exposed	4	2.48 (0.42-15.22) OR
	Most exposed	4	2.82 (0.30-26.42) OR
	During pregnancy		
	Least exposed	3	3.53 (0.22-58.14) OR
	Most exposed	7	14.30 (0.92-224.52) OR
	From birth to diagnosis		
	Least exposed	7	1.82 (0.31-10.84) OR
	Most exposed	5	0.90 (0.18-4.56) OR

[a]Hansen et al. (2001) study not cited in IOM (2003) report analysis for this particular cancer outcome, so included here as new information.
[b]Oral cavity.
[c]Digestive organs and peritoneum.
[d]Colon and rectum.
[e]Month and date when regulations on solvent use were promulgated.
[f]Results are for hepatic and biliary cancer combined.
[g]Lungs and bronchi.
[h]Trachea, bronchi, and lungs.
[i]Bone and articular cartilage.
[j]Female genital organs.
[k]Ovaries, fallopian tubes, and broad ligaments.

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[l]Testes and other male genital organs.
[m]Kidneys and other unspecified urinary organs.
[n]Bladder and other urinary cancers.
[o]Brain cancer only.
[p]All leukemias.
[q]Leukemia and aleukemia.
Abbreviations: CI = confidence interval, MOR = mortality odds ratio, OR = odds ratio, SIR = standardized incidence ratio, SMR = standardized mortality ratio.

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TABLE E-3a Studies of Noncancer End Points and Exposure to TCE

Reference	Study Population	No. Exposed Persons	OR (95% CI)
END-STAGE RENAL DISEASE			
Cohort Studies			
Radican et al. 2006	Aircraft workers (1973-2000)	56	1.91 (1.08-3.38)
	Aircraft workers (1973-2002)[a]	61	1.42 (0.87-2.31)
SYSTEMIC SCLEROSIS			
Case-Control Studies			
Diot et al. 2002	Hospital-based study in Tours, France		
	Men and women with occupational exposure:	13	2.39 (1.04-5.22)
	Men	7	4.67 (0.99-21.89)
	Women	6	2.10 (0.65-6.75)
	High final cumulative exposure (men and women)	7	7.58 (1.54-37.36)
Garabrant et al. 2003	Women in Michigan and Ohio:		
	Self-reported exposure	8	2.0 (0.8-4.8)
	Expert-confirmed exposure	4	1.9 (0.6-6.6)
CONGENITAL HEART DEFECTS			
Case-Control Studies			
Yauck et al. 2004	Infants born in Milwaukee, WI (1997-1999):		
	Maternal age, TCE exposure		
	<38 years, nonexposed		1
	<38 years, exposed		0.9 (0.6-1.2)
	≥38 years, nonexposed		1.9 (1.1-3.5)
	≥38 years, exposed		6.2 (2.6-14.5)
	Pre-existing diabetes		4.1 (1.5-11.2)
	Chronic hypertension		2.8 (1.2-6.7)
	Alcohol use during pregnancy		2.1 (1.1-4.2)
NEUROBLASTOMA			
Case-Control Studies			
De Roos et al. 2001	Offspring with paternal occupational exposure (Unites States and Canada):		
	Self-reported exposure to TCE	22	1.4 (0.7-2.9)
	Industrial-hygiene-reviewed exposure	9	0.9 (0.3-2.5)

[a]Attenuation observed was due to greater rate of end-stage renal disease in exposed subjects in 1973-2000. Rate of disease increased in unexposed subjects in 2001 (sharp increase) and 2002 while rate in exposed subjects remained approximately constant.
Abbreviations: CI = confidence interval, OR = odds ratio, TCE = trichloroethylene.

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TABLE E-3b Studies of Neurologic Effects and Exposure to TCE

End Point	Reference	Population	TCE Exposure, Duration	Results
Neurobehavioral (measured with neurobehavioral core test battery with profile of mood states in addition to two tests of visual perception)	Reif et al. 2003	143 residents in vicinity of Rocky Mountain Arsenal, 1981-1986	Four exposure groups: <5 ppb, mean 20.6 years 5-10 ppb, mean 20.5 years 10-15 ppb, mean 18.8 years >15 ppb, mean 24.7 years	Adjusted mean neurobehavioral test scores about 10-20% lower in highest-exposure group than in lowest-exposure group; some evidence of greater depression, confusion, tension-anxiety in highest- exposure group than in lowest-expopsure group, but difference not statistically significant (P = 0.08, 0.14, 0.24, respectively); study found strong interaction between TCE exposure and alcohol consumption in induction of neurobehavioral deficits
Parkinson disease, parkinsonism	Gash et al. 2008	30 industrial co-workers with Parkinson disease, parkinsonism, chronic exposure to TCE	Exposure pathway assumed to be inhalation with some dermal absorption. Exposure level not reported. Mean duration: 27 yr Median duration: 28 yr	Three workers had diagnosis of Parkinson disease before study; 14 workers self-reported parkinsonian symptoms, 13 self-reported no symptoms (according to Unified Parkinson's Disease Rating Scale); asymptomatic group had significantly slower fine motor movement than control group (P< 0.0001), slightly faster hand movement than symptomatic group (p < 0.01)

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TABLE E-4 Studies of Cancer End Points and Exposure to PCE

Reference	Study Population	No. Exposed Persons	MOR, OR, RR, SIR, or SMR (95% CI)
BUCCAL CAVITY, PHARYNGEAL CANCER			
Cohort Studies—Incidence			
Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	19	0.55 (0.33-0.86) SIR
	Women	42	0.96 (0.69-1.29) SIR
Cohort Studies—Mortality			
Blair et al. 2003	Dry cleaners in St. Louis, MO	10	1.1 (0.5-2.0) SMR
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	6	0.65 (0.50-0.83) SMR
	Women	10	0.71 (0.34-1.30) SMR
ESOPHAGEAL CANCER			
Cohort Studies—Mortality			
Blair et al. 2003	Dry cleaners in St. Louis, MO:	26	2.2 (1.5-3.3) SMR
	Little or no exposure	7	2.1 (0.9-4.4) SMR
	Medium-high exposure	16	2.2 (1.2-3.5) SMR
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	0	—
	Women	0	—
Case-Control Studies			
Lynge et al. 2006	Nordic dry-cleaning workers	8	0.76 (0.34-1.69) RR
GASTRIC CANCER			
Cohort Studies—Incidence			
Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	56[a]	0.73 (0.55-0.95) SIR
	Women	135[a]	0.93 (0.78-1.09) SIR
Cohort Studies—Mortality			
Blair et al. 2003	Dry cleaners in St. Louis, MO	20	0.9 (0.6-1.4) SMR
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	7	0.93 (0.37-1.91) SMR
	Women	24	1.11 (0.71-1.65) SMR
Case-Control Studies			
Lee et al. 2003	Community downstream of electronics factory in Taiwan (chlorinated hydrocarbons; males)	39	2.18 (0.97-4.89) MOR

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COLON CANCER			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	327[b]	0.86 (99%CI 0.74-0.99) SIR
Cohort Studies—Mortality			
Blair et al. 2003	Dry cleaners in St. Louis, MO:	60	1.2 (0.9-1.5) SMR
	Little or no exposure	28	1.1 (0.8-1.6) SMR
	Medium-high exposure	28	1.2 (0.4-1.5) SMR
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	3	0.65 (0.13-1.91) SMR
	Women	19	1.36 (0.82-2.13) SMR
	Employed <1 year (men and women)	12	1.33 SMR
	Employed 1-5 years (men and women)	3	0.85 SMR
	Employed >5 years (men and women)	4	2.94 SMR
Case-Control Studies			
Lee et al. 2003	Community downstream of electronics factory in Taiwan (chlorinated hydrocarbons; males)	26[b]	0.83 (0.24-2.89) MOR
RECTAL CANCER			
Cohort Studies—Mortality			
Blair et al. 2003	Dry cleaners in St. Louis, MO	15	1.3 (0.7-2.2) SMR
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	2	0.73 (0.08-2.65) SMR
	Women	13	1.67 (0.89-2.85) SMR
	Employed <1 year (men and women)	9	1.81 SMR
	Employed 1-5 years (men and women)	2	1.01 SMR
	Employed >5 years (men and women)	2	2.50 SMR
HEPATIC CANCER			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	28[c]	1.29 (99%CI 0.74-2.05) SIR
Cohort Studies—Mortality			
Blair et al. 2003	Dry cleaners in St. Louis, MO	10	0.8 (0.4-1.5) SMR
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	0	—
	Women	0	—
Case-Control Studies			
Lee et al. 2003	Community downstream of electronics factory in Taiwan (chlorinated hydrocarbons; males)	53	2.57 (1.21-5.46) MOR
Lynge et al. 2006	Nordic dry-cleaning workers	11	0.76 (0.38-1.52) RR

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TABLE E-4 Continued

Reference	Study Population	No. Exposed Persons	MOR, OR, RR, SIR, or SMR (95% CI)
PANCREATIC CANCER			
Cohort Studies—Mortality			
Blair et al. 2003	Dry cleaners in St. Louis, MO:	28	1.1 (0.7-1.5) SMR
	Little or no exposure	14	1.2 (0.7-2.0) SMR
	Medium-high exposure	11	0.8 (0.4-1.5) SMR
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	1	0.49 (0.01-2.73) SMR
	Women	5	1.39 (0.45-3.25) SMR
	Employed <1 year (men and women)	2	0.91 SMR
	Employed 1-5 years (men and women)	2	2.15 SMR
	Employed >5 years (men and women)	1	2.22 SMR
Case-Control Studies			
Lynge et al. 2006	Nordic dry-cleaning workers	57	1.27 (0.90-1.80) RR
LARYNGEAL CANCER			
Cohort Studies—Mortality			
Blair et al. 2003	Dry cleaners in St. Louis, MO:	6	1.7 (0.6-3.7) SMR
	Little or no exposure	0	—
	Medium-high exposure	6	2.7 (1.0-5.8) SMR
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	0	—
	Women	0	—
LUNG CANCER			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	356[d]	0.71 (99%CI 0.61-0.81) SIR
Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	20	0.94 (0.57-1.45) SIR
	Women	34	0.95 (0.66-1.33) SIR
Cohort Studies—Mortality			
Blair et al. 2003	Dry cleaners in St. Louis, MO:	125	1.4 (1.1-1.6) SMR
	Little or no exposure	34	1.0 (0.7-1.4) SMR
	Medium-high exposure	78	1.5 (1.2-1.9) SMR
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	13[e]	0.90 (0.48-1.53) SMR
	Women	25[e]	1.01 (0.65-1.49) SMR
Case-Control Studies			
Lee et al. 2003	Community downstream of electronics factory in Taiwan (chlorinated hydrocarbons; males)	41	1.75 (0.79-2.39) MOR

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BONE CANCER			
Cohort Studies—Incidence			
Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	1	0.61 (0.01-3.39) SIR
	Women	6	1.28 (0.47-2.78) SIR
Cohort Studies—Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	0[f]	—
	Women	4[f]	1.63 (0.44-4.18) SMR
	Employed <1 year (men and women)	2[f]	1.25 SMR
	Employed 1-5 years (men and women)	2[f]	3.23 SMR
	Employed >5 years (men and women)	0[f]	—
SOFT-TISSUE SARCOMA			
Cohort Studies—Incidence			
Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	3	1.4 (0.3-4.2) SIR
	Women	8	1.0 (0.4-2.0) SIR
Cohort Studies—Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	0	—
	Women	0	—
BREAST CANCER			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water (women only)	536	1.09 (99%CI 0.97-1.21) SIR
Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	0	0.00 (0.00-33.54) SIR
	Women	215	1.19 (1.03-1.36) SIR
Cohort Studies—Mortality			
Blair et al. 2003	Dry cleaners in St. Louis, MO:	68	1.0 (0.8-1.3) SMR
	Little or no exposure	30	0.8 (0.6-1.2) SMR
	Medium-high exposure	29	1.2 (0.8-1.7) SMR
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	0	—
	Women	51	1.14 (0.85-1.51) SMR
	Employed <1 year (women)	31	1.08 SMR
	Employed 1-5 years (women)	14	1.25 SMR
	Employed >5 years (women)	6	1.32 SMR

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TABLE E-4 Continued

Reference	Study Population	No. Exposed Persons	MOR, OR, RR, SIR, or SMR (95% CI)
Case-Control Studies			
Aschengrau et al. 2003	Women with breast cancer in Cape Cod, MA, towns:[g]		
	≤ median exposure (latency 0-15 years)	377	0.9-1.5 OR
	> median exposure (latency 0-15 years)	402	1.1-1.4 OR
	> 75th percentile exposure (latency 0-15 years)	253	1.6-1.9 OR
	> 90th percentile exposure (latency 0-15 years)	90	1.3-1.9 OR
Vieira et al. 2005	Women with breast cancer in Cape Cod, MA, towns:		
	0-year latency:		
	Nonproxy subjects	101	1.1 (0.8-1.5) OR
	All subjects	155	1.1 (0.8-1.4) OR
	5-year latency		
	Nonproxy subjects	87	1.2 (0.9-1.8) OR
	All subjects	129	1.1 (0.9-1.6) OR
	7-year latency		
	Nonproxy subjects	71	1.1 (0.8-1.6) OR
	All subjects	111	1.1 (0.8-1.5) OR
	9-year latency		
	Nonproxy subjects	63	1.1 (0.7-1.6) OR
	All subjects	97	1.1 (0.8-1.5) OR
	11-year latency		
	Nonproxy subjects	49	1.1 (0.6-1.7) OR
	All subjects	79	1.2 (0.8-1.7) OR
	13-year latency		
	Nonproxy subjects	43	1.3 (0.7-2.1) OR
	All subjects	61	1.3 (0.9-2.0) OR
	15-year latency		
	Nonproxy subjects	30	1.4 (0.7-2.6) OR
	All subjects	44	1.4 (0.9-2.3) OR
	17-year latency		
	Nonproxy subjects	15	1.0 (0.4-2.2) OR
	All subjects	21	1.0 (0.6-2.0) OR
	19-year latency		
	Nonproxy subjects	6	1.1 (0.3-3.5) OR
	All subjects	9	1.1 (0.4-2.9) OR
CERVICAL CANCER			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	29	0.65 (99%CI 0.38-1.02) SIR

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Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE (women):		
	Employed <1 year	177	1.1 (0.9-1.2) SIR
	Employed 1-5 years	69	1.1 (0.8-1.3) SIR
	Employed 5-10 years	26	1.6 (1.1-2.4) SIR
	Employed >10 years	1	0.1 (0.0-0.8) SIR
Cohort Studies—Mortality			
Blair et al. 2003	Dry cleaners in St. Louis, MO:	27	1.6 (1.0-2.3) SMR
	Little or no exposure	12	1.5 (0.8-2.7) SMR
	Medium-high exposure	11	1.4 (0.7-1.7) SMR
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE (women):	21	0.80 (0.49-1.22) SMR
	Employed <1 year	14	0.84 SMR
	Employed 1-5 years	6	0.89 SMR
	Employed >5 years	1	0.34 SMR
Case-Control Studies			
Lynge et al. 2006	Nordic dry-cleaning workers	36	0.98 (0.65-1.47) RR
UTERINE CANCER			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	124	1.35 (99%CI 1.06-1.70) SIR
Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE	337[h]	1.06 (0.95-1.18) SIR
Cohort Studies—Mortality			
Blair et al. 2003	Dry cleaners in St. Louis, MO	15	1.1 (0.6-1.8) SMR
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE (women):	5	0.91 (0.29-2.13) SMR
	Employed <1 year	3	0.88 SMR
	Employed 1-5 years	2	1.42 SMR
	Employed >5 years	0	—
OVARIAN CANCER			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	81	1.16 (99%CI 0.85-1.53) SIR
PROSTATIC CANCER			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	483	1.11 (99%CI 0.98-1.25) SIR
Cohort Studies Mortality			
Blair et al. 2003	Dry cleaners in St. Louis, MO	17	1.0 (0.6-1.6) SMR
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE (men)	0	—

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TABLE E-4 Continued

Reference	Study Population	No. Exposed Persons	MOR, OR, RR, SIR, or SMR (95% CI)
TESTICULAR CANCER			
Cohort Studies—Incidence			
Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE	1[i]	0.14 (0.00-0.76) SIR
Cohort Studies—Mortality			
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE (men)	0	—
RENAL CANCER			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	54	0.80 (99%CI 0.54-1.12) SIR
Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	8[j]	1.06 (0.45-2.08) SIR
	Women	12[j]	1.09 (0.56-1.91) SIR
Cohort Studies—Mortality			
Blair et al. 2003	Dry cleaners in St. Louis, MO:	8	1.0 (0.4-2.0) SMR
	Little or no exposure	1	0.3 (<0.1-1.6) SMR
	Medium-high exposure	7	1.5 (0.6-3.1) SMR
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	0[j]	—
	Women	3[j]	1.18 (0.24-3.44) SMR
	Employed <1 year	1[j]	0.62 SMR
	Employed 1-5 years	2[j]	3.08 SMR
	Employed >5 years	0[j]	—
Case-Control Studies			
Brüning et al. 2003	Hospital-based study in Arnsberg, Germany:		
	Self-reported exposure	7	1.64 (0.61-4.40) OR
	Self-reported narcotic symptoms	5	1.84 (0.57-5.96) OR
	Duration of self-reported exposure:		
	None	127	1 OR
	<10 years	4	2.46 (0.65-9.34) OR
	10+ years	3	1.02 (0.24-4.27) OR
Lynge et al. 2006	Nordic dry-cleaning workers	29	0.67 (0.43-1.05) RR
BLADDER CANCER			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	82	0.98 (99%CI 0.71-1.29) SIR
Cohort Studies—Mortality			
Blair et al. 2003	Dry cleaners in St. Louis, MO:	12	1.3 (0.7-2.4) SMR
	Little or no exposure	5	1.4 (0.4-3.2) SMR

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	Medium-high exposure	7	1.5 (0.6-3.1) SMR
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	1	0.96 (0.01-5.36) SIR
	Women	1	0.96 (0.01-5.33) SIR
Case-Control Studies			
Lynge et al. 2006	Nordic dry-cleaning workers:	93	1.44 (1.07-1.93) RR
	Employed 0-1 years	6	1.50 (0.57-3.96) RR
	Employed 2-4 years	10	2.39 (1.09-5.22) RR
	Employed 5-9 years	17	0.91 (0.52-1.59) RR
	Employed 10 years or more	53	1.57 (1.07-2.29) RR
SKIN MELANOMAS			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	137	1.42 (99%CI 1.13-1.77) SIR
Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	2	0.48 (0.05-1.73) SIR
	Women	13	0.99 (0.53-1.69) SIR
Cohort Studies—Mortality			
Blair et al. 2003	Dry cleaners in St. Louis, MO	4	0.8 (0.2-2.1) SMR
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	0	—
	Women	0	—
CENTRAL NERVOUS SYSTEM CANCER			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	37	1.54 (99%CI 0.96-2.31) SIR
Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	2	0.40 (0.05-1.46) SIR
	Women	15	0.97 (0.54-1.61) SIR
Cohort Studies—Mortality			
Blair et al. 2003	Dry cleaners in St. Louis, MO	5	0.6 (0.2-1.4) SMR
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	1	0.48 (0.01-2.66) SMR
	Women	6	0.91 (0.33-1.99) SMR
CENTRAL NERVOUS SYSTEM CANCER IN CIIILDREN			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	6	1.05 (99%CI 0.24-2.70) SIR
LYMPHATIC AND HEMATOPOIETIC CANCER			
Cohort Studies Incidence			

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TABLE E-4 Continued

Reference	Study Population	No. Exposed Persons	MOR, OR, RR, SIR, or SMR (95% CI)
Chang et al. 2005	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	6	0.73 (0.27-1.60) SIR
	Women	16	0.65 (0.37-1.05) SIR
Cohort Studies—Mortality			
MALIGNANT LYMPHOMA			
Case-Control Studies			
Seidler et al. 2007	Cases with occupational exposure in Germany:		
	>0 to ≤ 9.1 ppm-year	16	1.1 (0.5-2.3) OR
	>9.1 to ≤78.8 ppm-year	13	1.0 (0.5-2.2) OR
	>78.8 ppm-year	2	3.4 (0.7-17.3) OR
NON-HODGKIN LYMPHOMA			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	111	1.09 (99%CI 0.84-1.38) SIR
Cohort Studies Mortality			
Blair et al. 2003	Dry cleaners in St. Louis, MO	12	0.9 (0.5-1.6) SMR
Case-Control Studies			
Lynge et al. 2006	Nordic dry-cleaning workers	42	0.95 (0.65-1.41) RR
Miligi et al. 2006	Cases with occupational exposure in Italy:		
	Very low-low	18	0.6 (0.3-1.2) OR
	Medium-high	14	1.2 (0.6-2.5) OR
	≤15 years	10	1.3 (0.5-3.3) OR
	>15 years	3	—
Seidler et al. 2007	Cases with occupational exposure in Germany:		
	B-non-Hodgkin lymphoma:		
	>0 to ≤ 9.1 ppm-year	12	0.9 (0.4-2.0) OR
	>9.1 to ≤78.8 ppm-year	12	1.0 (0.5-2.3) OR
	>78.8 ppm-year	5	3.2 (0.6-16.7) OR
	T-non-Hodgkin lymphoma:		
	>0, ≤ 9.1 ppm-year	1	1.7 (0.2-14.4) OR
	>9.1 to ≤78.8 ppm-year	1	1.5 (0.2-12.5) OR
	>78.8 ppm-year	1	—
HODGKIN DIESASE			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE via drinking water	17	0.93 (99%CI 0.44-1.67) SIR
Cohort Studies—Mortality			
Blair et al. 2003	Dry cleaners in St. Louis, MO	5	2.0 (0.6-4.6) SMR
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		

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	Men	0	—
	Women	1	2.23 (0.03-12.40) SMR
Case-Control Studies			
Seidler et al. 2007	Cases with occupational exposure in Germany:		
	>0 to ≤ 9.1 ppm-year	3	1.7 (0.4-6.9) OR
	>9.1 to ≤78.8 ppm-year	1	0.7 (0.1-6.3) OR
	>78.8 ppm-year	0	—
MULTIPLE MYELOMA			
Cohort Studies—Mortality			
Blair et al. 2003	Dry cleaners in St. Louis, MO	7	0.8 (0.3-1.6) SMR
Case-Control Studies			
Seidler et al. 2007	Cases with occupational exposure in Germany:		
	>0 to ≤ 9.1 ppm-year	3	1.8 (0.5-6.7) OR
	>9.1 to ≤78.8 ppm-year	0	—
	>78.8 ppm-year	0	—
LEUKEMIA			
Cohort Studies—Incidence			
Morgan and Cassady 2002	Redlands, CA, community exposed to TCE, PCE in drinking water	77[k]	1.02 (99%CI 0.74-1.35) SIR
Cohort Studies—Mortality			
Blair et al. 2003	Dry-cleaners in St. Louis, MO	12	0.8 (0.4-1.4) SMR
Chang et al. 2003	Electronics-manufacturing workers in Taiwan exposed to TCE, PCE:		
	Men	2	0.44 (0.05-1.59) SMR
	Women	8	0.54 (0.23-1.07) SMR
CHRONIC LYMPHOCYTIC LEUKEMIA			
Case-Control Studies			
Seidler et al. 2007	Cases with occupational exposure in Germany:		
	>0, ≤ 9.1 ppm-year	1	—
	>9.1, ≤78.8 ppm-year	2	0.6 (0.1-2.8) OR
	>78.8 ppm-year	0	—
DIFFUSE LARGE B-CELL LYMPHOMA			
Case-Control Studies			
Seidler et al. 2007	Cases with occupational exposure in Germany:		
	>0 to ≤ 9.1 ppm-year	3	0.9 (0.3-3.9) OR
	>9.1 to ≤78.8 ppm-year	6	2.1 (0.8-5.9) OR
	>78.8 ppm-year	1	2.3 (0.2-26.0) OR
FOLLICULAR LYMPHOMA			
Case-Control Studies			
Seidler et al. 2007	Cases with occupational exposure in Germany:		

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TABLE E-4 Continued

Reference	Study Population	No. Exposed Persons	MOR, OR, RR, SIR, or SMR (95% CI)
	>0 to ≤ 9.1 ppm-year	2	1.2 (0.3-5.5) OR
	>9.1 to ≤78.8 ppm-year	0	—
	>78.8 ppm-year	0	—
MARGINAL ZONE LYMPHOMA			
Seidler et al. 2007	Cases with occupational exposure in Germany:		
	>0 to ≤ 9.1 ppm-year	1	—
Costas et al. 2002	Cases in Woburn, MA (drinking water contaminated with TCE, PCE, other chemicals):		
	Ever exposed:		
	From 2 years before conception to case diagnosis	16	2.39 (0.54-10.59) OR
	During 2 years before conception	8	2.61 (0.47-14.37) OR
	During pregnancy	10	8.33 (0.73-94.67) OR
	From birth to diagnosis	12	1.18 (0.28-5.05) OR
	Cumulative exposure:		
	From 2 years before conception to case diagnosis:		
	Least exposed	9	5.00 (0.75-33.50) OR
	Most exposed	7	3.56 (0.51-24.78) OR
	During 2 years before conception:		
	Least exposed	4	2.48 (0.42-15.22) OR
	Most exposed	4	2.82 (0.30-26.42) OR
	During pregnancy:		
	Least exposed	3	3.53 (0.22-58.14) OR
	Most exposed	7	14.30 (0.92-224.52) OR
	From birth to diagnosis:		
	Least exposed	7	1.82 (0.31-10.84) OR
	Most exposed	5	0.90 (0.18-4.56) OR
Infante-Rivard et al. 2005	Maternal occupational exposure:		
	2 years before pregnancy up to birth		0.96 (0.41-2.25) OR
	During pregnancy		0.84 (0.30-2.34) OR

[a]Digestive organs and peritoneum.
[b]Colon and rectum.
[c]Results are for liver and biliary cancer combined.
[d]Lungs and bronchi.
[e]Trachea, bronchi, and lungs.
[f]Bone and articular cartilage.
[g]Combined data from present and previous study by Aschengrau et al. (1998).
[h]Female genital organs.

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[i]Testes and other male genital organs.
[j]Kidney and other unspecified urinary organs.
[k]All leukemias.
Abbreviations: CI = confidence interval, MOR = mortality odds ratio, OR = odds ratio, PCE = perchloroethylene, RR = relative risk, SIR = standardized incidence ratio, SMR = standardized mortality ratio, TCE = trichloroethylene.

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TABLE E-5a Studies of Noncancer End Points and Exposure to PCE

Reference	Study Population	No. Exposed Persons	OR (95% CI)
SYSTEMIC SCLEROSIS			
Case-Control Studies			
Garabrant et al. 2003	Women in Michigan, Ohio:		
	Self-reported exposure	7	1.4 (0.6-3.4)
	Expert-confirmed exposure	5	1.1 (0.4-2.9)
PRETERM LOSS			
Sonnefeld et al. 2001	Infants of Camp Lejeune residents, 1968-1985:		
	Exposure 1-3 weeks	14	1.0 (90% CI 0.6-1.6)
	Exposure 4-10 weeks	55	1.3 (90% CI 1.0-1.7)
	Exposure 11-20 weeks	86	1.3 (90% CI 1.1-1.6)
	Exposure >20 weeks, less than entire pregnancy	94	0.8 (90% CI 0.7-1.0)
	Exposure, entire pregnancy, less than 1 year before last menstrual period	158	1.1 (90% CI 0.9-1.3)
	Exposure entire pregnancy, at least 1 year before last menstrual period	36	0.8 (90% CI 0.6-1.1)
SMALL FOR GESTATIONAL WEIGHT			
Sonnefeld et al. 2001	Infants of Camp Lejeune residents, 1968-1985		
	Exposure 1-3 weeks	15	0.9 (90% CI 0.5-1.3)
	Exposure 4-10 weeks	60	1.1 (90% CI 0.9-1.4)
	Exposure 11-20 weeks	84	1.0 (90% CI 0.8-1.2)
	Exposure >20 weeks, less than entire pregnancy	16	1.2 (90% CI 1.0-1.4)
	Exposure entire pregnancy, less than 1 year before last menstrual period	207	1.2 (90% CI 1.0-1.3)
	Exposure entire pregnancy, at least 1 year before last menstrual period	61	1.1 (90% CI 0.9-1.4)
	All births	622	1.2 (90% CI 1.0-1.3)
	Mother's age <35 years	611	1.1 (90% CI 0.9-1.2)
	Mother's age ≥ 35 years	11	2.1 (90% CI 0.9-4.9)
	Mother had no previous fetal losses	475	1.1 (90% CI 0.9-1.2)
	Mother had one previous fetal loss	104	1.5 (90% CI 1.1-2.0)
	Mother had at least two previous fetal losses	43	2.5 (90% CI 1.5-4.3)
MEAN BIRTH WEIGHT			
Sonnenfeld et al. 2001	Infants of Camp Lejeune residents, 1968-1985		
	Exposure 1-3 weeks	189	Mean difference: 18 g (90% CI -40 to 76)
	Exposure 4-10 weeks	597	Mean difference: -17 g (90% CI -51 to 17)
	Exposure 11-20 weeks	915	Mean difference: -31 g (90% CI -59 to -3)
	Exposure >20 weeks, less than entire pregnancy	1,551	Mean difference: -28 g (90% CI -50 to -5)

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	Exposure entire pregnancy , less than 1 year before last menstrual period	1,994	Mean difference: -15 g (90% CI -35 to 5)
	Exposure entire pregnancy, at least 1 year before last menstrual period	605	Mean difference: -18 g (90% CI -51 to 16)
	All births	6,039	Mean difference: -26 g (90% CI -43 to -9)
	Mother's age <35 years	5,968	Mean difference: -2 g (90% CI -17 to 13)
	Mother's age ≥ 35 years	71	Mean difference: -130 g (90% CI -236 to -23)
	Mother had no previous fetal losses	4,985	Mean difference: -2 g (90% CI -17 to 13)
	Mother had one previous fetal loss	806	Mean difference: -16 g (90% CI -79 to 24)
	Mother had at least two previous fetal losses	245	Mean difference: -104 g (90% CI -174 to -34)
NEUROBLASTOMA			
Case-Control Studies			
De Roos et al. 2001	Offspring with paternal occupational exposure (Unites States, Canada)		
	Self-reported exposure to PCE	8	0.5 (0.2-1.4) OR
	Industrial-hygiene-reviewed exposure	4	0.5 (0.1-1.7) OR
SCHIZOPHRENIA			
Cohort Studies—Incidence			
Perrin et al. 2007	Offspring of dry cleaners in Jerusalem	4	3.4 (1.3-9.2) RR
NEUROBEHAVIORAL			
Cohort Studies			
Janulewicz et al. 2008 (Note: end point included two diagnoses—ADD and HD—and six indicators of learning disabilities)	Offspring of Cape Cod, MA, residents born 1969-1983	1,349	
	Prenatal exposure:	1,244	
	Low exposure		1.0-1.5 (0.7-2.7) OR
	High exposure		0.8-1.1 (0.4-1.6) OR
	Exposure 5 years postnatally:	1,326	
	Low exposure		0.9-1.4 (0.7-2.5) OR
	High exposure		0.6-1.0 (0.3-1.7) OR

Abbreviations: ADD = attention deficit disorder, CI = confidence interval, HD = hyperactivity disorder, OR = odds ratio, PCE = perchloroethylene.

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TABLE E-5b Visual Contrast Sensitivity and Visual Acuity

Reference	Population	Exposure, Duration	Effects
Schreiber et al. 2002	Apartment residents above dry cleaner	Mean, 778 μg/m^3 Median, 350 μg/m^3 Mean residence, 5.8 years Lifetime dose, 3,400 μg/m^3	Visual contrast sensitivity trend in Lanthony D15-d; no change in visual acuity
	Day-care workers sharing building with dry cleaner	Mean, 2,150 μg/m^3 Median, 2,150 μg/m^3 Mean work, 4.0 years Lifetime dose, 1,978 μg/m^3	Visual contrast sensitivity; no change in visual acuity

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ground water

Issue Paper/

Complexities in Hindcasting Models—When Should We Say Enough Is Enough?

by T. Prabhakar Clement

Abstract

Groundwater models are routinely used in hindcasting applications to predict the past concentration levels in contaminated aquifers. These predictions are used in risk assessment and epidemiological studies, which are often completed either for resolving a court case or for developing a public-policy solution. Hindcast groundwater modeling studies utilize a variety of computer tools with complexity levels ranging from simple analytical models to detailed three-dimensional, multiphase, multispecies, reactive transport models. The aim of this study is to explore the value of using complex reactive transport models in hindcasting studies that have limited historic data. I review a chlorinated solvent exposure problem that occurred at a U.S. Marine Corp Base in Camp Lejeune, North Carolina and use it as an example to discuss the limits of hindcasting modeling exercises. The lessons learned from the study are used to reflect upon the following questions related to model complexity: How should we decide how much is enough? Who should decide when enough is enough?

Introduction

On April 15, 2009, Professor Elizabeth Warren of Harvard Law School, formerly the chief of the congressional oversight panel for the troubled asset relief program, appeared on Jon Stewart's late night talk show to discuss our government's plan to stress-test failing banks. With a cynical smile on his face, Stewart asked: "How do you stress test a bank, if you will?" Professor Warren replied: "Well, you basically run it through a bunch of mathematical models and figure out whether the thing (bank) is financially healthy or the thing is really dead;" (note, in this context, she was just explaining the testing process). To my surprise, Stewart did not challenge this modeling effort and never asked a single follow-up question. The idea of conducting a computer-simulated stress test on a real bank, which is a complicated entity embedded within a dynamic economic web, should make anyone a cynic. Stewart's acceptance of this response without a question indicates the level of trust our society places in complex computer modeling efforts, especially when it is perceived that the efforts might provide benefits. This type of trust is not limited to economics. Scientists in other fields, including groundwater hydrology, tend to have such trust in models.

When critics challenge this trust in models, experts counter: What is the alternative? For the bank stress-test problem, we can, to some extent, answer this question by examining the opinions of some experienced investors in the financial industry. For example, on May 3, 2009, one of the world's renowned investors, Warren Buffet, dismissed the importance of the government stress tests in helping him assess banks (Bloomberg 2009). He stated: "I think I know their future, frankly, better than somebody that comes in to take a look." He also added that he judges banks by their "dynamism" and their "ability" to attract deposits.

Given these two vastly different positions (i.e., one based on computer modeling and another on expert opinion), one might wonder which one is more worthy for supporting a decision-making process. For the bank problem, one might have the following dilemma: Should I trust

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the complex mathematical assessment that purports to provide quantitative numbers for future deposits, profits, and earnings, or should I trust the qualitative conceptual assessment of an expert that provides subjective indicators such as a bank's "dynamism" or "ability"? As hydrogeologists, we are often challenged by our clients who want us to help them resolve complex policy questions or court cases. It is not easy to decide whether we should resolve such issues by using complex cutting-edge models or by using a balanced analysis of simpler calculations combined with expert judgments.

In this article, I present a philosophical discourse on the simplicity vs. complexity dilemma in the groundwater modeling field. There is an on-going debate on this topic (e.g., Haitjema 2006; Hill 2006; Gómez-Hernández 2006); however, past discussions have not considered the unique issues related to hindcasting efforts that use complex models. This article specifically focuses on a hindcast modeling case study that employed reactive transport models. The case study, which was recently reviewed by a National Academy panel administered by the National Research Council (NRC 2009), involves a chlorinated solvent contamination problem at a US Marine Corps Base in North Carolina. I served on this 14-member, interdisciplinary panel for more than 2 years and had an opportunity to review a wide range of health assessment, site characterization, and modeling studies. In this article, I will first provide a brief summary of the groundwater problem and will then use the lessons I have learned from this experience to reflect on the following two questions: How do we assess the required level of model complexity for a given hindcasting problem? Who should make the final decision about the complexity level?

What Is a Hindcasting Model?

Mathematical models have been routinely used in the scientific literature to pursue epistemic research and/or policy research. The primary objective of an epistemic research effort is to create new knowledge that can help develop a mechanical scientific understanding of natural processes. The knowledge can then be used to generate testable hypotheses (predictions). A good example for an epistemic model is Einstein's general theory of relativity, which explained how gravity works and predicted, for example, the gravitational field would bend light. This prediction was later confirmed by Eddington's field data that documented the deflection of light by the sun's gravitational field from observations made during the solar eclipse in May 1919 (Dyson et al. 1920). The objective of policy-modeling efforts, on the other hand, is to provide "best possible estimates," which can be used by policy-makers to develop a timely decision to resolve a complex social problem that cannot be resolved using a mechanical scientific procedure. Policy models can be classified into forecasting models and hindcasting models. Forecasting models are used for predicting the future to resolve a potential problem. A good example of a forecasting exercise is the use of atmospheric models to predict the climate change effects.

Hindcasting models are used for predicting the past to understand and resolve historical problems. A good example of a hindcasting modeling application is the use of chemical fate and transport models to resolve public health issues related to a groundwater plume (e.g., the Woburn contamination problem; Bair and Metheny, 2011). Hindcasting applications are uniquely challenging because if we do not have the necessary past data for the system then there is no opportunity to collect the missing data. The scope of this article is limited to analyzing hindcasting policy models that employ complex reactive transport codes.

Details of the Case Study

The case study considered here is based on a drinking water contamination problem that occurred in the 1950s and 1960s at a U.S. Marine Corp Base in Camp Lejeune (CLJ), North Carolina. The base is a 246-square-mile military training facility located in Onslow County, southeast of the City of Jacksonville, North Carolina. The site has multiple contaminated areas that are impacted by several types of hazardous chemicals. In this article, I will focus on a tetrachloroethylene (PCE) plume present in the Tarawa Terrace (TT) area (Figure 1) for which extensive modeling information is available (Maslia et al. 2007; NRC 2009). The PCE plume originated from an off-site dry cleaning facility, ABC One Hour Cleaners, which started operation in 1953 (Figure 1). The site has a considerable amount of hydrogeological characterization data, but limited chemical/biological characterization data. Details of the site characterization data available are discussed in Harden et al. (2004), Maslia et al. (2007), and Faye and Green (2007).

The groundwater contamination problem was first discovered in the early 1980s when a routine water quality survey indicated the presence of unknown organic compounds in the drinking water. Further investigations revealed that the water supplied by the on-site water treatment plant, which extracted water from multiple wells installed in the local aquifer (see Figure 1 for well locations), was contaminated with PCE and its degradation products. Later, it was determined that the drinking water was also contaminated with other chemicals including petroleum products. As the modeling studies completed so far have solely focused on the PCE contamination problem, I will limit the discussions to chlorinated solvent-related issues.

At the CLJ site, it is estimated that more than a million people have been exposed to the contaminated water delivered between the mid-1950s and the mid-1980s. Currently, more than 156,000 people have formally registered with the Marines Corps to get more information about the contamination. Several former CLJ residents have moved forward with claims against the Marine Corps complaining that the contaminated water has caused a variety of cancers and other ailments. To address these complaints,

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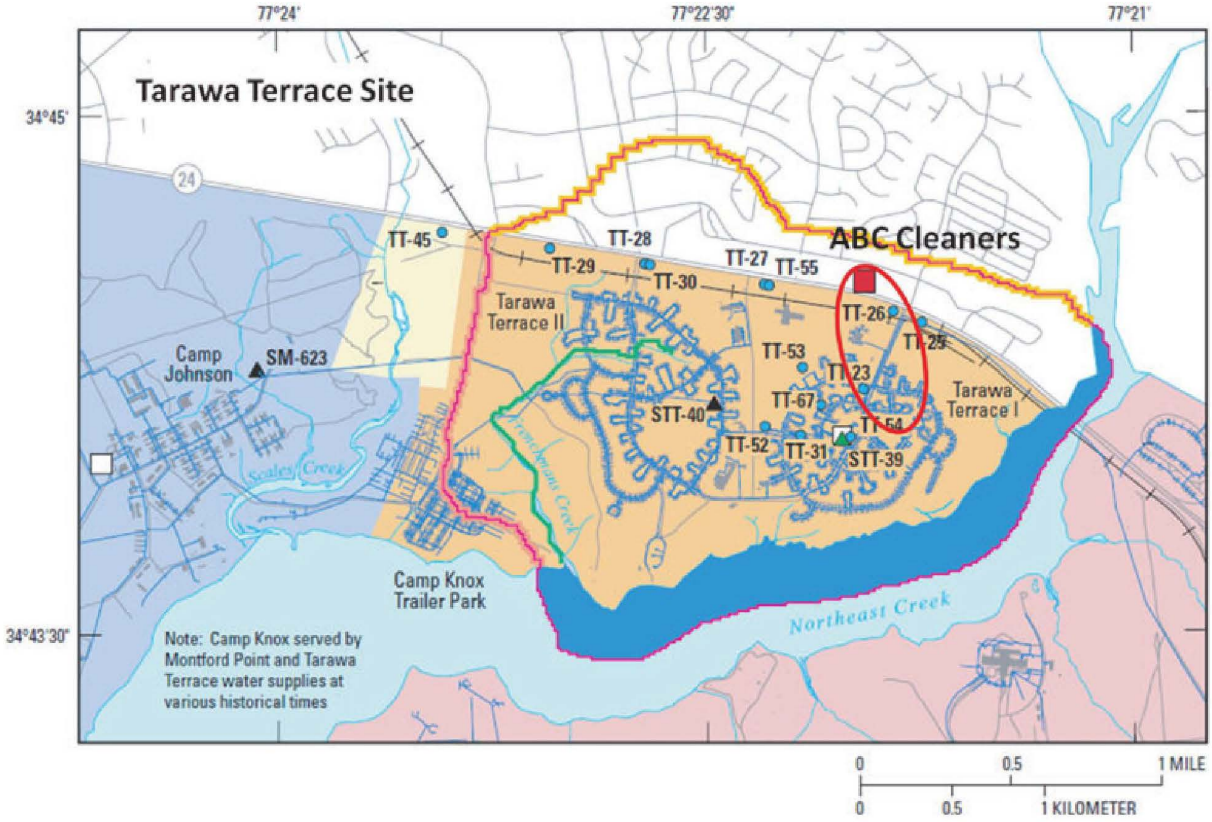

Figure 1. Details of the Tarawa Terrace site. Pumping wells are indicated by blue dots labeled with letters TT. The red square indicates the location of ABC Cleaners. Triangles are storage tanks and are not relevant to this discussion (from Maslia et al. 2007).

the Agency of Toxic Substances and Disease Registry (ATSDR) conducted a study that examined the association between well-defined, quantitative levels of PCE and TCE (trichloroethylene) in drinking water and the risk of developing specific birth defects—spina bifida, anencephaly, cleft lip, cleft palate, childhood leukemia, and non-Hodgkin's lymphoma (Maslia et al. 2007). The study included groundwater modeling efforts to reconstruct the past contamination scenarios and also interviews to obtain residential history, information on water consumption habits, and other risk factors. ATSDR postulated that by using model-derived drinking water concentrations and the interview data, associations between exposure to PCE and TCE and the risk of particular health outcomes could be thoroughly examined (Maslia et al. 2007). ATSDR used the public-domain codes MODFLOW and MT3DMS to predict the fate and transport of PCE, and an advanced research code TechFlowMP (Jang and Aral 2008), to predict the concentrations of PCE along with its degradation byproducts TCE, *trans*-1,2-dichloroethylene (*trans*-DCE), and vinyl chloride (VC).

Based on the modeling studies, researchers reconstructed the historical contamination levels and the model-predicted concentrations were widely disseminated to various groups. Figures 2 and 3 show example modeling results that were made available to scientists interested in conducting exposure assessment studies. Figure 2 shows probabilistic MT3DMS predictions for the historic PCE concentration levels in the drinking water, generated using the Monte Carlo approach. The range of PCE concentrations derived from the probabilistic analysis (shown as a band in the figure) represents 95% of all possible results. These values were derived from multiple realizations of the MT3DMS model runs. Figure 3 shows the results from a multispecies, multiphase research code TechFlowMP, which was used to predict the historic concentrations of the biodegradation byproducts TCE, *trans*-DCE (*cis*-DCE was not considered), and VC. It is important to note that, as shown in Figure 2, the model was calibrated to limited number of data points, which are PCE levels measured in finished water samples collected in the early 1980s. Also, note that Figure 3 does not report any measured data for the biodegradation products TCE, DCE, or VC.

These model results were presented to former CLJ residents (via websites, public meetings, and reports), health scientists, and congressional committees. All three groups appear to have accepted the results and the modeling methodologies. The results appeared to be reasonable because the Monte Carlo simulations indicated a narrow band within which 95% of the model-simulation results resided. The figure shows that the 95% confidence band becomes narrower as we move back from the 1980s (where there is no data); this implies that the groundwater model was able to make confident hindcasts

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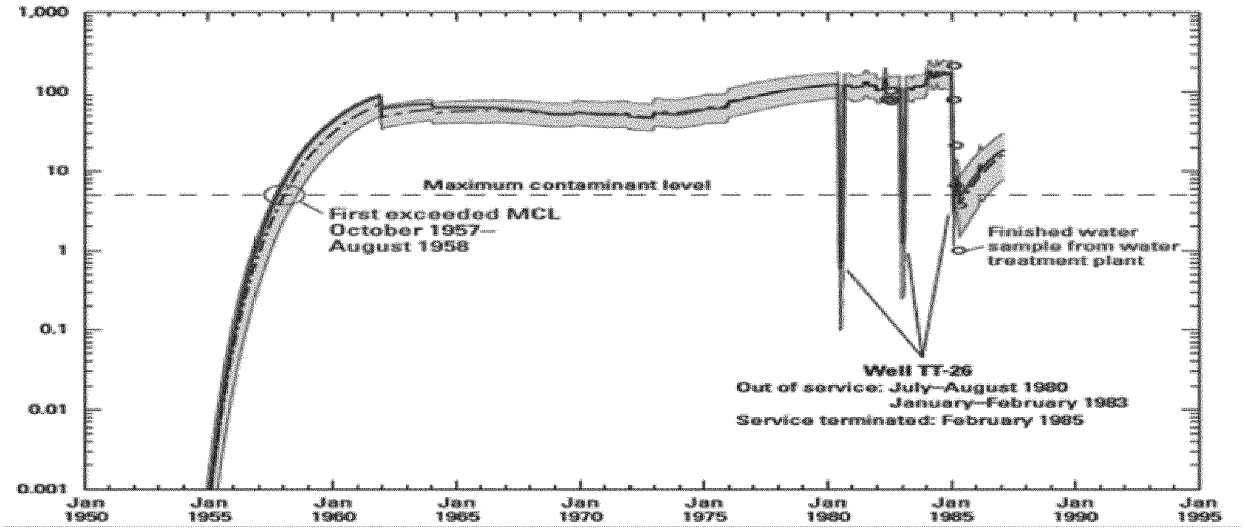

Figure 2. Predicted concentration levels of PCE (µg/L) in the finished water delivered by the Tarawa Terrace treatment plant. MT3DMS model results. The center line is the mean concentration, upper limit is the 97.5% and lower limit is the 2.5% of 510 Monte Carlo simulations (from Maslia et al. 2007).

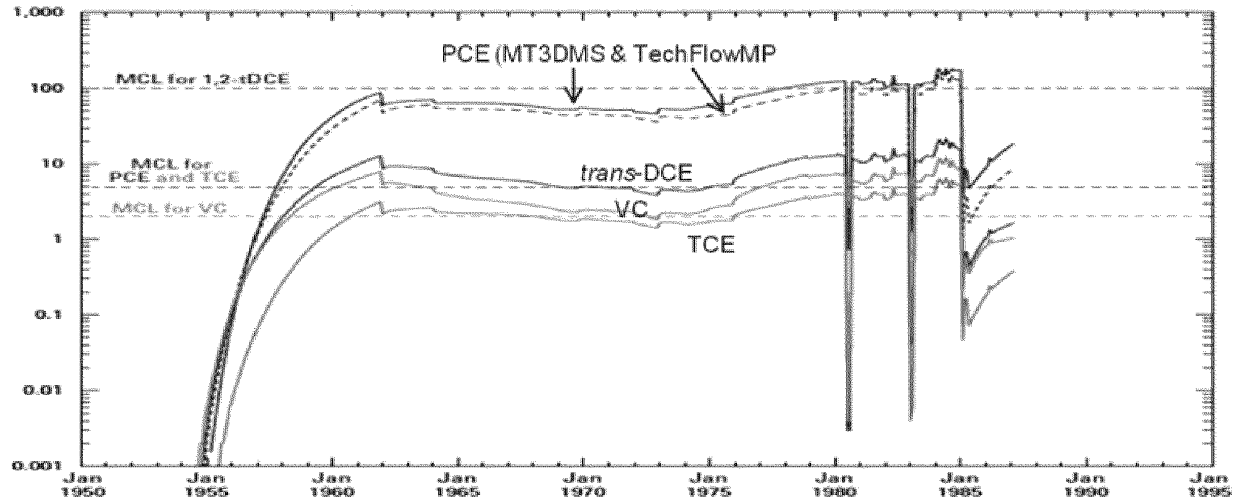

Figure 3. Predicted concentration levels of PCE, TCE, *trans*-DCE, and VC (µg/L) in the finished water delivered by the Tarawa Terrace water treatment plant. TechFlowMP model results (from Maslia et al. 2007).

for the 1950s and 1960s even if there are no past data to calibrate the model. The figure also shows that closer to the initial starting point the confidence band is almost 100%, implying that our knowledge of initial conditions, initial source loadings, and initial stresses is almost exact. Figure 3 shows the model-predicted values of various PCE biodegradation products. Health scientists found these TechFlowMP predictions to be useful because they provided quantitative concentration estimates for assessing the health impacts of more toxic biodegradation products such as VC. Based on some favorable feedbacks, researchers planned follow-up efforts to conduct additional modeling studies to make hindcasting predictions for other contaminated areas including Hadnot Point and Holcomb Boulevard, which are located within the CLJ site. One of the tasks of the NRC (2009) effort was to review these proposals and make impartial recommendations for future groundwater studies.

Constraints on Complexity Due to Process Uncertainties and Data Limitations

The overall objective of the CLJ study was to determine whether exposure to the contaminated water caused the reported health problems. The exposure assessment efforts not only required contaminant concentration levels, but also other site-specific historic data such as total water usage by various impacted residents and their daily water consumption patterns, which are possibly unknowable information. Furthermore, even if one had a "perfect" groundwater model, the final outcomes of the study would

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have considerable uncertainties due to lack of knowledge about actual exposures, their impacts on human health, and the difficulty of making causal inference from observational studies. Oreskes (1998) identified four possible limitations related to exposure/health assessment studies, which arise from theoretical, empirical, parametrical, and temporal uncertainties. Theoretical uncertainties are related to processes which we simply do not understand and hence do not have the correct theoretical (mathematical) description to model the process. Empirical uncertainties are related to factors that we cannot measure. This would include having limited resources to collect samples (e.g., blood samples of the exposed population) and analytical uncertainties in quantifying low levels of chemicals in tissues or blood samples. Parametric uncertainties are the errors introduced when we reduce complex phenomena to a single (fixed or varying) input parameter. Temporal uncertainties arise from the assumption that systems are stable in time. Oreskes argued that from a biological standpoint systems may not be stable in time; for example, high and low levels of blood concentration could be as important as the mean and might affect human health in ways that are neither fully understood nor fully measured.

The groundwater modeling field also has several issues that are quite similar to those pointed out by Oreskes. Over the past three decades, the groundwater modeling community has progressed considerably in addressing these issues. The basic theoretical framework for simulating flow and nonreactive transport is now reasonably well understood and has been routinely used for analyzing practical problems. Powerful analytical and numerical approaches are now available for efficiently solving groundwater problems. The analytical advances have led to the development of efficient close-form solutions to various reactive transport problems and public-domain screening tools (Aziz et al. 2000; Clement et al. 2002; Quezada et al. 2004; Srinivasan and Clement 2008). The numerical advances have led to the development of well-accepted public-domain codes such as MODFLOW and MT3DMS, and related reactive transport codes such as RT3D (Clement et al. 1998) and PHT3D (Prommer et al. 2003). In addition, calibration/uncertainly assessment tools such as PEST (Doherty 2005) and UCODE (Poeter et al. 2005) have also received widespread acceptance. Despite these advances, contaminant transport models, especially reactive transport models used for simulating the fate and transport of solvent plumes evolving from dense nonaqueous phase liquid (DNAPL) sources, still have several important limitations. Over 20 years ago, Anderson (1983) reviewed the state-of-the-art of groundwater modeling practices and warned: "Be careful! The Emperor has no clothes!" Hunt and Welter (2010) pointed out that complex groundwater models will always have structural (or theoretical) errors, also known as "unknown unknowns." More recently, Konikow (2011) reviewed the state of solute transport modeling and concluded that the secret to a successful solute transport modeling effort is simply to lower expectations.

Bioreactive transport problems involving DNAPL contaminants, such as PCE, often require model formulations that involve multiple parameters which make predictions more problematic. While recent research efforts have advanced our understanding of biological processes related to chlorinated solvents (McCarty 1997; Bradley et al. 2008), quantitative prediction of PCE biodegradation using reactive transport models is still beyond the state of standard practice. Given this state of knowledge, it is worth examining the value of CLJ hindcasts, which were derived from complex bioreactive transport models that were fitted to few data points, for developing a policy solution to the problem.

One of the important concerns that limit the use of bioreactive transport models at chlorinated solvent sites is the lack of problem-specific information on input parameters. A key input to any transport model is information related to the source. Unfortunately, this information is one of the most unreliable types of input deduced from qualitative assessments. This is especially true in hindcasting applications involving DNAPL wastes. At the TT site, the contaminant of concern, PCE (a DNAPL), was sporadically disposed by a dry cleaner in the DNAPL form, along with other waste products, into a septic tank. Site characterization data indicated that a shallow monitoring well installed close to the dry cleaning facility recorded an extremely high PCE concentration of 12,000 µg/L (Faye and Green 2007). Such high-concentration levels would indicate that the source region might still have residual DNAPL. At DNAPL-contaminated source regions spatial variability in mass is almost inevitable and consequently the mass detection process will be extremely difficult and uncertain (Abriola 2005). Detailed modeling of PCE migration processes from the septic tank requires input data related to waste disposal practices, historical infiltration levels, unsaturated zone properties, effective solubility level of the mixed-waste DNAPL, and its dissolution kinetics. In summary, the way (what, when, where, and how) PCE was discharged into the system and how long the PCE waste resided in DNAPL form are important factors controlling historic plume concentrations. Yet this critical past information cannot be obtained.

The TT water supply system extracted groundwater from multiple wells installed in a highly heterogeneous, multilayer aquifer. These wells were operated in a cyclic manner. The influent concentrations of degradation species (such as TCE, DCE, or VC) would have depended on the location of the pumped well from which the water was extracted at a given time and the level of subsurface microbial activity at that location during that time period. Literature data show that subsurface microbial reactions can be mediated by a complex set of biogeochemical mechanisms that are facilitated by a variety of microbes (McCarty 1997; Clement et al. 2000; Bradley et al. 2008). Microbiologists are still debating whether a specialized microbial species, such as *Dehalococcoides*, or a variety of natural microbial populations would facilitate degradation of chlorinated solvents (Major et al. 2003; Nyer et al. 2003). They are also debating, to some extent,

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whether the degradation byproduct DCE will be in *cis*-form or in *trans*-form (Miller et al. 2005), although most field studies have shown that DCE is predominately present in the *cis*-form (Wiedemeier et al. 1999).

It is now well established that reductive dechlorination reactions are limited by the availability of a degradable carbon source that can supply hydrogen (McCarty 1997; Yu et al. 2005; Bradley et al. 2008). However, it is difficult to accurately simulate this limitation in large-scale field problems that have multiple competing biogeochemical processes. Clement et al. (2000) proposed a reaction-zone approach to incorporate carbon limitations indirectly at a chlorinated solvent field site in Delaware, USA. Rolle et al. (2008) proposed a kinetic framework for modeling the interactions between carbon and terminal electron acceptors at a landfill site in Italy. However, these are research models that require extensive field-measured biogeochemical data.

Accurate reconstruction of biodegradation byproducts in the drinking water requires historical data for groundwater pumping rates, pumping patterns (recall that the TT treatment plant extracted groundwater from multiple wells in a cyclic manner), geochemical data, concentrations of microbial populations, microbial growth kinetics, and secondary removal rates within treatment units and pipelines. This would necessitate compilation of an enormous amount of past information, most of which is very likely not available at the TT site.

How Should We Decide How Much Is Enough?

The above discussions illustrate the inherent difficulties in developing a bioreactive transport model for reconstructing the PCE contamination scenarios at the TT site that occurred 30 to 40 years ago. Given these difficulties, for hindcasting applications such as the CLJ study, it is perhaps prudent to limit the required level of model complexity to a level that is consistent with the level of available data. This recommendation is not new; it is simply Occam's razor, a well-accepted principle that advocates model parsimony (Hill 2006, NRC 2007). This is a logical approach that necessitates the use of simple models when we have limited data. This practice is particularly more appropriate for hindcasting modeling exercises where it is virtually impossible to obtain missing historical data.

In the literature, researchers have criticized such simplistic modeling approaches, though most of the criticisms were developed in the context of model use in epistemic or forecasting applications. For example, Cunge (2003) argues that simple models add the certainty of a poor quality of modeling to the data uncertainty, and the synergy of the two is likely to result in a very poor representation of reality. He recommends that in a true good practice, a lack of adequate data necessitates the use of the most advanced and reliable modeling tools. It is important to note that Cunge's discussions were aimed toward epistemic (not policy) modeling exercises. Also, his recommendations assume that available "advanced" models would be able to realistically simulate all natural processes.

Oreskes (2003) noted that we tend to have more intuitive faith in complex models because they allow us to simulate more processes. However, as we add more processes (and parameters) to a model, the overall certainty of its predictions might decrease. Ironically, the "truer" the model, the more difficult it is to show that it is "true" (Oreskes 2003). Modeling critics have also pointed out several case studies to illustrate the failure of complex models at various levels; they have argued that mathematical complexities have little value in predicting the behavior of natural systems (Pilkey and Jarvis 2007). Complex computer models are based on reductionism, which assumes one can decompose natural complexity into simple components at an appropriate scale. Rigler and Peters (1995) critiqued such approaches and stated that computers gave reductionists the tools to approach an ecosystem as the sum of its parts, which leads to the conclusion that these tools are inadequate. Chave and Levin (2003) concluded that natural ecological processes (e.g., activity of microbial systems) are not only complex but are also adaptive; moreover, there is no single correct scale on which to study their dynamics.

Recently, the problem of equifinality in complex systems has been discussed extensively in the hydrological literature (Beven 1993). Equifinality is the recognition that different initial states, model structures, and/or parameter sets can lead to similar end states. For the CLJ problem, for example, the site only had a limited number of PCE data points, which were short-term averaged random grab measurements made in the early 1980s (Figure 2). The calibration exercises were aimed toward fitting the monthly-averaged model predictions to these limited data points, within a predefined fixed target level, with an assumption that the calibrated model would be able to hindcast the historical levels of PCE and its byproducts in the 1950s, 1960s, and 1970s. However, due to limitations in our understanding of natural processes and due to inaccuracies in measurement methods, several complex models with many different model structures and initial conditions might fit these limited observations equally well. Beck (1987) reviewed various water quality modeling methods and concluded that a lack of model identifiability has been an outstanding difficulty in the interpretation of observed system behavior and there is ample evidence to show that larger (more complex) models are easily capable of generating highly imprecise predictions. For the TT site, due to sparsity of observations, it will be difficult to identify a unique (or precise) model structure.

Given these limitations, numerical modeling approaches used in data limited, hindcasting policy applications should perhaps employ simpler conceptual approaches that use lower dimensionality (e.g., depth-averaged models), average flow, simpler reactions, spatially-averaged model parameters, temporally-averaged source loading patterns, to name a few. In addition, one could also use simpler tools such as analytical models

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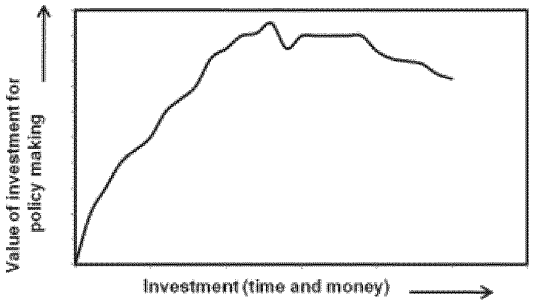

Figure 4. Conceptual relationship between modeling investment and its value for developing policy solutions.

(Haitjema 2006), conceptual calculations that are based on available data (Bredehoeft 2003), and approximations derived using mass-balance calculations. As summarized in NRC (2009), the level of uncertainty associated with such simpler models perhaps will not be lower than the complex predictions; however, these simpler models could be completed quickly in a cost-effective manner and this should help speed up the decision-making process. Simpler models could also provide opportunities to communicate the conceptual limitations of the hindcasting exercise more effectively to the broader user group (e.g., health scientists, politicians, and the concerned public). Denton and Sklash (2006) reviewed several case studies of model applications in court rooms and pointed out that complicated models add little value and could create more opportunities for confusion and challenges.

Figure 4 illustrates a hypothetical conceptual relationship between model investment and its value for aiding the public-policy development process. As shown in the figure, the initial investments made in a modeling effort can help develop a better understanding of the contamination scenario that can be useful for the decision-making process. However, the return on the investment might quickly become marginal and the value of the information gained from new studies would approach a plateau in a nonlinear manner. More importantly, it is possible that larger investments (to develop complex models or to conduct advanced scientific studies) could considerably delay and complicate the decision-making process and even have a negative impact. This is particularly true for hindcasting applications where higher levels of complexity could simply muddle the issues and make the decision-making process a lot more political, thus hampering the process rather than aiding it.

Model development is a dynamic exercise and it is difficult to complete an a priori assessment of model worthiness (i.e., its value related to decision making) at various investment levels for a given project. Therefore, the level of investment (in model complexity) needed for a problem is necessarily a subjective judgment that should be made after carefully considering the information related to available site data, available resources (time and money), and the modeling objectives. The conceptual relationship illustrated in Figure 4 can be a useful guide for integrating all the information to develop a balanced level of model complexity for a given problem. It can serve as a mental model that can help answer the rhetorical question—How much is enough?

Who Should Decide When Enough Is Enough?

Most practical modeling studies are performed by consulting companies that rarely use cutting-edge research tools. Years of model use in litigation efforts have made it clear that using research codes on high-visibility projects is not a good idea. However, in some cases, scientific teams with certain gravitas might convince agencies to support the application of their cutting-edge tools. In such cases, advocating the use of appropriate simpler tools is not easy for the experts who are performing the work. Jamieson (2000) pointed out that scientists live in a highly competitive environment where funding for research is limited. Involvement in policy-modeling projects helps scientists present themselves as real-world problem solvers, which helps secure funding for their scientific pursuits. Sarewitz and Pielke (2000) stated that advocating the use of advanced cutting-edge models is always an attractive short-term solution because it benefits not only the scientists who receive the funding, but also the politicians who fund their effort. It is a "win-win" strategy where the scientists receive direct funding to develop and test their latest tools, and politicians can point to these "scientific" projects as actions and safely defer making difficult decisions as they wait for the study results. Moreover, concerned citizen groups feel good about such scientific pursuits as they believe that the scientists and politicians are doing their best to resolve their problem. In the end, all three parties tend to rationalize the decision and convince themselves that they are doing the right thing. Hence, it will be difficult, if not impossible, for these interest groups to make an impartial judgment call on the required level of model complexity. Use of external peer reviewers, who have little or no self-interest in the project, would perhaps be the more appropriate option.

For the CLJ project, the judgment call was made by the NRC panel, which consisted of a diverse group of 14 experts who volunteered their time to study various aspects of the problem for 2 years and prepared a report, which was reviewed by 10 external reviewers. The panel made the following conclusions (NRC 2009):

> the Tarawa Terrace and Hadnot Point supply systems were contaminated with volatile organics, particularly PCE, TCE and DCE, for decades ending in the middle of 1980s (p. 64). There were divergent views among the committee members about the probability that each would assign to whether adverse health effects have in fact occurred, but there was consensus among them that scientific research is unable to provide more definitive answers (p. 22). [This implied that] it cannot be determined reliably whether diseases and disorders experienced by former residents and workers at Camp Lejeune are associated with their exposure to contaminants in the water supply because of

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> data shortcomings and methodological limitations, and these limitations cannot be overcome with additional study. Thus, the committee concludes that there is no scientific justification for the Navy and Marine Corps to wait for the results of additional health studies before making decisions about how to follow up on the evident solvent exposures on the base and their possible health consequences. The services should undertake the assessments they deem appropriate to determine how to respond in light of the available information (p. 13).

The panel also recommended:

> the use of simpler approaches (such as analytic models, average estimates based on monitoring data, mass-balance calculations, and conceptually simpler MODFLOW/MT3DMS models) that use available data to rapidly reconstruct and characterize the historical contamination (p. 65). Also, policy changes or administrative actions that would help to resolve the controversy should proceed in parallel with the studies (if they are continued) rather than in sequence (p. 22).

As voluntary expert committees, such as the NRC panel, do not have any direct self-interest, their collective wisdom is likely to recommend a reasonable practical solution, although by no means would it be the perfect solution.

The overall response to the NRC study was mixed. Various groups of health scientists, environmental activists, one of the modeling teams, and the former CLJ residents were disappointed and severely criticized the study's conclusion that additional scientific studies cannot provide more definitive answers. In 2009, two senators from North Carolina introduced a bill to furnish hospital care, medical services, and nursing home care to veterans who were stationed at the base while the water was contaminated. In February 2010, a North Carolina congressman introduced *The Janey Ensminger Act* in the House of Representatives to require the Department of Veterans Affairs to provide the healthcare benefits. These new policy developments directly address the healthcare needs of the community. The lead government agency, ATSDR, developed a professional response to the NRC study that included the following statements (ATSDR 2009):

> ATSDR will apply simpler modeling techniques for Hadnot Point and Holcomb Boulevard than those used for Tarawa Terrace. The Hadnot Point area is significantly larger than the Tarawa Terrace area and contains multiple contaminant source locations. Applying the complex numerical models used at Tarawa Terrace to the entire Hadnot Point and Holcomb Boulevard areas would be time consuming, costly, and add another level of uncertainty to the water-modeling analyses.

ATSDR's (2009) plan included continuation of some of the epidemiology studies, as they viewed these studies will be scientifically useful (will have epistemological value), and will also be helpful to the community of service men and women and their families (an important social value).

Concluding Remarks

Reactive transport models are useful tools that can help us gain insights into the importance of key biological and/or chemical variables and their causes and effects. As most of us are limited by our linear thinking, there is always a conceptual gap in our understanding of how all the various parts of a nonlinear biochemical system couple with transport and respond as the whole. Reactive transport models can help fill this gap by integrating an enormous amount of diverse information (physical, chemical, and biological data) into a unified rational framework. The simulation results can be used to construct reasonable qualitative arguments as to why certain processes or events can or cannot occur. However, it is important that we understand the limits of these tools and recognize that they are better viewed as computer-aided thinking tools rather than computer-aided prediction tools.

While critiquing the mathematical models used in sociology and economics, George Andrews, the current President of the American Mathematical Society, made the following statement (Andrews 1988): "Mathematics is not a mysterious substitute to educated common sense. When mathematics is abused—used in areas where measurements are extremely difficult or impossible—it is, at best, a nuisance and, at worst, a trick to disguise ulterior motives." If we simply replaced the word "mathematics" with "groundwater model," then these wise words would literally transform into a prophetic statement about groundwater modeling! Victor Baker, the former President of the Geological Society of America, said "allowing the public to believe that a problem can be resolved . . . through elegantly formulated . . . models is the moral equivalent of a lie" (Pilkey and Jarvis 2007, p. 188).

When debating the worthiness of hindcast modeling efforts that have direct implications on public policy, it is difficult to say whether it is a scientific debate or a moral debate. In such instances, it is perhaps worth reflecting upon some of the wise statements made by our scholarly peers. Such reflections might inspire us to raise a simple self-assessment question: Is this a worthy effort for developing a sound public-policy decision? It is extremely difficult to give an honest answer to this question, especially when personal interests are at stake. As scientists, we all suffer from some level of cognitive dissonance and have an uncanny ability to rationalize our futile efforts. However, we, the scientific community, owe an honest answer to our fellow citizens who put enormous faith in our abilities and fund us to explore the beauty of natural systems and their mystifying connection to mathematics. Also, I believe that such a self-assessment should provide the ultimate wisdom for understanding the worthiness of our scientific pursuits and would guide us when to say enough is enough. But I admit that accepting and acting upon this self-assessment is a lot easier said than done!

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EXHIBIT 31

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In a recent article, T.P. Clement (2010, hereafter referred to as TPC) discusses the complexities and limitations of "hindcasting" models and criticizes the use of complex models when undertaking investigations of subsurface reactive transport processes. TPC implies that complex numerical models that simulate reactive transport processes in groundwater are likely if not always an inappropriate tool to apply to "hindcasting" investigations and that scientists and engineers who implement these investigations using such models are somehow not aware of the technical and scientific complexities and limitations of such methods and approaches (p. 625). To illustrate his point of view, TPC uses a case study of an ongoing health study of exposure to volatile organic compounds (VOCs) in drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina (hereafter referred to as the case-control health study at Camp Lejeune). The article presents some thought-provoking points-of-view. However, we believe there is a lack of detail on several key issues that require specificity and clarification, particularly with respect to modeling approaches and methods, the physics of contaminant occurrence and reactive transport in the subsurface, and agency policies for the review and dissemination of data and reports. We thank the editors of *Ground Water* for allowing a multidisciplinary team

"Complexities in Hindcasting Models—When Should We Say Enough Is Enough," by T. Prabhakar Clement, v. 49, no. 5: 620–629.

Comment by Morris L. Maslia[1], Mustafa M. Aral[2], Robert E. Faye[3,4], Walter M. Grayman[5], René J. Suárez-Soto[6], Jason

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of scientists and engineers working on the Camp Lejeune case-control health study the opportunity to discuss and respond to the TPC *Ground Water* Issue Paper.

"Hindcasting" vs. Historical Reconstruction

TPC defines "hindcasting" as the use of models for predicting the past to understand and resolve historical problems (p. 621). This definition, we believe, is extremely narrow and does not address the significantly broader and multidisciplinary area of exposure assessment, which includes a variety of scientific disciplines such as environmental science, epidemiology, and toxicology. Rather, we believe a more correct term than "hindcasting" is that of *historical reconstruction*, which seeks to provide estimates of contaminant concentrations in drinking water (or other environmental media) when direct, past knowledge of contaminant concentrations is limited or unavailable. Characteristically, historical reconstruction includes the application of simulation tools, such as models, to re-create or represent past conditions. A plethora of examples that describe successful historical reconstruction analyses exist in the published literature (Rodenbeck and Maslia 1998; McLaren/Hart-ChemRisk 2000; Costas et al. 2002; Reif et al. 2003; Kopecky et al. 2004; Maslia et al. 2005; Sahmel et al. 2010). Application of historical reconstruction methods and approaches to the case-control health study at Camp Lejeune recognized and required the collective expertise of team members with diverse skills and knowledge and did not focus on one discipline, such as groundwater modeling, as implied in the TPC article.

Historical reconstruction, by definition, does not preclude the use of current or present-day sources of information. In fact, successful historical reconstruction utilizes all pertinent sources of information, historical, and present-day (Maslia et al. 2000; Sahmel et al. 2010). TPC also states there are unique issues and challenges related to "hindcasting efforts that use complex models" (p. 621), apparently because no present opportunity exists to collect historical data. He fails to mention that a calibrated "hindcasting" model can just as easily be applied to the simulation of future events as well as past conditions. In fact, whether a particular model simulates past events ("hindcasting") or future events (forecasting), generic issues related to model development, calibration, and analyses of uncertainty of results are similar for both models. The calibration of a model must either stand or fall on its own merits, without the benefit of future data collection that may be accomplished later in time or the lost opportunity for data collection previously foregone. At the time of calibration, when model results are provided to policy makers, a "hindcasting" model is *not* uniquely disadvantaged compared with a forecasting model just because model predictions are historical rather than latter in time. Few, if any, policy makers or the public would accept the premise that policy decisions must be delayed for several years or several decades to further validate an existing model when a decision must be forthcoming.

Application of "Complex" Models vs. "Simple" Models to Simulate Subsurface Reactive Processes

The Agency for Toxic Substances and Disease Registry (ATSDR) is directed by congressional mandate to perform specific functions concerning the effect on public health of hazardous substances in the environment—health studies being a specific example of this mandate (http://www.atsdr.cdc.gov/about/index.html). ATSDR seeks to advance the science of environmental public health by: (1) collecting, analyzing, and summarizing data related to environmental exposures and health and (2) conducting research to identify associations between environmental exposures and health risk. ATSDR's case-control health study and water-modeling investigations at Camp Lejeune include major components of data collection and analysis as well as research. To complete the health study at Camp Lejeune, ATSDR water-modeling investigations were tasked to determine (1) arrival date(s) of contaminants at water-supply wells; (2) mean monthly concentrations of contaminants arriving at base water treatment plants (WTPs) from individual wells; (3) mean monthly concentration of contaminants distributed to base housing areas; and (4) the reliability of and confidence in the simulated results (Maslia et al. 2007, 2009a, 2009b). ATSDR completed these tasks by applying the concept and methodology of *historical reconstruction*. These results are designed to provide epidemiologists with historical monthly concentrations of contaminants in drinking water at Camp Lejeune to evaluate the effects of exposure to contaminated water supplies with respect to specific birth defects (neural tube defects, cleft lip, and cleft palate) and childhood cancers (leukemia and non-Hodgkin's lymphoma).

TPC suggests that because of limited information and data and the complex nature of reactive transport processes in the subsurface, simpler models should be used. We point out, however, that simpler models will not necessarily reduce the level of uncertainty or meet project needs. It is our view that the most *appropriate* model(s) that can provide the needed information, rather than the simplest model, should be used. Thus, if a conceptually simpler model is an *appropriate* model that can meet the requirements of the Camp Lejeune case-control health study, we are in agreement that it should be applied during the historical reconstruction process. This approach is applied to all ATSDR water-modeling investigations. TPC further suggests that model complexity should be limited to a level consistent with a level of available data and invokes the notion of model parsimony or "Occam's razor" to support this point of view (p. 625). TPC's statement contradicts the fundamental precept of "Occam's razor" which, with respect to scientific thought and reasoning, requires that explanatory factors are not to be

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multiplied beyond necessity. Thus, selection of a "simple" or "complex" model to simulate reactive transport processes in groundwater, according to "Occam's razor," should be based on study objectives, not the "level" or availability of supporting data. Whether or not sufficient data are available to completely complement model development and calibration becomes apparent when a degree of uncertainty is assigned to simulation results.

With respect to reconstructing historical groundwater VOC concentrations at Camp Lejeune, "simple" models, by definition, probably imply the application of analytical fate and transport codes. Such "simple" models are limited to—among other limiting assumptions—uniform flow fields and constant velocities. Consequently, these analytical ("simple") models neither assess the transient aspects of water-supply well operations nor determine consecutive monthly contaminant concentrations in these wells—a goal and requirement of the case-control health study at Camp Lejeune.

While questioning ATSDR's historical reconstruction approach for not using "simple" models, TPC appears to contradict himself by implying that ATSDR's historical reconstruction analyses were not sufficiently complex to account for multiple competing biological-chemical processes (p. 625). After describing various complex research models that may address these complexities (e.g., incorporation of carbon limitations, modeling interactions between carbon and terminal electron acceptors), TPC concludes that such research models require extensive biochemical field data (p. 625). Thus, using "simple" models would probably always preclude consideration and simulation of complex biochemical degradation processes.

Correction and Clarification of Specific Contaminant Data Analyses and Modeling Issues

Objective of the Water-Modeling Effort

The TPC article implies that the objective for water modeling supporting the case-control health study at Camp Lejeune was for "policy-making" purposes, to advance the research interests (and funding) of the water modelers, or to satisfy politicians and citizens groups (p. 626). This is *not* the case. The water modeling was requested by ATSDR epidemiologists who required monthly drinking water contamination estimates to assess associations between in utero exposures by month and trimester and specific birth defects and childhood cancers. It is standard practice in epidemiological studies of adverse reproductive outcomes to assess exposures (whether environmental, occupational, or diet risk factors) at the monthly or trimester level (Rothman et al. 2008, 602-603).

Characterization of the Contaminant Source

TPC characterizes tetrachloroethylene (PCE) contamination in groundwater at the ABC One-Hour Cleaners site and at Tarawa Terrace base housing as a "free-phase" or "pure-phase" dense, nonaqueous-phase liquid [DNAPL (p. 5)]. This characterization directly contradicts and misrepresents field concentration data presented by Faye and Green (2007) and in other reports and documents (Shiver 1985; Weston 1992, 1994) that describe PCE and other contaminants in the subsurface in the vicinity of Tarawa Terrace and ABC One-Hour Cleaners. Those reports and documents unequivocally describe the PCE in groundwater in the vicinity of ABC One-Hour Cleaners as "dissolved-phase" PCE. As noted by Keuper and Davies (2009), assessing for the presence of DNAPL must be made using a weight-of-evidence approach with multiple lines of evidence combining to form either a positive or a negative determination. Using one groundwater sample point with a concentration of 12,000 µg/L (as TPC apparently does) and a solubility in excess of 150,000 µg/L (Pankow and Cherry 1996; Lawrence 2007; Clement 2011), does *not* constitute a weight-of-evidence approach for a positive determination for the presence of DNAPL in soil or groundwater at Tarawa Terrace and vicinity. Rather, the weight-of-evidence approach using all site data results in a negative determination for the presence of DNAPL. It is noteworthy that more than 100 soil-boring and 140 groundwater samples were collected in the immediate vicinity of the ABC One-Hour Cleaners at depths ranging from a few feet to more than 60 feet below land surface. These data, which were tabulated and described in detail by Faye and Green (2007, Figure E2, Tables E5 and E7), did not indicate any free-phase DNAPL. Thus, while the one data value cited by TPC (12,000 µg/L) may be indicative of a contaminant source, it is definitely not indicative of free-phase DNAPL at ABC One-Hour Cleaners and Tarawa Terrace and vicinity. Furthermore, in describing the disposal practices from the ABC One-Hour Cleaners, TPC states that free-phase PCE (DNAPL) was disposed into a septic tank (p. 624). What TPC did not state is that the cleaners also continuously discharged wash and wastewater to the septic tank, thereby continuously diluting the PCE (Faye and Green 2007).

The characterization by TPC of PCE in the vicinity of ABC One-Hour Cleaners as a DNAPL is further discredited by the process selected by government agencies to remediate the PCE contamination in the groundwater. Processes selected to remediate free-phase (DNAPL) PCE in groundwater are totally different from processes used to remediate dissolved-phase PCE in groundwater. The remediation process currently in progress at the ABC One-Hour Cleaners and at Tarawa Terrace is conducted under the auspices of the U.S. Environmental Protection Agency (USEPA) and was approved by the North Carolina Department of Environment and Natural Resources (NCDENR). This process is correctly described as "groundwater extraction by wells and treatment by air stripping"—pump-and-treat (NCDENR 2003; Weston Solutions Inc. 2005, 2007). This remediation process is appropriate only for dissolved-phase PCE—not for DNAPL PCE.

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Degradation Products of PCE

The biodegradation products of PCE are trichloroethylene (TCE), 1,1-dichloroethylene (1,1-DCE), *trans*- and *cis*-1,2-DCE, vinyl chloride, and ethene (Lawrence 2007; Wang and Aral 2008). As pointed out by TPC, our multispecies simulations using the TechFlowMP code did not consider *cis*-1,2-DCE as a degradation product. Although some scientific literature indicates that *cis*-1,2-DCE is the predominant product of TCE reduction under in situ groundwater conditions (NRC 2009, 49), the primary byproduct of the TCE bioreaction (biodegradation) highly depends on the chemical-biological conditions (especially microorganisms and nutrients) at contaminated sites (Bradley 2003), meaning that the biological degradation of TCE in the subsurface is highly site-specific. For example, Christiansen et al. (1997) and Miller et al. (2005) reported that the anaerobic biological degradation of TCE produced more *trans*-1,2-DCE than *cis*-1,2-DCE. At the TCE-contaminated site in Key West, Florida, the ratio of *trans*-1,2-DCE to *cis*-1,2-DCE was greater than 2 (SWMU9 2002). Griffin (2004) reported that the ratio could reach up to 3.5, based on field data for several sites, including Tahquamenon River, MI; Red Cedar River, MI; Pine River, MI; and Perfume River, Vietnam.

To calibrate reactive transport models at Tarawa Terrace and vicinity, limited field data regarding the concentrations of PCE, TCE, and *trans*-1,2-DCE were available and provided by Faye and Green (2007). TPC apparently ignored or was not aware of these data, although he frequently cites the reference by Faye and Green (2007) in the *Ground Water* article. Review of degradation byproduct data analyses, provided to ATSDR by the Department of the Navy, U.S. Marine Corps, the NCDENR, and others indicated that the predominant degradation byproduct of TCE at Tarawa Terrace and vicinity was *trans*-1,2-DCE (Faye and Green 2007, Tables E2 and E7). Because the primary byproduct of the biological degradation of TCE depends on site-specific conditions, selecting *trans*-1,2-DCE instead of *cis*-1,2-DCE as the primary TCE-bioreaction-byproduct in the study area was clearly the appropriate choice.

Model Calibration

The TPC article states that the Tarawa Terrace groundwater fate and transport model were calibrated to a limited number of data points, which are PCE levels measured in finished water samples collected in the early 1980s (p. 622). The fact is that a four-stage calibration process was used and compared with published field data at every calibration stage. Specifically, these four stages are (Maslia et al. 2007)

- Stage 1: a predevelopment calibration of the groundwater flow model, which compared simulated and measured predevelopment water levels in monitor wells (Faye and Valenzuela 2007, Figure C9),
- Stage 2: a transient calibration of the groundwater flow model, which compared simulated and transient water levels in monitor and supply wells (Faye and Valenzuela, Figures C10 through C17 and C20),
- Stage 3: a groundwater fate and transport model, which compared simulated and measured PCE concentrations in water-supply wells (Faye 2008, Table F13 and Figures F12 through F17), and
- Stage 4: a mixing model calibration, which compared computed and measured PCE concentrations in finished water at the Tarawa Terrace WTP (Maslia et al. 2007, Table A10 and Figure A12).

TPC also implies that reactive transport model results were presented without calibrating to degradation product field data (p. 622). Calibration field data were not presented by TPC in his Figure 3 (taken from Maslia et al. 2007, Figure A19). However, available field data used for calibration were presented by Faye and Green (2007) and were compared with simulation results in Jang and Aral (2008, Figures G6 and G10).

Research Models vs. Public Domain Codes

TPC (p. 622) states that ATSDR used an advanced research code TechFlowMP (Jang and Aral 2008) to predict (simulate) the concentration of PCE along with degradation products TCE, *trans*-1,2-DCE, and vinyl chloride and that applying research codes on high-visibility projects is not a good idea (p. 626). It is important to note that public-domain/open-source codes such as MODFLOW and MT3DMS were developed under the auspices of U.S. government-sponsored research programs and were once classified as "research codes." What then constitutes an acceptable model code, be it applied to a site of interest or a "high-profile site"? The answer may be found in Jakeman et al. (2006) who propose and describe 10 iterative steps in development and evaluation of environmental models. Thus, model validation (verification) should not be determined by the number of practitioners that use and apply a particular model (e.g., "consulting companies"), as implied by TPC (p. 626). Rather, models should be validated (verified) by following a consistent and defensible development protocol and comparing model predictions to known mathematical (analytical) solutions and site-specific field data when available. The TechFlowMP code was validated using just such a process. TechFlowMP is open-source and can be accessed through the website of the Multimedia Environmental Simulations Laboratory at Georgia Tech (http://mesl.ce.gatech.edu/). Additional application and testing of the code is welcomed and encouraged.

Note as well the use and application of specialized codes to address specific problems, including problems that routinely or commonly used codes do not or cannot address are not shunned by government-based scientific organizations, but rather it is recognized and encouraged (USEPA 2009). The point being that the most *appropriate* model should be applied to characterize a system, not necessarily, the most popular or frequently used model. This is the modeling philosophy and approach that

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ATSDR used when applying any of the models (including the TechFlowMP model) to simulate subsurface conditions at ABC One-Hour Cleaners and Tarawa Terrace and vicinity.

Uncertainty and Variability of Simulation Results

All modeling analyses have "inherent" uncertainties. ATSDR openly acknowledges this concept. Uncertainty is not limited solely to the historical reconstruction analyses of Tarawa Terrace as critiqued by the TPC article. Uncertainty is an inherent feature of all models even when useful data are plentiful. The "profound limitation" that seemed to so concern some in evaluating the ATSDR historical reconstruction analyses (NRC 2009, 50), should not be that uncertainties exist with respect to model results but that no effort is made to explain and quantify those uncertainties. In this respect, ATSDR has provided very detailed analyses of uncertainty pertinent to the Tarawa Terrace models (Maslia et al. 2007, 2009; Wang and Aral 2008).

Review and Dissemination of Water-Modeling Results

The TPC article implies that results of ATSDR's modeling analyses were going to be used in a decision-making process by the Department of Navy (DON). Therefore, some outside body [e.g., National Research Council (NRC)] had to be assigned the responsibility to assess the complexity of analyses being used and the impact of this complexity on time and resources. This premise is incorrect. ATSDR is a *public* health agency and part of our responsibility is the dissemination of information—technical and nontechnical—using a variety of communication methods (e.g., websites, reports, and meetings) to all interested parties and stakeholders, such as those listed by TPC (p. 622). The TPC article further states that reconstructed historical concentrations were "widely disseminated to various groups" (former Camp Lejeune residents, health scientists, and congressional committees) via websites, public meetings, and reports (p. 622). These statements imply that ATSDR somehow intentionally or unintentionally avoided a rigorous external peer review of its modeling approach, methodology, and results. The facts are that every chapter report published in the Tarawa Terrace historical reconstruction report series (available at http://www.atsdr.cdc.gov/sites/lejeune/index.html) underwent extensive external peer review (review comments and ATSDR responses can be produced by the project officer if needed). Authors completely addressed all external peer review comments; the majority of which were accepted by the authors and included in the final published reports.

In passing, we point out that the reference to Faye and Green (2007) cited by TPC (p. 622 and p. 628) is incorrect. Faye (2007) describes the geohdyrologic framework and Faye and Green (2007) describe the occurrence of contaminants in groundwater. We provide the correct citations in the References section.

Concluding Remarks

In the *Ground Water* article, TPC proposes the following idea: Should we go with a complex model or the expert opinion (simple model)? This implies there is no option but to choose one approach or the other. As engineers and scientists, we propose that applying and evaluating the results of several different approaches and types of models is often the best path. A good model will inherently include expert opinion because models are typically developed beginning with a simple conceptual model that is then transformed into a more complex model. We agree with Bredehoeft's opinion (2010) in that the model (simple or complex) is not an end in itself, but a tool by which to organize one's thinking and engineering judgment. In the case of the case-control health study at Camp Lejeune, models are powerful tools used to assist epidemiologists in facilitating the estimation of historical exposures during each month of the mother's pregnancy.

Finally, the *Ground Water* article states (p. 627) that the overall reaction to the NRC report (2009) was mixed. Similar to the TPC article, the NRC report contained numerous factual errors, incorrectly characterized the contaminant PCE source, and overlooked data (that ATSDR had inventoried, compiled, and published) and other pertinent epidemiological and toxicological issues that are beyond the scope of this discussion. Although the case-control health study at Camp Lejeune is a complex endeavor, ATSDR continues to maintain the scientific credibility and thoroughness of its analyses—from both the water-modeling and epidemiological perspectives—through the use of expert panels and external peer review. It is our aim that by addressing the complex issues associated with the process of historical reconstruction in this discussion, our colleagues who have developed and applied models solely in the groundwater modeling and remediation fields, will broaden their horizons and come to appreciate the need and usefulness of extending and incorporating modeling into the multidisciplinary field of exposure assessment science.

Disclaimers

The findings and conclusions in this Discussion article are those of the authors and do not necessarily represent the views of the ATSDR.

The use of trade names and commercial sources is for identification only and does not imply endorsement by the ATSDR.

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EXHIBIT 32

IN THE UNITED STATES DISTRICT COURT
FOR THE EASTERN DISTRICT OF NORTH CAROLINA
SOUTHERN DISTRICT
No. 7:23-CV-897

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IN RE: :
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CAMP LEJEUNE WATER LITIGATION :
: :
This Document Relates to: :
ALL CASES :
- - - - - - - - - - - - - - - - - - - -X

Videotaped deposition of Mustafa Mehmet Aral, taken at the offices of Weitz & Luxenberg, 700 Broadway, New York, New York, before Clifford Edwards, Certified Shorthand Reporter and Notary Public, in and for the State of New York on Thursday, February 6, 2025, at 9:02 a.m. EST.

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ON BEHALF OF THE U.S. DEPARTMENT OF JUSTICE:

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A P P E A R A N C E S:
(continued)

ALSO PRESENT:
Ingrid Rodriguez, videographer

VIA ZOOM:
Alex Spiliotopoulos (via Zoom)
Bill Williams (via Zoom)
Corissa O'Neill (via Zoom)
Deanna Havai (via Zoom)
Dennis Reich (via Zoom)
Ed Bell (via Zoom)
Morris Maslia (via Zoom)
Giovanni Antonucci, DOJ (via Zoom)
Haroon Anwar, DOJ (via Zoom)
Kailey Silverstein, DOJ (via Zoom)

EXAMINATION

EXHIBITS

EXHIBITS

(continued)

EXHIBITS

(continued)

(Reporter's Note: Exhibits retained by the court reporter and forwarded to Golkow for production.)

THE VIDEOGRAPHER: We are now on the record.

My name is Ingrid Rodriguez. I'm a videographer for Golkow Litigation Services.

Today's date is February 6, 2025, and the time is 9:03 a.m. This video deposition is being held at Weitz & Luxenberg, in New York, New York, in the matter of In Re: Camp Lejeune Water Litigation in the United States District Court for the Eastern District of North Carolina.

The deponent is Professor Mustafa Aral.

Would counsel please state your appearances for the record?

MS. O'LEARY: Allison O'Leary for the Department of Justice.

MS. HORAN: Alana Horan for Department of Justice.

MR. DEAN: Good morning. Kevin Dean here on behalf of the plaintiffs.

MS. BAUGHMAN: Laura Baughman for the plaintiffs.

MS. BOLTON: Devin Bolton for the plaintiffs.

THE VIDEOGRAPHER: And on Zoom, I have "Alex Spiliotopoulos," "Bill Williams," "Corissa O'Neill," "Deanna Havai," "Dennis Reich," someone who's just "Ed."

MR. DEAN: Ed Bell.

THE VIDEOGRAPHER: Okay.

MR. BELL: Ed Bell.

THE VIDEOGRAPHER: "Giovanni Antonucci," "Haroon Anwar," "Kailey Silverstein," and "Morris Maslia."

The court reporter is Cliff Edwards and will now swear in the witness.

MUSTAFA MEHMET ARAL,

having first been duly sworn, deposed and testified as follows:

(Whereupon, there was a discussion off the record.)

COURT REPORTER: All set. Thank you.

DIRECT EXAMINATION

BY MS. O'LEARY:

Q I'm Allison O'Leary and I'm an attorney for the U.S. Department of Justice. Thank you for being here this morning.

I have a few, just kind of, logistics points to go over with you.

So if you don't understand a question, you can ask me to clarify. Can you do that?

A Sure.

Q And do you understand that the court reporter here is transcribing what you are saying today?

A Yes.

Q And do you understand that the videographer is also recording your deposition today?

A Yes.

Q Do you understand that your testimony in today's deposition could be used in court?

A Yes.

Q And do you understand that you are under oath to testify truthfully?

A Yes.

Q Okay. Is there anything today that is impeding your ability to testify?
A No.
Q Did you do anything to prepare for today's deposition?
A We had a meeting yesterday.
Q When you say "we," are you re-referring --
A These three attorneys on this side.
Q Okay. So you are indicating the plaintiffs' attorneys?
A Excuse me?
Q You are -- you are indicating the plaintiffs' attorneys?
A Yeah. Yeah.
Q Okay.
A Of course.
Q And did you review any documents to prepare for today?
A From yesterday to today or early --
Q No, just in general.
To prepare for today's deposition, did you review any --
A Yeah. I --
Q -- documents --

A -- reviewed my expert's report.
Q Your report?
Did you review any other expert reports?
A Much earlier --
Q Okay.
A -- than two days.
Q Much earlier?
What other reports did you review?
A Probably in -- last month.
Q Okay. Which reports did you review last month?
A Okay. I have reviewed Dr. Konikow's report, Dr. Sabatini's report, I have reviewed Alex Spiliotopoulos' report, I have -- I have reviewed Dr. Hennat's report, Morris Maslia's report, Morris Maslia's deposition.
I don't remember the name but there's a historian expert on the -- the -- the government side. I didn't review that because that's a historical review. It's not my area.
I believe that's it.
Q Okay. And you said you'd reviewed Morris Maslia's deposition; is that right?
A Yeah.
Q Was that his deposition from 2024?

A I think -- let's see.
No. No. It's a -- did I say a deposition?
Q I thought you had said the transcript from Morris Maslia's deposition?
A I read Morris Maslia's rebuttal report --
Q Oh, rebuttal report?
A Right.
Q Okay.
A I -- I was mistaken on that. And I read his expert report.
Q Okay. Thank you for clarifying. You mentioned you had reviewed reports.
Is there anything from your report in this case that you'd like to correct?
A No.
Q Okay. Did you review any reports by Norman Jones and Jeffrey Davis?
A Oh, yes. That's the post audit --
Q Okay.
A -- study.
Yes, I did review that.
Q Did you read the rebuttal report and the original report by Norman Jones and Jeffrey --
A Yes.

Q -- Davis?
A Both of them.
Q Okay. And am I correct that the only report you prepared in this is the report that came out last fall in --
A Yes.
Q -- 2024?
A The expert report.
Q Okay. So do I understand correctly that you are not offering opinions on Dr. Konikow's or Dr. Sabatini's rebuttal reports?
A No. I mean, I didn't write a rebuttal report to their --
Q Okay.
A -- expert report.
Q Okay. So you have not offered a -- a rebuttal report?
A No. No.
MS. O'LEARY: And can we get number eight?
I'm sorry. There will be a little delay as we pull out documents --
THE WITNESS: Okay.
MS. O'LEARY: -- and get them marked.

THE WITNESS: Okay.

(Whereupon, there was a discussion off the record.)

(Whereupon, Government's Exhibit Aral 1, Résumé of Professor Aral, was marked for identification.)

BY MS. O'LEARY:

Q Professor Aral, I've handed you what's marked as --

A Can you speak a little bit --

Q Yeah.

A -- louder?

Q I'm sorry.

A Okay.

Q Professor Aral, I've happened you what's been marked as Government Exhibit 1.

Do you recognize this document?

A It looks like my résumé.

Q Okay. Is there anything on this résumé -- on this résumé that you'd like to correct?

A No.

Q Okay. And do I understand correctly that you were approached about serving as an expert in this Camp Lejeune Justice Act litigation by Morris Maslia?

A No. By Kevin.
Q Oh, by Kevin.
Kevin Dean?
A Yeah, Kevin Dean.
Q When was that?
A Probably two years ago, maybe. I'm not sure.
Q Okay. Why did you decide to --
A The -- the reason I think you mentioned Morris Maslia is that Morris Maslia introduced me to Kevin.
Q Oh, okay. I understand.
A Okay.
Q Thank you. And why did you decide to serve as an expert in the Camp Lejeune Justice Act litigation?
A Well, because I did a lot of work at Camp Lejeune.
Q Okay. Are there any other reasons why you decided to serve as an expert?
A No.
No.
Q No? Okay.
And am I correct that you've been retained, specifically, by the Bell Legal Group?

A Yes. My contract with -- is with the Bell --
Q Okay. And did --
A -- Group.
Q -- that contract begin in August of 2022?
A Probably.
Q Prob- -- okay.
Prior to that contract beginning with Bell Legal Group, had you communicated, either verbally or through writing like e-mail, with anyone from the Bell Legal Group?
A No.
Q Had you communicated prior to being retained by the Bell Legal Group with anyone from Motley Rice?
A No. No.
Q And prior to being retained by the Bell Legal Group, had you communicated with any attorney related to Camp Lejeune?
A No.
Q Okay.
A As far as I know -- I mean, I have attended expert panels. They may be there. I may have exchanged some ideas.
I'm not sure.

Q Okay. You don't recall --
A No --
Q -- specifically?
A -- I don't recall.
Q Prior to being retained by the Bell Legal Group in the Camp Lejeune Justice Act litigation, did you have any communications with a man named Mike Partain related to Camp Lejeune?
A I think I communicated with -- not communicated but talked to him in year 2005, maybe.
Q Where was it that you spoke to him?
A Expert panels.
Q And what did you speak to Mike Partain about?
A I don't recall.
Q After the 2005 expert panel, had you communicated with Mike Partain again prior to being retained by the Bell Legal Group?
A No.
Q And prior to being retained by the Bell Legal Group, did you communicate with a person named Terry Dyer about anything related to Camp Lejeune?
A Terry Dyer?
Q Yes.
A No.

Q Have you ever communicated with United States Senate or House of Representative members related to Camp Lejeune?
A No.
Q And have you ever communicated with Dr. Frank Bove about Camp Lejeune?
A Yes.
Q And in what sorts of contexts?
A Again, expert panels, some meetings probably at the ATSDR starting from 2005.
Q Okay.
A But when you say "communication," this is verbal, meeting communications, not e-mails, etc. I don't --
Q No, I mean both.
Like --
A You mean both? Okay.
Q Yeah. So does that change your answer --
A I may --
Q -- for Mike Partain?
A I may have received e-mails from ATSDR, which included his name as well.
Q Included --
A Frank --
Q -- Mike Partain?

A No. No.
Frank Bove.
Q Frank Bove?
A Frank Bove.
Q Okay.
A Yeah.
Q So you may have had e-mails with Frank Bove?
A Yeah. Not personally exchanging e-mails but if they send e-mail to group of people, I may be included into that e-mail.
Q Okay. Did you ever specifically e-mail Dr. Frank Bove?
A No.
Q Okay. And did he ever send you personally an e-mail from --
A I don't recall.
Q Okay. And I understand that you were the director of the Multimedia Environmental Simulations Laboratory at Georgia Tech at some point, is that correct?
A That's correct.
Q And were the years that you were the director 1993 to 2018?
A That's correct.

Q And how do you usually refer to the Multimedia Environmental Simulations Laboratory?
A It's a reser- -- research center at --
Q Do you call --
A -- Georgia --
Q I'm sorry. Go ahead.
A Yeah.
-- at Georgia Tech.
Yeah.
Q Do you call it MESL or M-E-S-L?
A Yeah. MESL.
Q MESL?
A Yeah.
Q And you said it's a research center?
A Yes.
Q Can you explain what area of research it works on?
A Groundwater modeling, surface water modeling, model development, applications off these models in different areas.
Q Is it -- are there anything else it works on?
A Can you repeat that --
Q Yeah.
A -- please?

Q Is there any -- are there any other areas where the MESL works?

A It depends on what type of projects we had during this period. I think we had a project on coastal issues at Georgia. I think we had issue -- or a NSF grant to facilitate a conference related to our studies.

Several other projects may be included in it, which is outside the area of groundwater modeling.

Q And is the MESL still operating?

A I don't think so.

Q Okay. When you were the director -- so 20- -- excuse me -- 1993 to 2018, how many people worked in MESL?

A I had about 25 Ph.D. students; they were all in there. I had -- I had about 60 master's students; they came in and went out during their master programs.

As a faculty member, I was the only one.

Q Okay. And you said about 25 Ph.D. students. Do you mean --

A That's right.

Q -- at once or during the time --

A Oh, during the --

Q -- you were the director?
A -- the time. It takes about five years to get the Ph.D.
Q And for the -- about 60 master's students --
A Yup.
Q -- is that at once or through time?
A Oh, through time. Of course.
Q Okay. Did any other professors work with MESL --
A I answered --
Q -- at a --
A -- that --
Q -- part-time --
(Whereupon, the court reporter requests clarification.)
BY MS. O'LEARY:
Q Yeah. Did any other professors work at MESL on a part-time basis?
A No.
Q Okay. And then I understand you became professor emeritus in 2018, is that right?
A Emeritus.
Q Emeritus?
A Yes.

Q Okay. And what is an emeritus professor?
A A retired professor.
Q Do you teach anything now?
A No.
Q When did you last teach?
A Retired 2019, went to Turkey. I taught there.
Probably 2020. In that range, yeah.
Q Around --
A I was --
Q -- 2000 --
A -- a professor there.
Q At -- did I understand that was not at Georgia Tech?
A No, it wasn't at Georgia Tech, it was in Turkey.
Q Okay. Do you currently supervise any graduate students?
A No.
Q And do you currently do any research?
A Yes.
Q Okay. What types of research do you do now?
A That's like a hobby for me. I do population analysis. I do model development in

different areas. A lot simpler models, but still research. Yeah.

Q Models related to geohydrology?

A Not really. Different areas.

Q Oh. What sorts of areas?

A Population --

Q Oh.

A -- topics.

Q Okay. I understand.

How else do you spend your time now?

A I walk a lot, I exercise a little bit, I visit my grandchildren. That's my total exposure to what I do here in New York, especially.

Q And I'm sorry, I didn't hear the last part?

A I am here in New York to visit my grandson.

Q Oh, okay.

A I live in Turkey most of the time. I live in Atlanta when I visit friends and other relatives in Atlanta.

Q And what city do you live in in Turkey when you are there?

A Istanbul.

Q Istanbul.

What are your income sources in retirement?

A My income?

Q Yeah. What are the sources of your income in retirement?

A Oh, retirement benefits from Georgia Tech.

Q Any others?

A I am paid by this task for Camp Lejeune.

MS. O'LEARY: Okay. And I have a few questions about your report.

So this will Be 33.

So just a minute again as we pull out the exhibit.

THE WITNESS: Uh-huh.

(Whereupon, there was a discussion off the record.)

(Whereupon, Government's Exhibit Aral 2, Report by Professor Aral, was marked for identification.)

BY MS. O'LEARY:

Q And one last question, going back to what your current research that you do on population.

What is the purpose of the research you do on population?

A My interest is general. It covers a lot of areas and that's one of my research interests.

And I do population research, meaning how does the population change, what is the transition from one country to the other, immigration/migration and all that. And I do that in mathematical analysis.

Q Okay. And why is that of interest to you?

A Because I have general interests in many topics.

Q Okay. So if you could go to the fourth page of your report, which is Government Exhibit 2?

A Okay.

Q Do you see a paragraph underneath the bullet points that starts, "Around the year 2000, the Multimedia Environmental Simulations Laboratory, MESL, a research center at the School of Civil and Environmental Engineering, Georgia Institute of Technology, entered into a cooperative agreement with the Agency for Toxic Substances and Disease Registry, ATSDR, Centers for Disease Control and Prevention, CDC, to provide technical support to ATSDR in all aspects of the Camp Lejeune study for all three study areas on an as-needed basis."

Did I read that correctly?
A Yeah.
Q So if that was in 2000, does that mean that when MESL started working with the ATSDR, the ATSDR's water models for Tarawa Terrace and Hadnot Point were not --
MR. DEAN: Also --
BY MS. O'LEARY:
Q -- yet complete?
MR. DEAN: Object to the form.
BY MS. O'LEARY:
Q Did you understand my question, Professor Aral?
A I think you didn't finish your question --
Q Let me -- I'll say it again.
MS. BAUGHMAN: I think it would be good if you would speak a little louder.
THE WITNESS: Yeah.
MS. BAUGHMAN: I don't think he can hear you.
THE WITNESS: Yeah. It --
BY MS. O'LEARY:
Q Sure. Yeah.
A I would prefer --

Q I'll try to --
A -- that, yeah.
Q So that section I just read --
A Yeah.
Q -- from --
A Yeah.
Q -- page four of your report, it says that MESL entered into the agreement with ATSDR in 2000.
MR. DEAN: Object to the form. That's not what the document says.
BY MS. O'LEARY:
Q Is that correct?
MR. DEAN: It says "around."
MS. O'LEARY: That's --
MR. DEAN: Okay.
MS. O'LEARY: -- that's fine, we can make it --
THE WITNESS: Yeah.
MS. O'LEARY: -- around.
Is it --
MR. DEAN: I just want you to understand what I'm -- it's not a -- I'm not trying to interfere, but I'm just objecting to the form because that's --
MS. O'LEARY: Yeah.

MR. DEAN: You said "in 2000," that's --

MS. O'LEARY: Yeah.

MR. DEAN: -- not what it says.

MS. O'LEARY: I understand. That's fair.

THE WITNESS: Okay.

BY MS. O'LEARY:

Q So Professor Aral, is it around 2000 that MESL entered into an agreement with ATSDR?

A Yes. The agreement was around 2000, yeah.

Q Okay. So does that mean when MESL entered into the agreement with the ATSDR, the ATSDR's models for Tarawa Terrace and the Hadnot Point-Holcomb Boulevard area were not yet complete?

A No, of course not.

Q Meaning they were -- it's true they were not yet complete?

A They were not completed, yeah.

Q Okay. And is it true that no other Georgia Tech faculty were part of the cooperative agreement between MESL and the ATSDR?

A There's no other faculty involved.

Q Did the MESL enter into cooperative

agreements with any other entities besides the ATSDR?

A Of course. Many.

Q Okay. What was the scope of those agreements with other entities?

A Other research topics, which is summarized in my résumé.

Q Okay. Other than in the work you did with the ATSDR on Camp Lejeune, have you ever been asked in a cooperative agreement to calculate historic contaminant levels on a monthly basis?

A That was the purpose of our modeling, overall.

Q You mean at -- at Camp Lejeune that was the purpose?

A Yeah, at Camp Lejeune.

Q Yeah?

A Yeah.

Q So other than at Camp Lejeune, did the MESL ever work on projects that were calculating historic contaminant levels on a monthly basis?

A We had several models which used different time frames, different time intervals. Some of them may be monthly, yeah.

Q Okay. Do you recall any that were --

A I don't recall.
Q -- monthly?
A No.
Q Do you recall any that were shorter time frames than monthly?
A Yeah, of course.
Q What's an example of one that was a shorter time frame?
A Surface water modeling that we did. We may have used shorter time frames.
Q Surface modeling of what?
A I think that was a coastal aquifer around Savannah, I believe.
Q And who was requesting that coastal aquifer modeling around Savannah?
A That was the research center at University of Georgia.
Q And what was the timescale on the model?
A I don't recall exactly but we may have used different timescales to answer different questions.
Q What was the purpose of that model?
A It's a contaminant transport analysis.
Q But why did they want to know about the --

A No.
Q -- contaminate --
A We wrote --
Q -- transport?
A -- a proposal to develop a model, a generic model in a coastal application, and they agreed to fund it.
Q Right. And what were they using it for?
A I have no idea.
Q Okay. And was that a historical model?
A It's a groundwater model. A research center proposes a topic --
Q Uh-huh.
A -- to a funding agency. If they like it, they approve it; if they don't like it, they reject it.
Q And what you proposed, was that to do a -- a model that would look at times in the past or look at going forward?
A No. It was a generic model. It can be used for the time in the past and future predictions.
Q Okay. Do you know if it was going to be used for past predictions?
A I don't know what they have used it

for --
Q Okay.
A -- but it's a generic model.
Q Uh-huh.
A It can be used.
Q You can run it forwards or backwards --
A Yeah.
Q -- is that what you mean?
A Yeah.
I don't know what you mean, by the way, "backwards."
Q I mean, to estimate things that happened in the past.
A Starting from today going backwards, is that what you mean?
Q I mean, starting from whenever the model is calibrated to.
A Okay.
Yeah, it can be used --
Q To go --
A -- for that purpose --
Q -- in the --
A Yeah.
Q I'm sorry. I just --
A To predict -- it can be used to predict

historical behavior or future behavior.

Q From the time of calibration?

A Yup.

Q Okay. But for the coastal aquifer surface modeling project, you don't know if it was going to be used for going backwards from the time of calibration or forwards?

A I don't know what they have used it for.

Q Other than your work in Camp Lejeune, were you ever asked to calculate contaminate levels more than 25 years before the time the -- of calibration of the model?

A No.

Q Other than at Camp Lejeune, have you ever been asked to model all of mass loading, groundwater flow, contaminant fate and transport, and variable multiwell pumping mixing models?

A In several research applications we have worked at MESL, all of those models were developed or applied in -- in an integrated manner or a application of each model, separately. Two different ways.

Q I'm not sure I understand.

So are you saying that all of those types of models have been done at MESL at some time?

A No. We use generic models as well, coming from other sources.

Q But did -- did the mass loading, groundwater flow, contaminant fate and transport, and variable multiwell pumping mixing models that MESL did, were those done together in one project or were those used in --

A Oh, no.

Q -- individually or --

A If you -- if you are referring to TechFlowMP, for example, that's a generic model we have developed --

Q Uh-huh.

A -- for use in different projects, not for Camp Lejeune. But we used it for Camp Lejeune as well.

Q And had -- in any other projects, not Camp Lejeune so other projects -- have you used TechFlowMP in combination with modeling mass loading and groundwater flow and, like, a well pumping mixture model?

MR. DEAN: Object to the form of the question.

A TechFlowMP is a generic model which starts from groundwater modeling --

BY MS. O'LEARY:
Q Uh-huh.
A -- all the way to contaminant transport modeling, within itself.
Q But it doesn't involve mixing, is that correct?
A What do you mean by mixing?
Q Like, mixing of multiple wells, that's not a part of TechFlowMP.
A Why shouldn't it? It will, of course.
Q How does TechFlowMP model well mixing?
A Well, because you have -- in an area you have water supply wells. You put them into the model as a discharging point or a source point --
Q Uh-huh.
A -- and the whole thing is integrated in a single application.
Q But doesn't TechFlowMP model the contaminant movement to the wells, not the mixing of the wells?
A Oh, you are talking about mixing of the wells in a water treatment plant --
Q That's right.
A -- is that right?
Q That's right.

A Okay. Let's clarify that.
Q Okay. So --
A So what is your question?
Q So TechFlowMP does not model, like, mixing of wells in a water treatment plant?
A No, it does not.
Q All right. Other than at Camp Lejeune, have you done any other projects where what MESL was doing was using TechFlowMP coupled with something to model mixing in a water treatment plant?
A Not a water treatment plant.
Q Was it used in conjunction with something other than a water treatment plant?
A Yeah. We -- we used it in an application, like how to treat contaminated sites.
Q Like a remediation project?
A Yeah. As a remediation project.
Q Okay. And am I correct that you have not tested --
A Please speak louder.
Q I'm sorry.
Am I correct that you have not testified or been deposed in the last four years?
A That's correct.
Q Have you ever been deposed before?

A No.
Q Have you ever testified at a trial?
A Can you speak louder, please?
Q I'm sorry.
MS. BAUGHMAN: You are not speaking louder. You keep speak --
MS. O'LEARY: Yeah.
THE WITNESS: You have a very --
MS. O'LEARY: Well --
THE WITNESS: -- soft voice.
MS. BAUGHMAN: He can't hear you.
MS. O'LEARY: So can you hear me, ma'am?
THE VIDEOGRAPHER: I can --
MS. O'LEARY: Can you hear me, Mr. Court Reporter?
COURT REPORTER: Sorry?
MS. O'LEARY: Can you hear me?
COURT REPORTER: Sure.
MS. O'LEARY: I'll try and speak louder but it seems that my voice is coming through.
MR. DEAN: Because you have a --
MS. BAUGHMAN: He doesn't have the same hearing level, okay? He's retired.

MS. O'LEARY: Yeah.

MS. BAUGHMAN: You need to speak louder.

BY MS. O'LEARY:

Q So have you ever testified in a trial?

A No.

Q Have you ever testified in any other setting?

A Not a setting like this.

Q Like a --

A Not --

Q -- a deposition?

A -- not --

Like a deposition, no.

Q Have you testified in some setting that's different than this?

A Yeah. We had a face-to-face dialogue with a opposing expert and me on the other side.

Q In what case are you talking about?

A I'm talking about Atlanta Gas Light pollution problem.

Q Okay. And when was that face-to-face?

A I don't recall exactly but it must be late 1990s.

Q And were you an expert for one of the

sides in that Atlan- -- Atlanta Gas Light pollution problem?

A I was one of the experts on the other side of the Atlanta Gas Light pollution problem or --

Q Who is on the other side? I'm not sure what you mean.

A Some law firm hired me to question the work done at the Atlanta Gas Light site.

Q Okay. And then you had a sitdown with the expert from the --

A Right.

Q -- Atlanta Gas Light site?

A Exactly.

Q Okay. Other than that Atlanta Gas Light site, have you ever served as an expert before for some sort of dispute?

A Not for a dispute but I served for expert -- as an expert in other studies.

Q What does it mean to serve as an expert in other studies?

A A consulting company comes and asks me as to what I think about this and that related to environmental pollution. It doesn't have to be groundwater. I offer my opinion --

Q Uh-huh.
A -- and that's a expert opinion.
Q Okay. And when was the last time you did that sort of consulting?
A Probably it was my work with Geosyntec. I don't recall the time, it's in my résumé.
Q And you said Geosyntec?
A Yeah, Geosyntec.
Q All right. Do you have any family members who filed claims under the Camp Lejeune Justice Act?
A No.
Q And do you have any acquaintances who have filed claims under the Camp Lejeune Justice Act?
A No.
Q Huh. And you can turn back to the same exhibit, so this is Government Exhibit 2, to page 49.
A Yes.
Q And in the last paragraph, so near the bottom of the page --
MR. DEAN: What page are you on?
MS. O'LEARY: Forty-nine.

BY MS. O'LEARY:

Q The last paragraph, do you see where it says, "It is important to note that the review comments I am providing below are only associated with the water-modeling aspects of the ATSDR health study and the NRC report and do not cover any epidemiologic study aspects since those topics are outside my ar- -- expertise areas."

Did I read that correctly?

A Yes.

Q Is that accurate that epidemiologic studies are outside your expertise areas?

A That's correct.

Q Does it follow that the level of detail on exposure data needed for an epidemiological case control study is not within your area of expertise?

MR. DEAN: Object to the form.

A Yes. I -- I don't know what they would need.

BY MS. O'LEARY:

Q Okay.

A I'm told what I should do, so I do it.

Q And is it accurate then that the level of detail on contaminant exposure to an individual needed to render an opinion on causation from

contaminant exposure is not within your area of expertise?

A It's not. It's not within my area.

Q Okay. And do you agree that you are not an expert on whether a contaminant can cause a disease?

A I think you have to clarify that question.

Q Is that something that you render -- have ever, like, done consulting opinions on, on whether a contaminant can cause a disease?

A No, I did not.

Q And is that something that your university training study was -- was whether contaminants can cause a disease?

A That's a generic question, "contaminants." I'm not going to respond to that.

Q Well, do you study whether certain chemical compounds cause diseases?

A All foreign environmental contaminants will have some adverse effects on human health.

Q And how do you know that?

A Well, that's -- in terms of the literature that I have reviewed, in terms of the research work that I have done, that information was

made available to me.
Q So that's something you know from reading literature?
A That's right.
Q Okay. Have you ever studied epidemiology?
A No.
Q Your report, Government Exhibit 2, discusses maximum contaminant levels or MCLs. Do you know what I'm talking about?
A Yeah.
Q And do you understand that maximum contaminant levels are set by the Environmental Protection Agency, the EPA?
A That's correct.
Q Have you ever been involved in the setting of an MCL?
A No.
Q Are you familiar with the methodology that the EPA uses to establish MCLs?
A No.
Q Are you familiar with how MCLs are related to health risk?
A No.
Q Why did you discuss MCLs in your report

in this litigation?
A Because that was the criteria set by ATSDR.
Q So ATSDR asked you to consider MCL levels in the water modeling?
A I didn't consider MCL levels. I just predicted a continuous contaminant transport. Whether it's higher or lower, that was decided by ATSDR, right?
Q Higher or lower than --
A MCL.
Q -- like an MCL?
Okay.
A Right.
Q I understand, I think.
And am I correct that for your work on the Camp Lejeune Justice Act, you've been paid $600 per hour?
A That's correct.
Q How many hours, approximately, have you worked on the Camp Lejeune Justice Act litigation?
A I have to check my billing.
Q Do you think it's more than 50?
MR. DEAN: Object to the form.
You have the invoices.

BY MS. O'LEARY:
Q Do you think it's more than 50 hours?
A Probably. I don't --
Q Okay.
A -- recall.
Q Do you think it's more than a hundred hours?
MR. DEAN: Object to the form.
A I don't recall.
BY MS. O'LEARY:
Q You don't recall? Okay.
Do you know -- sorry.
Have you received any compensation related to the Camp Lejeune Justice Act other than your work as an expert witness?
A From?
Q Well, from any source? So other than your work as an expert witness.
A A -- A -- ATSDR funded the corporate agreement --
Q And --
A -- but I didn't get personal income from that, Georgia Tech did.
Q So when you were working at MESL on Camp Lejeune, was your salary paid by Georgia Tech?

A Repeat that, please?
Q When you were working on Camp Lejeune water modeling --
A Right.
Q -- at MESL --
A Right.
Q -- was your salary paid by Georgia Tech?
A My salary was, of course, paid by Georgia Tech.
Q Did the ATSDR fund MESL's work on Camp Lejeune?
A That's correct.
Q Okay. Are you familiar with a -- a text by Dougherty (phonetic) from 2015?
A Which text?
Q The one from 2015?
A I'm sure he has written many texts.
Q Okay. Is Dor- -- does Dougherty have a good reputation in the fields you work in?
MR. DEAN: Object to the form of the question.
A I don't recall who Dougherty is.
Does he have a first name?
BY MS. O'LEARY:
Q Are you familiar with Panko and Cherry

(phonetic)?
A Yeah.
Q All right. Their 1996 text, is it considered a reliable authority in your field?
A As good as any other reference textbooks.
Q Okay. So I have some -- a few questions about the extent of your involvement in the ATSDR's water modeling.
A Right.
Q But I just wanted to see, would you like to take a break or are you okay to keep going?
A I'm okay.
Q All right.

MS. O'LEARY: So if we could get -- that would be 56.

So this will end up being Government Exhibit 3.

(Whereupon, Government's Exhibit Aral 3, Tarawa Terrace Chapter A Report, was marked for identification.)

BY MS. O'LEARY:
Q And Professor Aral, if you could go to the page that's numbered A6 in the -- it will be in the bottom left?

All right. Do you see a table that says,

"Table A2, Summary of ATSDR Chapter Reports" --
A Uh-huh.
Q -- at the top?
Okay. And am I understanding correctly that table A2 lists the chapter reports from the ATSDR water modeling on Tarawa Terrace?
A Yeah. These are the --
Q Okay. And --
A -- reports, yeah.
Q -- as I look at this table, it looks like you authored -- you are an author on chapter A, "Summary of Findings"; chapter G, "Simulation of Three-dimensional Multispecies Multiphase Mass Transport of Tetrachlorethylene and Associated Degradation Byproducts"; chapter H, on "The Effect of Groundwater Pumping Schedule Variation on Arrival of Tetrachlorethylene at Water Supply Wells at the Water Treatment Plant"; chapter I, "Parameter Sensitivity Uncertainty and Variability Associated with Model Simulations of Groundwater Flow Contaminant Fate and Transport" --
(Whereupon, the court reporter requests clarification.)
BY MS. O'LEARY:
Q -- "and Distribution of Drinking water."

And then Chapter K, "Supplemental Information."

Is that correct that those are the only chapters you authored on the ATSDR reports?

A I didn't author, I contributed to them.

Q Okay. So I see on table A2, that you are listed as an author for those ones. What is the difference to you between contributing to a report and being an author?

A There are several other names, probably. The names that I see, for example, in G --

Q Uh-huh.

A -- it's a -- a graduate student of mine and me.

Q All right. So you both --

A So we --

Q -- wrote that?

A -- we both contributed to that.

Q Okay. And what role if any did you have in writing or reviewing the other chapters from table A2 where you are not listed as an author?

A Probably I have looked at them, reviewed --

Q What do you mean, you looked at them?

A Reviewed them.

Q And reviewed them for what purpose?
A For my understanding of what they are doing.
Q Okay. Did you offer comments on chapters you did not author -- you are not listed as an author on this table?
A I don't recall but I could have.
Q Okay. And --
MR. DEAN: For correction of the record, chapter K was never issued or published.
BY MS. O'LEARY:
Q So Professor Aral, what was Morris Maslia's role in the Tarawa Terrace water modeling project for ATSDR?
A He was the lead person at exposure of those reconstruction -- reconstruction program at ATSDR.
Q Okay. And were you happy with the performance of the team working on the Tarawa Terrace modeling at ATSDR?
A Yes.
MR. DEAN: Object to the form.
A Yes.

BY MS. O'LEARY:

Q And did you have any role on chapter J, "Field Test Data Analysis and Simulation of the Distribution of Drinking Water"?

A I think that's the least contribution that I had in any of these reports.

Q Was chapter J?

A Yeah.

Q Were you involved in data collection for the Tarawa Terrace water modeling?

A No.

Q Okay. Why were you not involved?

A Because they didn't ask me. I didn't go to the site, that's why.

Q Were you involved in field test design?

A No.

Q And have you been to Camp Lejeune?

A No.

Q And just one question about chapter K that Mr. Dean brought up.

Do you consider that chapter finished?

MR. DEAN: Object to the form of the question.

The chapter was never issued.

A I -- I don't recall that chapter at all.

MS. O'LEARY: Okay. And you can set aside Exhibit 3 for a moment and we are going to pull out -- this is 42.

That will be exhibit -- Government Exhibit 4.

(Whereupon, Government's Exhibit Aral 4, Document, was marked for identification.)

THE WITNESS: Uh-huh.

BY MS. O'LEARY:

Q And Professor Aral, if you could go to page A4?

A Eighty-four?

Q A4.

MR. DEAN: A4.

A A4?

BY MS. O'LEARY:

Q "A," as in chapter A.

A Yes.

Q All right. Do you see, starting on A4 and going onto page A5, table A1, summary of ATSDR chapter reports and supplemental information sections for the Hadnot Point-Holcomb Boulevard study area?

A Yup.

Q Okay. And looking at this table, it seems to show that you -- you are listed as an author for chapter A, "Summary and Findings"; sup- -- I guess it's chapter A, supplement two, "Development and application of a methodology to characterize present day and historical water supply well operations"; supplement five, "The theory, development, and application of Linear Control Model Methodology to Reconstruct Historical Contaminant Concentrations at Selected Water Supply Wells"; supplement seven, "Source characterization and simulation of the migration of light nonaqueous phase liquids in the vicinity of the Hadnot Point industrial area"; and supplement eight, "Field test data analysis and simulation of the distribution of drinking water with emphasis on intermittent transfers of drinking water between the Hadnot Point and Holcomb Boulevard water distribution sys- --"

Is that correct that those are the --

(Whereupon, the court reporter requests clarification.)

BY MS. O'LEARY:

Q Holcomb Boulevard water distribution.

Is that correct, Professor Aral, that those are the only chapters where you were listed as

an author?
A Yeah.
Q And similarly, did you contribute to those or did you author the whole thing?
A No, I contributed to them.
Q Okay. And in supplement eight, what field tests were involved in that?
A The field tests probably refers to the field studies that ATSDR has done on Camp Lejeune. I'm not involved in that. However, intermittent transfers of drinking water between the Hadnot Point and Holcomb Boulevard water distribution system is the part that I have contributed.
Q Okay. And were you involved in collecting historical data about the water distribution systems at Hadnot Point and Holcomb Boulevard?
A No.
MR. DEAN: Object to the form.
A No.
BY MS. O'LEARY:
Q Did you personally review historical documentation about the operations of the Hadnot Point/Holcomb Boulevard water distribution system?
A The intermittent transfer issue or the

operation of the water treatment plant?
Q Let me break that down farther.
A Okay.
Q So were you involved in reviewing historical documentation about intermittent transfers between the Hadnot Point area and Holcomb Boulevard areas?
A I have reviewed the data that was collected at the --
Q Okay.
A -- site.
Q Did you review data collected at the site other than for those intermittent transfers?
A Yes.
Q Okay.
A Several of them. Yeah.
Q And what sorts of things did you review other than for the intermittent transfers?
A Water treatment plant data --
Q Uh-huh.
A -- groundwater levels data, pumping data of supply wells --
Q Uh-huh.
A -- data collected from observation wells, any other data that was given to me in terms of

doing what we did at Georgia Tech.

Q Were --

A Yeah.

Q Thank you. I think I understand.

Were you personally involved in collecting that data --

A No.

Q -- that you reviewed?

A No.

Q Okay. Okay.

Thank you. You can set aside that exhibit --

A Uh-huh.

Q -- for now. And a few more questions about your role in the water modeling with ATSDR.

First about some of the people you worked with. So starting with Morris Maslia --

A Yes.

Q -- how long have you known Morris Maslia?

A I think he was a graduate student at Georgia Tech.

Q How many projects have you worked on together over the years?

A I worked as a consultant at Geosyntec. I think he was working at Geosyntec at that time, as

well.

Q Were there any other things besides the Geosyntec work?

A Other than conclusion, I don't recall.

Q Okay. Do you consider Morris Maslia a friend?

A Yes, of course.

Q Do your families know each other?

A No.

Q When's the last time you spoke to Morris Maslia about anything other than the Camp Lejeune Justice litigation?

A We had dinner several years ago in Atlanta.

Q Okay. Was that dinner before or after you'd been retained as an expert in the Camp Lejeune Justice Act litigation?

A I don't recall, honestly.

Q Have you ever served as a reviewer on any journals or a member of any committees that gave an award to Morris Maslia for his work?

A No.

Q Were you ever a reviewer on the American Society of Civil Engineers Water Planning and Management?

A Probably.
Q Okay. And --
A I have been a reviewer for many journals.
Q Okay. Which journals have you been a reviewer for?
MR. DEAN: Object to the form.
A It's in my résumé. It's about two pages long.
BY MS. O'LEARY:
Q Okay. Were you a reviewer of the ASCE Journal of Water Resources and Management in 2000?
A I could have been.
Q Were you a reviewer of the ASCE Journal of Water Resources and Management when they published a study about the ATSDR's modeling work on Dover Township --
A Not on that --
Q -- Toms River?
A Not on that study.
Q What do you mean, "not on that study"?
A I mean, that wasn't submitted for my review.
Q Ah. You mean you didn't review that --
A No.
Q -- study?

But you were a reviewer on the ASCE Journal of Water Resources and Management at the same time?

A Yeah. If they send me a paper to review, I do that.

Q Okay. Were you the editor in chief of the journal, Water Quality, Exposure and Health in 2009, when it published a study about the ATSDR's work on the Tarawa Terrace modeling?

A That's correct.

Q Were you a reviewer of the journal, Water, in 2016 when they published a study about the ATSDR's work on the Hadnot Point/Holcomb Boulevard --

A No.

Q -- area model?

A No.

Q And were you Morris Maslia's professor when he was getting a master's degree at Georgia Tech?

A Yeah, I think I was. Yeah.

Q Would you consider yourself Morris Maslia's mentor when he was getting that master --

A Can you --

Q -- degree?

A -- speak louder, please?
Q Sure.
Would you consider yourself as having been Morris Maslia's mentor when he was getting his master's degree?
A Yes.
MS. O'LEARY: We had -- this will be number nine and will be Government Exhibit 5.
(Whereupon, Government's Exhibit Aral 5, Document Regarding Development of Environmental Management Models, was marked for identification.)
(Whereupon, there was a discussion off the record.)
MR. DEAN: Dr. Aral, if you have any difficulty whatsoever hearing the question, don't hesitate to tell her she's talking too softly --
THE WITNESS: Okay.
MR. DEAN: -- to confirm. I know it's kind of repetitive, but do it anyway.
THE WITNESS: Okay.

BY MS. O'LEARY:

Q So Professor Aral, I've handed you what's been marked as Government Exhibit 5.

Do you recognize this document?

A Yes, I do.

Q What is this?

A It just talks about the development of environmental management models over the years.

Q Okay.

A And I'm trying to explain how it evolved into the present day analysis.

Q And did you author this?

A I see my name on it.

Q But do you recall authoring this?

A Yes, of course.

Q Okay.

MS. O'LEARY: And if we could take a break for about five minutes, I need to...

THE WITNESS: Okay.

MS. O'LEARY: Just a minute.

THE VIDEOGRAPHER: The time right now is 10 a.m. We are off the record.

(Whereupon, there was a recess taken from 10:00 a.m. to 10:09 a.m.)

THE VIDEOGRAPHER: The time right now is 10:10 a.m. We are back on the record.

MS. O'LEARY: All right. Thank you.

BY MS. O'LEARY:

Q And Professor Aral, just to remind you, you remain under oath.

Do you understand?

A Okay.

Q Okay. So we are going to set aside that exhibit and I'm going to hand you a different one.

MS. O'LEARY: This will be Government Exhibit 6.

(Whereupon, Government's Exhibit Aral 6, Environmental Modeling and Health Risk Analysis, by Mustafa M. Aral, was marked for identification.)

BY MS. O'LEARY:

Q Professor Aral, the front page of this says, Environmental Modeling and Health Risk Analysis (Acts/Risk), and it has your name, "Mustafa M. Aral."

Do you know what Environmental Modeling and Health Risk Analysis (Acts/Risk) is?

A Yes.

Q What is it?
A Environmental modeling is a procedural analysis of environment using models. Health risk analysis is another procedural use of health risk effects --
Q Okay.
A -- of environmental contaminants.
Q And if -- as you look through Government Exhibit 6, does this looks like excerpts from a textbook that you authored?
MR. DEAN: Object to the form of the question.
You used the term "excerpts." I'm just pointing out this is not the whole text, it goes to page 16.
A Yes, it looks like parts of it. Yeah.
BY MS. O'LEARY:
Q And did you author a textbook called Environmental Modeling and Health Risk Analysis?
A Yes. It has my name on it.
Q And if you could go on Government Exhibit 6 to the page -- it should say 17?
A Uh-huh.
Q Okay. In the bottom paragraph on page 17, could you read that paragraph, Professor Aral?

A "On the other hand, there are at least three reservations one should always bear in mind while constructing and using a model (Rubinstein -- Rubinstein 1981). First, there's no guarantee that the time and effort devoted to modeling will return useful results and satisfactory benefits. Occasional failures are expected to occur because of limited resources allocated to modeling. More often, however, failure results when the investigators relies too much on the method and not on the ingenuity and construct of the -- construction -- constructing the model. The proper balance between the two is the key to success in modeling.

"The second reservation concerns the tendency of the investigator to treat his or her mathematical description of the problem as the best representation of the reality. One should be open minded in understanding the limitations of the proposed model."

"The third reservation concerns the use of model outside the predictive range of the model developed. When working with a model, care must be given to ensure that the analysis remains within the valid representation range of the model. These are

important concepts of concern when working with a model -- with models."

Q And Professor Aral, did you write that paragraph that you just read?

A Yeah.

Q Do you --

A Yes.

Q -- agree with it still?

A Yes.

Q Okay. When it said "the use of the model outside the predictive range of the model developed is a reservation in modeling," why is that?

So why is it that the use of the model outside the predictive range of the model development should be considered?

A Okay.

MR. DEAN: Object to form.

A When someone develops a model, it involves some approximation of the environment. If the construct of the model does not include all the important aspects of the modeling aspects of the environment, then some of the processes that exist in the environment may not -- may not be represented in the model. That's a problem. That's what I'm referring to there.

BY MS. O'LEARY:

Q Okay. And in that paragraph when it refers to the predictive range of the model, what is the predictive range of the model?

MR. DEAN: Object to the form.

A Predictive range is what I have described. For example -- just to give you an example, if you are working with surface water models, if you exclude advective transport and use only diffusive transport, than the predictive range is defined wrong.

The main transport parameter in a surface water model is the advective range. So if you -- if your model construct is wrong, its predictive range is limited.

BY MS. O'LEARY:

Q Okay. How do you determine the predictive range of a model?

A You have to understand what's going on in the environment as the major contributors to what you are trying to model.

Q Okay. And what does it mean to have the valid representation range of the model?

A As I have explained a minute ago, all the dominant characteristics of the environment should

be represented for the model to be successful.

Q How do you determine what the dominant characteristics are?

A You have to understand the environmental processes that you are modeling.

Q And how do you determine which environmental processes you are modeling?

A You have to understand the environmental processes that you are working with.

Q Okay. How -- with that understanding of the environmental processes you are working with, how do you determine what representation range would be valid for a model of those processes?

A As I have said a minute ago, if you exclude the dominant processes from a model, it will not be a successful model.

As I have described in surface water modeling, if you ignore advective transport and only include diffusive transport, that's not going to be a successful model.

Q Staying on the same exhibit, could you go to page 18, which is the next page?

A Page what?

MR. DEAN: Eighteen.

BY MS. O'LEARY:

Q Page 18, just the next page?

A Okay.

Q And the bottom paragraph on page 18 that starts, "Model accuracy and reliability," do you see that?

A Yes.

Q Could you read that paragraph, please?

A "Model accuracy and reliability are two of the more important aspects of modeling which should not be overlooked if a model is to be accepted as a reliable predictive tool numerical error bounds generated in computation should be within acceptable limits and the model should be calibrated regionally or locally using available data. Proceeding in the -- in this direction much of the recent work done in environmental quality modeling has been -- has been oriented towards improving models and incorporating better numerical solution techniques, the accuracy of which by far surpasses the availability and accuracy of the field parameter data that have to be used with such models. Scarcity of the field data, especially in air, groundwater, surface water quality modeling is well known to researchers and engineers working in

this field.

"Currently, there is some disagreement among researchers as to whether higher priority should be placed on still further developments and model sophistication or on parameter prediction to improve accuracy."

Q And do you agree with this paragraph still today?

A What does it say?

Q Do you agree with --

A Oh, yeah.

Q -- what it says today?

A Yes, I do.

Q Okay. And how do you determine acceptable limits for numerical error bounds?

MR. DEAN: Object to the form.

A Well, I'm trying to say in here is that as the computers or the field of computer applications advanced, we are using more, faster, and higher precision computers. Using that base, we are able to come up with more sophisticated numerical algorithms to predict the behavior of a -- or calculate the behavior of a model in a more precise manner.

What I am trying to say here is that

there should be a balance between computational aspects as opposed to model construct.

BY MS. O'LEARY:

Q And when you say a balance, a balance in what? In terms of sophistication or something else?

A The balance is in reference to how we represent the environment, computational aspects refers to how we compute the mathematics of the algorithms that we have proposed.

Q Okay. And what does it mean to calibrate a model regionally?

A Well, you use the data available at the site and either manually or statistically try to adjust some of the parameters of the model that you have developed to match the observed database that you have at the site. And that's the standard calibration process.

Q And why -- why should you use available data from the site as opposed to, like, a literature reference?

A Well, both can be used.

Q Okay. So in -- in page 18, it -- it says using field parameter data.

A Yeah.

Q Is that right?
A Yeah.
Q Why -- why reference field parameter data?
A Because we are trying to fee- -- represent some environment at the field. We have -- if you are developing a model for that field, we would like to use field parameters.
Q Okay. What does it mean to calibrate a model locally?
A Oh, this -- this is a matter of dimensions. You can calibrate a regional aquifer, like Floridan aquifer, which includes the aquifer system in Georgia and Florida --
Q Okay.
A -- as USGS is doing or I would call a local analysis, like Camp Lejeune application, which is relatively small in reference to a Floridan aquifer.
Q Okay. And similarly to regional calibration, why would you use --
A Can you speak, please, louder?
Q Yes.
So why would you use available field data for calibrating a model locally?

A For the same reason as we would use a regional model -- to calibrate a regional model.

Q Okay. Staying on this same exhibit, if you can be on page 19, so where the --

A Uh-huh.

Q -- last paragraph ended, can you read the next paragraph that starts, "A very simplistic model"?

A The whole paragraph I should read?

Q No. Actually, just -- I'll -- I'll -- do you mind if I just stop you when I need you to stop?

A Okay.

Q Okay. Go ahead.

So if you could start reading and I'll just ask you to stop.

A I see. Okay.

"A very simplistic model may use a very crude -- crude definition of a physical process with few parameters to define the process. A very complex model may use a very detailed definition of a physical process, which is a significant increase in -- with a significant increase in parameters that is used to define the process.

"Naturally, improved sophistication of the models is associated with the increase and the

number of model parameters. Since it's likely that many of the additional parameters included in the model will be defined only in qualitative terms or with lesser accuracy, a relatively more sophisticated model can be less reliable than the simpler version. On the other hand, some systems and some physical phenomenon are so complex in nature that it's often little reason to believe that good simulations are possible with simplified representations."

Q And you can stop there --

A Okay.

Q -- Professor Aral. Thank you.

And do you agree with the portion of that paragraph you've just read?

A Yes.

Q And how would parameters defined only in qualitative terms or with lesser accuracy lead to a less-reliable sophisticated model relative to a simpler one?

MR. DEAN: Object to the form of the question.

A Can you repeat that so that I can understand what you are --

BY MS. O'LEARY:

Q Would you like me to rephrase?

A Yes. Rephrase, please.

Q So Professor Aral, the paragraph said that when parameters are defined only in qualitative terms or with lesser accuracy, this can lead to situations where a sophisticated model is less reliable than a simpler one.

Do you agree?

MR. DEAN: Object to the form of the question.

A Well --

MR. DEAN: It mischaracterizes --

THE WITNESS: Yeah.

MR. DEAN: -- misstates --

A I'm assuming here is that a complex model is going to need more database to implement the model. If we are talking about more database, some of those databases may not be available and can be only determined through some qualitative analysis of what we know about the database.

In that case, the -- the database being qualitative may result in model response not being as accurate as we would like to see.

BY MS. O'LEARY:

Q So in those situations where you don't have the databases for some parameters, is that where a simpler model could be more reliable than a sophisticated model?

MR. DEAN: Object to the form of the question.

A If there's no database available, yes, that would be a better idea.

BY MS. O'LEARY:

Q What if you had sophisticated models where you had some databases for parameters but very few, could that still lead to situations where the sophisticated model that needs that, you know, small bit of information available is less reliable than a simpler model?

MR. DEAN: Object to the form.

A No, I don't think so.

BY MS. O'LEARY:

Q Why not?

A Because a complex model can be used with partial databases available at the site. And then there are other databases, if needed, can be associated with the database that you are using, characterization of the site --

Q Uh-huh.
A -- and other information that you have at the site.
Q So that would allow you to run the sophisticated model --
A Yeah.
Q -- is that right?
A Yeah.
Q But how do you know it's more reliable than a less sophisticated model?
A Oh, it is reliable because we are representing the environment in a better form. In other words, as I said earlier, if you omit dominant features of an environmental process, your model will become simple but, at the same time, much more uncertain or inaccurate.
Q Okay. Another portion of what you read said that, "On the other hand, some systems and some physical phenomena are so complex in nature that there is often little reason to believe that good simulations are possible with simplified representations."
And my --
A Yeah.
Q -- question is: How do you determine

whether physical phenomena are so complex that good simulations are unlikely?

A Well, you have to have experience in the environmental analysis and modeling techniques.

Q But specifically, how would you approach those techniques to determine when physical phenomena are so complex that a good simulation --

A You should --

Q -- is unlikely?

A -- you need to have an education in that field to understand what you are doing and what you are doing properly.

Q And is there agreement in the field on when it is that physical phenomena are so complex that good simulations are unlikely?

A Mostly, yes.

Q You said "mostly."

Where is there --

A Some people --

Q -- remaining disagreement?

A -- may not understand the environmental processes properly so they may end up using simpler models. That will be a problem.

Q But I mean, you agree then there are some times when physical phenomena are so complex that a

good simulation is unlikely?

A Please --

MR. DEAN: Object to the form of the question.

A -- speak louder.

BY MS. O'LEARY:

Q Yeah.

This exhibit says that "physical phenomena can be so complex that good simulations are unlikely."

Do you agree?

MR. DEAN: Object to the --

MS. BAUGHMAN: Object to the --

A I don't understand the relevance of the question in reference to the Camp Lejeune modeling.

BY MS. O'LEARY:

Q So right now my question is just about what this textbook says.

A Okay.

Q So the -- where it says, "On the other hand, some systems and some physical phenomena are so complex in nature, that there is often little reason to believe that good simulations are possible with simplified representations," that section; do you agree that that's true?

A That's true.
Q Okay. And then I think we are going to jump forward on this exhibit.
A Uh-huh.
Q -- to -- there's a page 56.
(Whereupon, there was a discussion off the record.)
A Fifty-six. Oops.
Yeah. Okay.
BY MS. O'LEARY:
Q And there's a figure and then a paragraph below that, that starts, "The uncertainty and errors."
Do you see that?
A Yes.
Q Would you mind reading that paragraph, please?
A "The uncertainties and errors in simulation may arise from uncertainty in model inputs or parameters, i.e., parametric -- parametric or data uncertainty. When a model application involves both model and data uncertainties, it's important to identify the relative magnitudes of the uncertainties associated with the data and model formulation."

Q And you can -- sorry. Go ahead.
A "Such a comparison is useful for focusing resources where they are most appropriate, data gaps versus model refinement."
Q Thank you, Professor Aral.
And why is it important to identify the relative magnitudes of the uncertainties associated with data and model formulation?
A Because the model itself uses some database from some field and the effects of the uncertainty on the database need to be characterized through some analysis. That is what is uncertainty analysis is.
Q But why -- why do they need to be characterized?
A Because we would like to understand whether the model is behaving properly in reference to the uncertainty that exists at the database.
Q So does that make it important to the model's reliability?
A Model's -- model reliability is a different subject. Uncertainty analysis is a different subject.
Q Okay. I'm not sure I understand then what the uncertainty -- why identifying the relative

magnitude of uncertainties is important.

MR. DEAN: Object to the form of the question.

BY MS. O'LEARY:

Q Why --

MR. DEAN: You need to ask a question.

BY MS. O'LEARY:

Q Why is it that it's important to know the relative magnitude of uncertainties?

A Right. Because it refers to the uncertainty on the database. If there's uncertainty on the database, the model response will give us a range of error bounds.

Q Uh-huh.

A So the model's behavior can be characterized to see whether it's working in -- within that model uncertainty band -- band that we have developed in terms of uncertainty analysis.

Q Okay. You can set aside that exhibit. Thank you.

MS. O'LEARY: And can we pull 23?

(Whereupon, there was a discussion off the record.)

BY MS. O'LEARY:

Q Actually, we will move on, actually, to some questions, more specifically, about the ATSDR water modeling at Tarawa Terrace.

A Okay.

Q So could you --

A Are we --

Q -- go back --

A -- skipping this?

Q We're skipping that one for right now, yeah.

A Okay.

Q Could you go back to -- could you go back to Exhibit 3, please, Government Exhibit 3?

It should be the -- I think it's in that stack, actually --

A Excuse me.

Q -- Professor Aral.

A It's --

Q Oh, it's there?

A Yeah.

Q Okay. Perfect. Thank you.

MR. DEAN: Can you tell me what Exhibit 3 was? Was it A -- chapter A or --

MS. O'LEARY: Chapter A for Tarawa Terrace.

MR. DEAN: Okay.

A Yes.

BY MS. O'LEARY:

Q Okay. So Professor Aral, can you go to one of the early pages on this report. This will be page iii, so little Roman numeral iii.

A Three. Yeah. Okay.

Forward.

Q Yeah. It should say, "The Forward."

And can you read the first paragraph, please?

A "The Agency for Toxic Substances and Disease Registry, ATSDR, an agency of the U.S. Department of Health and Human Services, is conducting an epidemiologic study to evaluate whether the -- whether in utero an infant up to one year of age exposure to volatile organic compounds in contaminated drinking water at U.S. Marine Corps Base Camp -- Base Camp Lejeune, North Carolina, were associated with specific birth defects and childhood cancers.

"The study includes births occurring during the period 1968 to 1985 to women who were

pregnant while they resided in family housing at the base. During 2004 -- or -- at the base.

"During 2004, the study protocol received approval from the Centers for Disease Control and Prevention Institutional Review Board and the U.S. Office of Management and Budget."

Q And -- so Professor Aral, when you were working on the Tarawa Terra- -- Terrace water modeling with the ATSDR, were you aware that the ATSDR was conducting an epidemiological study to evaluate whether in utero and infant exposures to VOCs in contaminated drinking water at Camp Lejeune were associated with childhood cancers?

A I heard that in expert panels and so forth.

Q And were you aware of the time frame of that study of 1968 to 1985?

A Yes, I'm aware of that.

Q Okay. And then the next paragraph says, "Historical exposure data needed for the epidemiological case control study are limited. To obtain estimates of historical exposure, ATSDR is using water modeling techniques and the process of historical reconstruction. These methods are used to quantify concentrations of particular

contaminants in finished water and to compute the level and duration of human exposure to contaminated drinking water."

Did I read that correctly?

A Yeah. That's correct.

Q When you were working on the Tarawa Terrace water modeling, were you aware that the modeling work you were doing was intended for this epidemiological study?

A Yes.

Q And were you aware that it was not intended for estimating an individual's exposure?

MR. DEAN: Object to the form of the question.

A I -- I am -- I don't have any idea on that --

BY MS. O'LEARY:

Q Okay.

A -- question.

Q When you were working on the Tarawa Terrace water modeling, were you aware that the modeling work you were doing was not intended to be used so that a particular individual could determine whether an estimated exposure from the model caused his or her health condition?

A I can't --
MR. DEAN: Object --
A -- answer that.
MR. DEAN: Let me -- let me object to the form of the question, please.
BY MS. O'LEARY:
Q Why can't you answer that?
A Because that's a "epi" topic that I'm familiar with --
(Whereupon, the court reporter requests clarification.)
A "Epi," epidemiologics.
BY MS. O'LEARY:
Q So are you saying you don't know?
A What it is going to be used for --
Q You --
A -- I don't know what the models are going to be used for. Is -- is it for a public exposure? Individual exposure? Community exposure? I have no idea.
Q So when I look at page iii on this Exhibit, the Tarawa Terrace chapter A, it looks like it's saying the historical exposure data were needed for the epidemiological case control study.
MR. DEAN: Object to the form.

BY MS. O'LEARY:
Q Am I understanding that correctly?
MR. DEAN: Object to the form of the question. Mischaracterizes --
A That's --
MR. DEAN: You are not reading the paragraph -- the paragrapher correctly.
A Well, that's what ATSDR, as a whole within different units, are going to investigate that, but that has nothing to do with what I'm doing.
BY MS. O'LEARY:
Q But you are listed as an author of chapter A; correct?
A I am not an author on the "epi" study. I am on the -- on the author -- I am the author on the modeling aspects of this. So this is probably a group of people doing different work, different fields and using each other's inputs, outputs.
Q Okay. Professor Aral, can we go to your report again?
A Yes.
Q And this is Exhibit 2, Government --
A Yeah.
Q -- Exhibit 2.

Give me just a minute while I try to find the page I want you to turn to.

All right. If you could go to pages four to five of your report?

A My expert report?

Q Of your report, yes.

MR. DEAN: Uh-huh.

A Yes.

MR. DEAN: What page? I'm sorry.

MS. O'LEARY: I had said four to five.

MR. DEAN: Okay.

MS. O'LEARY: But we may be moving. Oh, excuse me. Page 12.

THE WITNESS: Okay.

BY MS. O'LEARY:

Q And, Professor Aral, this is in a section called, "Principles of water modeling and application at Camp Lejeune," and subsection 4.1 "Water Modeling."

Do you see the sections?

And then --

A Yeah.

Q Okay. There's a -- it says -- in the middle of the page, it says, "My opinions within a

reasonable degree of scientific and engineering certainty on modeling techniques, their principles and their application to the Camp Lejeune site include the following," and then there's a list of -- a bulleted list.

Do you see that?

A Yes.

Q Okay. So the second to the last bullet from the bottom says, "The models and techniques used by the ATSDR for historical reconstruction, including fundamental equations, input parameters, parameter estimates, calibration uncertainty and sensitivity analyses were and remain reliable, scientifically valid and state of the art procedures that are consistent with standard practices used and are generally accepted in this field."

Do you agree with that statement still?

A Yes.

Q Okay. And -- and then if you go onto page 13, the last bullet, do you see where I'm looking at?

A Yeah.

Q It says, "The analyses published in all ATSDR chapter reports, ATSDR 2007 and ATSDR 2013, and supplemental information regarding Camp Lejeune,

see figure two, including the conclusions and monthly concentration data, were all done applying proper scientific and engineering methodologies and remain to this day to be mathematically reliable, statistically, accurate and correct."

Did I read that properly?

A Yes.

Q Do you agree with that?

A Yes.

Q Okay. So if you are saying that the analyses -- analyses published in all ATSDR chapter reports and supplemental information on Camp Lejeune were done applying proper scientific and engineering methodologies and remain to this day to be mathematically reliable, statistically accurate and correct, then if we come back to my questions about the forward in the ATSDR chapter A report --

(Whereupon, the court reporter requests clarification.)

BY MS. O'LEARY:

Q Yes.

-- the chapter A report for Tarawa Terrace --

MS. BOLTON: Exhibit 3.

MS. O'LEARY: Yes, Exhibit 3.

A Uh-huh.
BY MS. O'LEARY:
Q -- I mean, aren't you saying that this isn't correct?
MR. DEAN: Object to the form. I'm not sure what the question is.
A As far as I understand the question, what I am referring to in my expert report refers to modeling aspects of the environment that we are trying to model, they are accurate, scientifically correct, mathematically correct, statistically correct.
But this paragraph that you are referring to is associated with the use of these outcomes in "epi" studies. That is outside my expertise area.
Probably ATSDR is correct in putting that paragraph in there but that's not my expertise area. Is -- I am only a contributor to this chapter, not the author of this chapter.
BY MS. O'LEARY:
Q Okay. So the limit on your statement about the -- that we just read from your report -- is -- is limited to the -- the modeling aspects of --
A Exactly.

Q -- the ATSDR reports?
Okay.
A Exactly.
Q If you can stay in the chapter A report and go to page 90 -- A 98, is how it's labeled.
A A 90?
MR. DEAN: Ninety-eight.
BY MS. O'LEARY:
Q Ninety-eight.
A Ninety-eight.
Yes.
Q Okay. So Professor Aral, there are two columns; do you see that?
A Yeah.
Q The column on the left, the bottom question, it starts "ATSDR's historical reconstruction analysis."
Do you see that?
A Yeah.
Q All right. In the paragraph that's to the right of that, so in the other column, do you see where it says "ATSDR's exposure assessment cannot be used to determine whether you or your family suffered any health effects as a result of past exposure to PCE contaminated drinking water at

Camp Lejeune. The study will help determine if there is an association between certain birth detects and childhood cancers among children whose mothers used this water during pregnancy. Epidemiological studies such as this help improve scientific knowledge of the health effects of these chemicals."

Did I read that correctly?

A Yes.

Q Do you agree?

A It's outside my expertise area.

Q Okay. And staying in this same report but flipping back to page A67?

A Yes.

Q And there's a -- two columns. The one on the right says, "Summary and Conclusions."

A Yeah.

Q Do you see that column?

A Yeah.

Q The first paragraph there begins, "Two of the three drinking water systems that served family housing at U.S. Marine Base Camp Lejeune were groundwater with VOCs. Groundwater was the sole source of drinking water supply. One system, the Tarawa Terrace drinking water system, was mostly

contaminated with PCE when water supply wells were contaminated by off-base dry cleaning operations at ABC One-Hour Cleaners." And then it cites Shriver, 1985.

Did I read that correctly?

A Yes.

Q Do you agree that the Tarawa Terrace drinking water system was mostly contaminated with PCE?

A That's -- that's correct.

Q And I apologize for jumping around within this exhibit --

A That's okay.

Q -- but can you go back to page A1, please, and going onto page A2, which is farther from the beginning than you might think. The Roman numerals go on for a little ways.

A Okay.

Q You should be on a page that says "Abstract," on the left.

Do you see that?

A A2?

Q A1, going --

A A1.

Q -- into A2.

A Okay.
Yes.
Q Okay. So the -- the column on the right, the last paragraph that starts, "Models and methods."
Do you see that?
A Yes.
Q So it says, "Models and methods used as part of the historical reconstruction process for Tarawa Terrace and vicinity included one, MODFLOW-6 used for simulating steady state, predevelopment, and transient groundwater flow; two, MT3DMS, used for simulating three-dimensional single-specie contaminant fate and transport; three, a materials mass balance model simple mixing used to compute the flow-weighted average concentration of PCE assigned to the finished water at the Tarawa Terrace Water Treatment Plant, WTP; four, TechFlowMP used for simulating three-dimensional multispecies, multiphase mass transport; five, PS Ops used for simulating the impacts of unknown and uncertain historical well operations; six, Monte Carlo simulation and sequential Gaussian simulation used to conduct probabilistic analyses to assess uncertainty and variability of concentrations of

PCE-contaminated groundwater and drinking water; and seven, EPANET 2, used to conduct extended period hydraulic and water quality simulations on the Tarawa Terrace water distribution system."

Did I read that correctly?

A Yes.

Q Am I understanding this correctly that the ATSDR -- that this is describing ATSDR's process for historical reconstruction of contaminants at Tarawa Terrace?

A I think it describes the models used in that process.

Q In that process, okay.

Oh, sure distinguished as from, like, data collection or --

A Yeah.

Q -- other aspects?

A Different aspects are different.

Q Yeah. Okay. I understand.

But in terms of the modeling, am I understanding correctly that at Tarawa Terrace, ATSDR's historical reconstruction process for modeling did not include simulating historical benzene concentrations at Tarawa Terrace?

A TechFlowMP can model PCE -- oh, this is

in reference to Tarawa Terrace, right?
Q Right.
A Okay.
Q At Tarawa Terrace.
A Right. Of course.
We didn't use -- we didn't analyze benzene at Tarawa Terrace.
Q Okay. And would you agree that in your report you have not offered opinions about simulated historical benzene concentrations at Tarawa Terrace?
A We did not simulate that.
Q And so you -- is that why you didn't offer any in your report?
A Well, can you repeat that question?
Q Yeah. Let me rephrase.
So your report in this litigation, it also does not offer opinions on historical benzene contamination levels at Tarawa Terrace.
A It --
Q Is that right?
A It -- we did not simulate benzene concentrations at Tarawa Terrace.
Q Okay. Staying in the Tarawa Terrace chapter A report, could you go to page A17, please?
A Okay.

Q And in the column on the left, there's a label in the middle that says, "Relation of contamination to water supply production and distribution."

Do you see that?

A Yes.

Q Okay. So within that paragraph, there's a sentence that starts, "The supply of drinking water to Tarawa Terrace."

Do you see that?

A Yes.

Q Okay. So that says, "The supply of drinking water to Tarawa Terrace was composed of two components. One, the supply of water from groundwater wells to the Tarawa Terrace Water Treatment Plant; and two, the delivery of finished water from the water treatment plant through the network of pipelines and storage tanks of the water distribution system."

Did I read that correctly?

A Yes.

Q Does that mean that the Tarawa Terrace drinking water supply, from the period that the ATSDR modeled, consisted of water supplied from groundwater wells that went to the Tarawa Terrace

Water Treatment Plant and after going through the plant they were delivered as finished water to the housing or other buildings on the Tarawa Terrace water distribution system?

A That's correct.

Q Okay. And just going onto the next page, so page A18 -- actually, sorry. If you could go onto page A19?

So one more page.

A Okay.

Q And there's a table "A6." Do you see that?

A Yes.

Q It says, "Historical operations for water-supply wells, 1952 to 1987, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina."

Is this table then showing all of the water supply wells that were providing water to the Tarawa Terrace Water Treatment Plant through that 1952 to 1987 time span?

A That's the data that ATSDR presented --

Q Okay.

A -- yes.

Q So according to this table then, in the

column on the left that says "well identification," do you see the --

A Yeah.

Q -- "TT-23."

So "TT-23"?

A Yes.

Q And does -- is this table saying that that well started supplying water in August of 1984?

A Yes, I see that.

Q Okay. And then it -- it's saying that it was offline in February of 1985; is that right?

A Yes, it says that.

Q And now the same table, looking at well that's "TT-26," so TT-26?

A Yes.

Q Is the table reflecting that that well started supplying water in January of 1952?

A Yes.

Q And was offline in July and August of 1980 and January and February of 1983, is that correct?

A Yes.

Q And then the -- its service was terminated in February of 1985?

A Yes.

Q And sorry, going back up to Tarawa Terrace, TT-23 --
A Yes.
Q -- does the table reflect that service was terminated from TT-23 in May of 1985?
A Yes, it says that.
Q And if you could set aside this exhibit, Exhibit 3, for a moment.
MS. O'LEARY: And if we could get 57, this will be Government Exhibit 7.
(Whereupon, Government's Exhibit Aral 7, ATSDR's Chapter C Report for Tarawa Terrace, was marked for identification.)
THE WITNESS: Thank you.
BY MS. O'LEARY:
Q So Professor Aral, on Government -- oops, I think I handed you the wrong one. I did. I have the one with the sticker.
So let me trade you so you have the --
A Okay.
Q -- one that's marked.
So on Government Exhibit 7, do you agree this is -- looks like a copy of the ATSDR's chapter C report for Tarawa Terrace?

A Yes.
Q Okay. And if you could go to page C76, please?
A Yes.
Q Okay. And do you see a table C3.10?
A Yes.
Q And it says, "Capacity and operational history of water supply well TT-23 Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina."
A Yes.
Q Do you agree this is the ATSDR's table showing capacity and operational well history at TT-23, which is a supply well?
A Yes.
Q And do you agree this table shows that ATSDR concluded TT-23 was out of service in February of 1985?
A I am not the author of this report so if it says that here, that's what it should be.
Q Okay. Do you see on this table in -- the date, it says -- the second to last entry, it says, "Four, 1985, service terminated."
Do you see that?
A Table six, three, ten or what?

Or what num- --
Q Table C310. So the same --
A Yeah.
Q -- table we have been looking at --
A Okay.
Q -- that's --
A Uh-huh.
Q -- the entry for -- if -- that starts, "Four --

(Whereupon, the court reporter requests clarification.)

BY MS. O'LEARY:
Q "Four 1985," in the date column.

MR. DEAN: Four, slash, 1985 --

MS. O'LEARY: Right.

MR. DEAN: -- next to last entry on the bottom.

BY MS. O'LEARY:
Q So we are looking at the column on the left --
A Okay.
Q -- that says date --
A Okay.
Q Yeah, the entry that starts, "4/1985." Do you see that?

A I don't see that.
Where do you --
Q So on my copy, it's right here.
A Okay. Right there.
Okay.
Q Do you see it?
A Yeah.
Q And then -- so that's April 1985, correct?
A Yeah.
Q And it says, "Service terminated." Correct?
A Yeah.
Q Do you know why this table says TT-23 service was terminated in April of 1985, but the last table we just looked at, table A6, says TT-23 service was terminated in May of 1985?
MR. DEAN: Mis- --
A I --
MR. DEAN: I'm going to object to the form of the question. It also mischaracterizes the document.
You are also misrepresenting what the table says because in the entry just below -- above that it says, "4/30/1985,"

which is the end of the month, out of service.

So you are mischaracterizing the chart and I'd ask that you provide the witness with accurate information, please.

MS. O'LEARY: I don't see where it says "4/30" on this exhibit.

MR. DEAN: It -- it does. If you look just above the entry you just read, you didn't --

MS. O'LEARY: Oh, that one? Okay.

MR. DEAN: Oh. Yeah, that one.

A I'm not the author of this chapter so I have no comment.

BY MS. O'LEARY:

Q Okay. You mean, you don't know?

A I don't know whether it was terminated at this date or the other date or whether the other one was correct. I think the authors of the chapters should answer that question.

Q Okay. And Professor Aral, could you go back to the Tarawa Terrace chapter A report, which should be marked as Government Exhibit 3?

A Uh-huh.

Q And then go to page A27.
A Yes.
Q Okay. Do you see a table A9 on that page?
A Yes.
Q And it's labeled, "Summary of model-derived values and observed data of tetrachloroethylene at water supply wells Tarawa Terrace, U.S. Marine Base Camp Lejeune, North Carolina."
Did I read that correctly?
A Yes.
Q And the -- the data in this table, is this the sort of data you were relying on when you were building the models at Tarawa Terrace?
A Yes. This must be the data that we relied on.
Q Okay. And do you agree that table A9 purports to summarize observed and model-simulated values of PCE at the Tarawa Terrace water supply wells?
A Can you speak louder, please?
Q Yeah, I'm sorry.
Do you agree that table A9 summarizes observed and model-simulated values of PCE at the

Tarawa Terrace water supply wells?

A Unless there's a typo -- typo error, it must be the correct numbers.

Q Okay. And do you agree that according to this table, between -- between January of 1952, so the earliest date on this table --

A Uh-huh.

Q -- and December of 1987, PCE was detected in only Tarawa Terrace 26. So TT-26, TT-23 and TT-25.

So looking at the column on, "Observed data for PCE concentration."

A Uh-huh.

Q So --

A Yes, I see that.

Q All right.

MS. BAUGHMAN: I'm going to object to the form. That's not correct.

BY MS. O'LEARY:

Q And so if we start with the section on supply well TT-23, you agree there are detections of PCE in TT-23?

A Yes, I saw that.

Q And do you agree that the highest PCE detection on the table was 132 micrograms per liter,

and that's from January 16, 1985.

Is that correct?

A That's correct.

Q And do you agree that for TT-23, there were non-detections, meaning no PCE detected, in February of 1985, in April of 1985, and July of 1991?

MR. DEAN: Object to the form.

A Yes, I see that here.

BY MS. O'LEARY:

Q Okay. And looking at the -- the next supply well, so supply well TT-25, the next section.

A Uh-huh. Yes.

Q Do you agree that the only PCE detection in -- detections in TT-25 were 0.43 micrograms per liter in September of 1985, and 23 micrograms per liter in July of 1991?

A Yes, I see that.

Q Do you know what the "J" means next to the "0.43"?

A "J"?

Q Yeah. If you look at the entry for September 1985 for supply well TT-25, the PCE concentrations says, "0.43 J."

A I didn't notice that even.

Q Okay.
A I don't know what it means.
Q Okay. And do you agree that at supply well TT-25, there were non-detections of PCE in February, in April of 1985, as well as October, November, and December of 1985?
MR. DEAN: Object to the form.
A I see that.
BY MS. O'LEARY:
Q Okay. And at -- if we go down to supply well TT-30, TT-31, TT-52, TT-54, TT-67, and RW1, there are only non-detections of PCE listed.
Is that correct?
A I see that, yes.
Q But then for supply well RW2, there is a detection.
A I see that, yes.
Q And that's in 1991?
A Yeah.
Q And then at supply well RW3, only a non-detection.
A Yes.
Q Okay. Could you go, in the same report, so still Tarawa Terrace chapter eight, to page 40 of this?

And the page A40, it should say -- the label should say, "Concentration of tetrachloroethylene, PCE, in finished water."

A Yes.

Q Do you see that?

All right. In the first paragraph on the left column that starts, figure A18 -- do you see where I am?

A Yes, I see that.

Q All right. The next sentence -- no, not the next one.

About --

A "A monthly listing of..." --

Q Just a second.

All right. Near the bottom of that first paragraph --

A Uh-huh.

Q -- there's a line that starts with a number, "1.3 micrograms per liter."

Do you see that?

A Yes.

Q Okay. Right next to that, there's a sentence that starts, "The PCE concentration of finished water at the Tarawa Terrace Water Treatment Plant is less than the PCE concentration of water

supply well TT-26 because the mixing model uses water supplied to the water treatment plant from all wells, contaminated and uncontaminated."

Do you see that?

A That's correct.

Q And do you agree that the PCE concentration in water distributed from the Tarawa Terrace Water Treatment Plant had lower PCE concentrations than in TT-26?

A We can look at the data. If that's the case, that might be.

Q I mean --

A Yeah.

Q -- do you agree with what the document says?

A That's what the document says, yes.

Q Okay. Do you have any reason to think that's not true?

A No, I don't have any reason to think that's not true.

Q Okay. And then in the same paragraph, still on page A40 --

A Yes.

Q -- but a little farther up, there's a line that starts -- it's the one, two, three, four,

five -- the seventh line down that's -- on the left the first word is, "Period."

A Okay.

Q Okay. At the end of that row, there's a sentence that says, "PCE contamination of water supply well TT-26 was the primary contributor to contamination in the finished water of the water treatment plant."

Do you agree that TT-26 was the primary contributor of PCE contamination to Tarawa Terrace Water Treatment Plant?

A Yes, I do.

Q And do you agree -- looking back at table A6, which is on page A19, that according to the ATSDR --

MR. DEAN: Give him time to get there, if you don't mind?

MS. O'LEARY: Sure.

BY MS. O'LEARY:

Q So this was A19.

A Uh-huh.

Q Okay. Do you agree that this shows that TT-26 had its service terminated in February of 1985?

A Which table are we looking at?

Q A6.
A A6. Okay.
Q So in the --
A Yeah.
Q Don't --
Service terminated TT-26, February 1985; you agree?
A Yup.
Q Okay. So if TT-26 was the primary contributor of PCE to the Tarawa Terrace Water Treatment Plant and it shut down in February of 1985 --
A Uh-huh.
Q -- do you agree that after that happened, PCE concentrations at Tarawa Terrace Water Treatment Plant would have significantly decreased?
A Would have decreased, yes. Significantly or not it depends on the contributions of the other wells.
Q Well, if it's the primary contributor --
A Yeah, of course.
Q -- doesn't that make it significant decreases?
MR. DEAN: Object to form.
A I don't think so.

BY MS. O'LEARY:
Q Why not?
A Because the contribution is not only coming from TT-26 --
Q Uh-huh.
A -- but other wells as well.
We have to go back and look at all the other contaminant concentrations in all the other wells to see whether it's significant or not.
Q Sure. So if we go to table A9 again, which was on page A27 --
A Twenty-seven.
Okay.
Q And -- and I think we went through this earlier, but the highest detection of PCE at TT-23 was 132 micrograms per liter.
And at TT-25, the highest detection before 1987 was 0.43 micrograms per liter. And there were no detections in any other wells before 1987 --
A Uh-huh.
Q -- is that correct?
And then if we look at --
MR. DEAN: You didn't read, with all due respect, or for the record, that this

is "0.43 J."

And 0.43 J, the "J" means estimated.

THE WITNESS: Okay.

MS. O'LEARY: I don't -- I don't know that that's accurate.

BY MS. O'LEARY:

Q But if we look then at supply well TT-26, the highest concentration there, it looks like it's 1,580 micrograms per liter. So almost -- more than ten times higher than the next highest concentration in a well.

Do you agree?

A Which one are you referring to?

Q I'm on page A27, table A9?

A Yes.

Q All right. So --

A Okay.

Q So if we look at TT-26 --

A Yes.

Q -- its highest concentration measured is the 1,580 --

A That's correct.

Q -- micrograms per liter, and that's more than ten times higher than the 132 micrograms per liter, that's the highest measured concentration in

another supply well before 1987.

Do you see that?

A Which well are you comparing this 1580 number with?

Q All of the other wells.

A Can you speak louder, please?

Q Yeah. All the other wells.

But the specific --

A All the other wells?

Q Yeah.

A Combined?

Q No, not combined.

Individually.

A Individually, they are less than 1580.

Q I mean, more than ten times less than 1580, right?

A Yeah.

Q Okay. And if you could go to page A18 --

MR. DEAN: For the record, on page A27, at the top in the definitions, under the table A9, in parentheses, it gives a definition of the "J."

It says, "Estimated."

BY MS. O'LEARY:

Q And Professor Aral, are you on page A18?

A Yes.
Q Okay. And there's a large figure that covers most of the page. The text at the bottom is where --
A Okay.
Q -- I'd like to direct your attention.
The column on the left, there's a sentence that begins, "Once a well was put in service." It's the third line from the bottom.
Do you see that?
A Yes.
Q Okay. So that says, "Once a well was put in service, it was assumed to operate continuously for modeling purposes until it was permanently taken offline, the exception being temporary shutdowns for longterm maintenance. Breaks in continuous operation, such as those for wells TT-26 and TT-53, are also shown on figure A5 and are based on documented information detailing periods of maintenance for a specific wells."
Did I read that correctly?
A You read that correctly.
Q Is it true that in the ATSDR model, Tarawa Terrace supply wells were modeled such that they are assumed to operate continuously unless

there was documentation that they had been temporarily shut down for maintenance?

A That's correct.

Q And if you could go onto page A20 of the Tarawa Terrace report?

Can you go onto page --

A A what?

Q A20.

Just one -- two pages forward.

A Okay.

Yes.

Q And there's a figure A6 on the bottom. Do you see that?

A Yes.

Q Okay. It's labeled, "Total annual groundwater pumpage at water supply wells, 1952 to 1987, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina."

And --

A You have to speak sl- --

Q Yeah.

On this table --

A Yeah.

Q -- A6, is -- is this showing -- I guess my first question is: What is pumpage of a water

supply well?
A The amount of water contributed to water treatment plant.
Q Okay. So is table A6 showing the amount of water that the -- at the Tarawa Terrace Water Treatment Plant that the ATSDR model had coming from each well at each year?
A At each year at each --
Q For each --
A -- pumping --
Q -- well?
A Yeah, okay.
Yes.
Q Okay. And do you agree that in looking at A6, TT-26 and TT-23 are not modeled as contributing any water to the Tarawa Terrace Water Treatment Plant in 1986 and 1987?
A That's right.
Q Okay. And so the wells where contamination was detected before 1987, we had TT-26, TT-23, and TT-25.
Is that correct?
A Uh-huh. Yes.
Q Okay. So according to figure A6, for 1986 and 1987, the only well that the ATSDR's Tarawa

Terrace model of those three that was still pumping was TT-25.

Is that right?

A Repeat that question, please?

Q Yeah. So on figure A6, for just the last two years, 1986 and 1987 --

A Yes.

Q -- of -- of the three wells where contamination was found before 1987, the only one that the ATSDR model had as contributing water to the Tarawa Terrace Water Treatment Plant in '86 and '87, was TT-25.

Is that correct?

A TT-25?

TT-25, yes. It's contributing, according to this figure, yes.

Q But TT-26 and TT-23 are not --

A Are not.

Q -- correct?

A Yes.

Q Okay. And TT-25 was the well that had the only detection before 1987 of PCE was 0.43 micrograms per liter with the "J"?

A Yes.

Q Still in Tarawa Terrace chapter A, so the

same exhibit, but could you go to page A93?

A Yes.

Q All right. So this is -- says it's appendix A2.

I'll give you a minute to get to that. All right.

So we are looking at appendix A2, where it says, "Simulated tetrachloroethylene and its degradation by-products in finished water, Tarawa Terrace Water Treatment Plant, January 1951 to March 1987, continued."

So is this the simulated P- -- or contaminant concentration levels from the ATSDR's Tarawa Terrace model?

A It has -- this -- this table includes the MT3DMS results as -- also, TechFlowMP results.

Q Okay. But both of those aren't, like -- those are the simulated concentrations from the Tarawa Terrace water model; is that correct?

A That's correct.

Q All right. So if I -- the column on the left is called "Stress periods." And I want to look at the -- the last two. So four, 30 -- well, actually, not quite the last -- the last three. 433 and 434, that say they are January 1987 and

February 1987.

Do you see that?

A Yes.

Q And do you agree on the MT3D model, those show PCE concentrations of 17.85 micrograms per liter and 18.49 micrograms per liter?

A Yes.

Q And on the TechFlowMP version, it shows 8.28 micrograms per liter and 8.71 micrograms per liter of PCE.

A Yes.

Q Okay. And these levels in appendix A2, that's at the water treatment plant; correct? That's all of the wells' contributions, combined?

A Yes.

Q So the only well contributing in this simulation where there was a detection of PCE is TT-25, right?

A According to the earlier pumpage records.

Q Okay.

A TT-25 --

Q Yeah.

A -- is there, TT-28 is there, TT-54 is there --

Q Uh-huh.

A -- and TT-27 is there. That's what I see.
Q Okay. And -- but of those wells, it was only TT-25 that had a detection of PCE?
A In terms of site observations --
Q Right.
A -- or in terms of simulated results?
Q In terms of site observations.
A That's what was on the table, yes.
Q Okay. We can set aside Tarawa Terrace chapter A for a few minutes.
A Okay.
MS. O'LEARY: If you can grab seven.
(Whereupon, Government's Exhibit Aral 8, December 2004 Report by AH Environmental Consultants, Inc., was marked for identification.)
BY MS. O'LEARY:
Q So Professor Aral, Government Exhibit 8 should be -- it looks like a report that's labeled, "ATSDR Support Estimation of VOC Removal, Marine Corps Base Camp Lejeune."
And it says the date is December 2004, and it's by AH Environmental Consultants, Inc.
Do you see that?

A Yes.
Q Have you ever seen a report from AH Environmental Consultant, Inc.'s [sic] about estimating VOC removal ATSDR -- for ATSDR before?
A I don't recall that.
Q Okay. Can you go to -- this one is numbered interestingly -- but page five, dash, one -- you know what might be easiest, do you see the -- there's little numbers at the bottom that all -- right --
A Yeah.
Q -- that start, "CLJA water modeling," yeah. Can you go to the page where the last part of that is -71486?
A Yes.
Q Okay. So this is labeled, "Summary," and it --
A Uh-huh.
Q -- says, "Where MCB Camp Lejeune is currently the subject of an epidemiological study by the ATSDR to ascertain the health impacts of certain VOCs including TCE and PCE, which were present in the Hadnot Point, Tarawa Terrace, and Holcomb Boulevard water supply systems in the early 1980s.

AH assisted in the development of referenced estimates of the VOC removal rates that might have occurred within the treatment units that existed at the three plants during 1968 to 1985."

Were you aware that AH Environmental had -- had assisted in the development of referenced estimates of VOC removal rates that might have occurred at the treatment plants?

A No, I have not.

Q Okay. And the same page, the third paragraph, it says, "The calculations revealed that VOC removal due to volatization -- volatilization from quiescent basins was negligeable at MCB Camp Lejeune. The only significant VOC removals must have occurred at the spiractor effluent pipe where the falling water undergoes some aeration. Considering the uncertainty in the estimates for the fall height over the weir formed by the pipe, the removal for TC- -- removals -- excuse me -- for TCE and PCE were likely to be less than 15 percent."

A Yes.

Q Do you agree that the date range referenced in this page, the 1968 to 1985, that corresponds to the epidemiological study that the Tarawa Terrace water modeling was supporting?

A The period of "epi" study -- yes, that's what it was.

Q Okay. And -- so do you agree that this report is saying that AH Environmental, who authored it, estimated VOC losses of TCE and PCE from spiractors at the water treatment plant would be significant, though they estimated them as less than 15 percent?

MR. DEAN: Object to the form of the question. Out -- this is not something for which this witness has opined on.

A I haven't seen this report before. I haven't seen these calculations before so I can't answer that question.

MS. O'LEARY: Okay. Can we get -- you can set this aside for a minute. And could we get 60, please?

This will be Government Exhibit 9.

(Whereupon, Government's Exhibit Aral 9, ATSDR's Chapter F, "Simulation of the Fate and Transport of Tetrachloroethylene, PCE, for Tarawa Terrace," was marked for identification.)

BY MS. O'LEARY:

Q So Professor Aral I've handed you Government Exhibit 9, that appears to be the ATSDR's chapter F, "Simulation of the Fate and Transport of Tetrachloroethylene, PCE, for Tarawa Terrace."

A Yes.

Q Do you agree that's what this exhibit --

A Yeah.

Q -- appears to be?

Okay. And can you go to page F42?

A Yes.

Q All right. Professor, in the column on the left, it says, "Level four calibration."

Do you see that?

A Yes.

Q Okay. After that, it says, "The final stage of model calibration employed a simple mixing flow-weighted average model to compute PCE concentrations delivered to the Tarawa Terrace Water Treatment Plant from all active water supply wells and, subsequently, to the Tarawa Terrace water supply network. For each stress point month of the simulation period, from January 1951 to December 1994, the PCE concentration simulated at each active water supply well is weighted by the

respective well discharge to compute a weighted-average PCE concentration. This weighted-average concentration was considered the monthly average PCE concentration delivered to the Tarawa Terrace Water Treatment Plant."

A Yes.

Q One question: When this mentions "well discharge," does that mean the water coming out of the well and going to the water treatment plant?

A Yes.

MR. DEAN: Object to the form.

A Yes.

BY MS. O'LEARY:

Q And do you agree that a -- a simple mixing flow-weighted average has no calculation where contaminants in the water coming out of a well are lost from the water supply before being distributed?

A Can you repeat that --

Q Sure.

A -- question.

Q Do you agree that a simple mixing flow-weighted average --

A Uh-huh.

Q -- calculation does not have a

calculation where contaminants in the water from wells is lost in the water treatment plant?

MR. DEAN: Object to the form.

A Where -- where does the loss come into this calculation --

MR. DEAN: That's --

A -- in your understanding? I don't understand that.

BY MS. O'LEARY:

Q I don't -- I'm not trying to suggest it does, Professor Aral. I'm trying to confirm that -- I'm understanding correctly that there is no loss calculation of contaminants in a simple mixing flow-weighted average calculation.

MR. DEAN: Object to the statement --

A At the water treatment plant?

BY MS. O'LEARY:

Q At the water treatment plant?

A Yeah. Yeah. That's what it means.

Q Okay. So you would agree that in a simple mixing flow-weighted average calculation, no -- no contaminants that enter the water treatment plant are modeled to be lost in the water treatment plant?

MR. DEAN: Object to form.

A Well, that's -- what numbers are we using to calibrate the water treatment plant database is important here. But that equation does not include contaminant losses, definitely.

BY MS. O'LEARY:

Q Okay. Would you agree that a simple mixing flow-weighted average does not have any calculation to simulate physical processes whereby contaminants could be loss in treatment?

A That's correct.

Q Okay. Professor Aral, do you agree that the ATSDR Tarawa Terrace model simulated PCE concentrations in water coming out of the water treatment plant as the same as the mixture of water entering the water treatment plant?

A It depends on the data available. If the data we have used or ATSDR has used is the treated water, that's the -- that should include the losses that is happening in the water treatment --

Q Uh-huh.

A -- plant. If not, it's just the entry concentrations.

Q My question is -- is about how the model function not about which data it was calculated to.

A The mixing model does not include any loss effects.

Q Okay. And the mixing model is what was used to simulate the water treatment plant in the ATSDR's model; is that correct?

A That's correct.

Q If we go back to Exhibit 8, which was that report from AH Environmental --

A Yes.

Q -- it's the one that had on page 5-1, but it's -- at the bottom right -- -71486.

A Yes.

Q Okay. That last paragraph, the last sentence, is where it says, "Considering the uncertainty and the estimates over the fall height from weir formed by the pipe, the removals for TCE and PCE were likely to be less than 15 percent."

Now, I understand you, you know, you haven't --

A You have to speak louder, please.

Q Sure.

So I understand you didn't -- you haven't seen this report before. I just have a -- a question about, you know, what could be done on the Tarawa Terrace model.

Could you have applied a percentage reduction to the numbers that come out of the Tarawa Terrace mixing model?

MR. DEAN: Object to the form of the --

A Arbitrarily?

MR. DEAN: -- question.

BY MS. O'LEARY:

Q Well, no. Not arbitrarily --

A I mean --

Q -- but -- but could you -- I mean, just as a calculation, could that have been done?

A Right.

MR. DEAN: Object to the form.

A We -- we wouldn't do that.

BY MS. O'LEARY:

Q What do you mean?

A We wouldn't --

Q Who is "we"?

A We wouldn't apply a certain percentage of loss, in quotes, arbitrarily to any computation of our environment.

Q I -- I understand that. I don't mean to suggest you would.

My -- my question is though, like, if the

ATSDR had, you know, told you that they estimated treatment losses at a certain percentage, could you have applied that percentage to reduce the simulated values?

A We wouldn't do that.

Q Why not?

A Because we have to compute something that we use. It's that -- simple as that.

Q What do you mean you have to compute something you use?

A If there's a certain loss in a process --

Q Uh-huh.

A -- we have to model that, understand that process, and that process gives us a certain percentage of loss. And then we can use that number as the outcome of treatment at water --

Q Okay.

A -- treatment plant.

Q So if someone else had calc- -- had calculated what that would be, you could have used it?

A In ATSDR calculations on Camp Lejeune, we never relied on somebody else's calculations, we relied on our calculations.

Q Right.

A You just said --
Q Well, I'm --
A -- if somebody else --
Q Uh-huh.
A -- has calculated something, wouldn't you have used it?
My answer is no.
Q But couldn't someone -- some other part of ATSDR other than MESL have done that and given it to you to --
A If --
Q -- use?
A If they had done an analysis of that, yes, of course.
Q Okay. And would you expect to see gains in contaminant concentrations going through a water treatment plant?
A That's very unusual.
Q Why is that very unusual?
A If you treat some chemical through a treatment plant, it's supposed to reduce the concentration.
Q Okay. And Professor Aral, would you like to take a -- a break or would you like to keep going?

A I'm okay.
Q Okay.
MS. BAUGHMAN: I think we are having lunch at noon so you want to keep going for 20 minutes?
MS. O'LEARY: Sure.
MS. HORAN: Can we just take a two-minute break for water and then can take a break in 20 minutes for our lunch break?
MS. BAUGHMAN: Sure.
MS. O'LEARY: All right. Can we go off record for -- just briefly.
THE VIDEOGRAPHER: The time right now is 11:39 a.m. We are off the record.
(Whereupon, there was a recess taken from 11:39 a.m. to 11:39 a.m.)
THE VIDEOGRAPHER: The time right now is 11:39 a.m. We are back on the record.
MS. O'LEARY: Thank you. Professor Aral, we are going to stay in the same exhibit, it's the Tarawa Terrace chapter A report.
Oh, sorry. I guess that's not the

same, is it? It's going back from the environmental report. It should be -- it should have --

THE WITNESS: Chapter A?

MS. O'LEARY: Chapter A. It should have a sticker that says --

THE WITNESS: Exhibit 3?

MS. O'LEARY: -- Government Exhibit -- yes.

THE WITNESS: Okay.

MS. O'LEARY: You are ahead of me.

THE WITNESS: Okay.

BY MS. O'LEARY:

Q Okay. Can you go to page A26 in the -- you should see a table A8.

A Yes.

Q Okay. So this table, it says it's a, "Summary of calibration targets and resulting calibration statistics for simulation models used to reconstruct historical contamination events at Tarawa Terrace and vicinity, U.S. Marine Base Camp Lejeune, North Carolina."

And the question I have for you is about the third line. So the column on the left says there's a "calibration level" and then next to it it

says "analysis type."

So the Calibration Level 3 says it's, "Contaminant fate and transport supply wells."

Do you see that?

A Yes.

Q And then is -- is this saying that the calibration target for contaminant fate and transport at the supply wells was one half order of magnitude or model bias ranging from 0.3 to 3?

A That's what it says, yes.

Q Okay. And is it -- is it saying if you look at number four the calibration level four --

(Whereupon, the court reporter requests clarification.)

BY MS. O'LEARY:

Q The calibration level four, is it saying the -- for the mixing model treated water at the water treatment plant --

(Whereupon, the court reporter requests clarification.)

BY MS. O'LEARY:

Q Treated water at the water treatment plant, the calibration target is the same as in contaminate fate and transport at supply wells. So that plus or minus one half order of magnitude or

model bias ranging from 0.3 to 3.

A Yes, I see that.

Q Okay. Is --

MR. DEAN: For the record, the document reflects that there are two footnotes. Specifically, footnote number two that's applicable to calibration levels three and four and you did not point that out to the witness.

MS. O'LEARY: Okay. That -- that footnote says there's more details in chapter F report; correct?

MR. DEAN: Correct.

MS. O'LEARY: Yeah.

BY MS. O'LEARY:

Q So Professor Aral, you said that's what the table says. Is that your understanding of what the calibration targets for calibration levels three and four were, the plus or minus one half order magnitude or model bias ranging from 0.3 to 3?

A That's what the table says, yes.

Q But I mean, from your memory, is that what they in fact were, the calibration targets?

A I think we looked at the ensemble of what we see at the water treatment plant as opposed to

specific numbers being in a certain range.
Q Is that at Hadnot Point or Tarawa Terrace, where you looked at the ensemble?
A I think with respect to mixing model, it was also Tarawa Terrace.
Q Would that be in the Tarawa Terrace reports somewhere?
A I don't recall.
Q If we could go to -- this will be 60, which is Exhibit 9, that you should have. It's the chapter F report.
A Yes.
Okay.
Q Okay. On page 33 --
MR. DEAN: F33?
MS. O'LEARY: That's right.
MR. DEAN: Okay.
BY MS. O'LEARY:
Q And...
A Yes.
Q Okay. So Professor Aral, on F33, on the left-hand side you should see a table F13.
Do you see that?
A Yes.
Q Okay. And then -- oh, I'm sorry. I

directed you slightly off.

Can you go back one page to F32? So just the previous page.

Okay. Underneath the table there, there's some text. And in the column on the left there's a paragraph that begins, "Simulated and corresponding observed PCE concentrations at Tarawa Terrace and local water supply wells are listed in table F13 and are portrayed in this report as a scatter diagram, F12, and as time-series graphs at individual wells, figures F13 to F17."

Do you see that?

A Yes.

Q And then if we go onto the next page, we have F13, the table.

Do you see that?

A Yes.

Q And then there's a figure 12 as well on F33.

A Yes.

Q Do you see that?

Okay. So do you agree that table F13 shows all of the supply well observed PCE measurements that were used for calibrating, in level three, the contaminant fate and transport

model?

A Can you speak louder, please?

Q Yeah.

Do you agree that table F13 --

A Yes.

Q -- shows the supply well observed measurements that were used for calibrating the contaminant fate and transport models, so level three?

A I believe so, yeah.

Q Okay.

A I mean, I have to check every one of them separately. If they have made a typo error, I'm not sure.

Q Okay. Do you have any reason to think they have made a typographical --

A I don't --

Q -- error?

A -- think so.

Q And as you look at table F13, do you agree that these observed measurements are only from the years 1984, 1985, and 1991?

A Where did you see the '84? I didn't see the '84.

Q Actually, right. I don't see the 1984.

So only 1985 and 1991?

A That seems correct.

Q Okay. So if this table is the observed measurements that were used for calibrating contaminant fate and transport --

A Yes.

Q -- does that mean the Tarawa Terrace fate and transport model was calibrated without observed concentrations from 1953 to 1984?

A That's correct.

MS. O'LEARY: Then can we get 59?

(Whereupon, Government's Exhibit Aral 10, Document, was marked for identification.)

MS. O'LEARY: There you go. This will be Government Exhibit 10.

BY MS. O'LEARY:

Q And if you could go to page A10, please?

A Yes.

Q So there -- table E5 there says --

A Yes.

Q -- "Summary of selected analyses for tetrachloroethylene, PCE; trichlorethylene, TCE; and total dichloroethylene, DCE; and water samples collected at monitor wells during ABC One-Hour

Cleaners operable units one and two, and by the North Carolina Department of Natural Resources and Community Development, Tarawa Terrace and vicinity, U.S. Marine Base Camp Lejeune, North Carolina."

Do you see that?

A Yeah.

Q Am I correct in understanding that these PCE and TCE measurements from monitor wells around ABC One-Hour Cleaning -- Cleaners, excuse me, were not used in calculating the fate and transport model of Tarawa Terrace?

A If I recall this report, there were 36 databases that were used. And if this is the 36 database that -- that existed in that analysis, that must be it.

Q Well, if -- if you go back to Exhibit 9, which was chapter F that we were just looking at, we were just looking at table F13. So that was on page F33.

A Okay. I think this table refers to monitoring wells, the other table refers to pumping wells.

Q To supply wells, right?

A Supply wells.

Q Yes. And so am I correct in

understanding that these monitoring well measurements in table E5 were not used in calibrating the fate and transport model?

A I think you should ask the author of that.

As far as I know, the numbers of wells that were used in calibrating this model was 36. And that was the total available database at the site at that time.

Q Right. So just -- if we go back to table F13, that was on page F33, there are 36 entries --

A Okay. So --

Q -- in that table?

A Okay. If that's the case, then that's the 36 number that is coming to my mind.

Q So that's all that was used for calibrating --

A Right.

Q -- the fate and transport model?

MR. DEAN: Object to the form.

A That was reported in chapter F as such, yes.

BY MS. O'LEARY:

Q Okay. And I'm going to go back to Tarawa Terrace chapter A. And --

MR. DEAN: I feel like I'm playing tennis.

BY MS. O'LEARY:

Q -- page A16.

So I have some questions for you about mass loading at Tarawa Terrace.

A Yes.

Q Okay. On page A16, there is a figure, figure A3 that says it's a, "Chronology of events related to supply and contamination of drinking water, Tarawa Terrace and vicinity."

Do you see that?

A Yes.

Q Okay. I see in figure A3 in -- there's an entry for 1953 that says "ABC One-Hour Cleaners begins operations using existing ST-STA" --

(Whereupon, there was an interruption.)

BY MS. O'LEARY:

Q -- "ST-STA for disposal of wastewater."

Do you see that?

It's --

A Okay.

Q -- here.

A Yes.

Q Okay. Was the start date of ABC Cleaners used as an input in the Tarawa Terrace water models?

A I think it was 1953.

Q Okay. Was that input as a start of mass loading date in the Tarawa Terrace models?

A Yes.

Q Okay. Is the start of the mass loading significant to the output of the model?

MR. DEAN: Object to the form.

A It affects the output, yes.

BY MS. O'LEARY:

Q Okay. And did you -- no.

If I look again at figure A3, it says, in the -- the third bar down on the left, around 1960 --

A Uh-huh.

Q -- the's an entry that says "1960s ABC One-Hour Cleaners installs floor drain to septic system."

Do you see that?

A Yes.

Q Okay. Did ABC -- did the ATSDR model of Tarawa Terrace include changes in the mass loading rate of PCE?

A Mass loading rate in our models were

calibration parameters. That's what we did in calibration, used numbers to adjust the mass loading rate to match the water --

(Whereupon, the court reporter requests clarification.)

A -- match the water treatment plant concentrations.

BY MS. O'LEARY:

Q Okay. But the input that was used in the calibrated TT-model for mass loading of PCE --

A Uh-huh.

Q -- was that constant throughout the Tarawa Terrace model timeframe from when it started to when it stopped?

A That's correct.

Q Okay. So does that mean the model did not have any change in mass loading that would correspond to this ABC One-Hour Cleaners installing floor drain to septic system?

A That -- that's a internal process where the contaminants gets into the aquifer system. We are not looking at the internal processes of how contaminants are manipulated in the ABC cleaners. We are interested in what is discharged into the aquifer as a dilute phase contaminant level.

Q So if ABC Cleaners changes where they -- where they discharged their -- you know, whatever waste had the PCE, if that changed location, wouldn't that change how the contaminant moved through the aquifer?

MR. DEAN: Object to the form of the question.

A I mean, if you are talking about acres of land and you are talking about distances of miles, kilometers, discharge points separately discharging into an aquifer, it would affect the groundwater models. But ABC Cleaners is -- I assume is a point in our modeling idealization.

BY MS. O'LEARY:

Q What do you mean, is a point in our modeling idealization?

A In modeling we use mesh -- meshes. We describe the aquifer in terms of blocks of subsurface environments --

Q Uh-huh.

A -- that we input parameters that we know are coming from the -- either the aquifer database or the source database. This model is so large that the ABC Cleaners entry point is just a point on that mesh.

Q And -- and --
A It can't be more than that.
Q So if I understand correctly, then it spreads through the mesh according to the way the model operates?
A That's correct.
Q Okay. But AB- -- but the model had just constant mass loading?
A Yes, constant mass loading.
Q Okay.
A Whatever the calibrated value was.
Q Uh-huh. And we are going to go back to chapter F again, which is Exhibit 9.
A Okay.
Q And to page 12.
A F12 --
Q Yes.
A -- did you say?
Q And there's a table on the left, and on the right there's text.
A Okay.
Q Okay. That column on the right, at the top it says, "ABC One-Hour Cleaners always used PCE in its dry cleaning operations beginning during 1953 when the business opened.

"Hoff (phonetic) and" --

(Whereupon, there was an interruption.)

(Whereupon, the court reporter requests clarification.)

BY MS. O'LEARY:

Q Yeah.

"...when the business opened.

"Hoff and Higley PA (phonetic) deposition of Victor John Milts (phonetic) written communication April 12, 2001.

"A primary pathway of contaminants from drive cleaning operations at ABC One-Hour Cleaners to the soil and subsequently to groundwater was apparently through a septic tank soil absorption system to which ABC One-Hour Cleaners discharged waste and wastewater."

And it says, "Shriver 1985 reported that an inspection of the PCE storage area at ABC One-Hour Cleaners indicated that PCE releases could and did enter the septic system through a floor drain probably as a result of spillage in the storage area."

That's Roy F. Weston Inc. 1994. In addition -- F. Weston, Inc., 1994.

"In addition, spent PCE was routinely reclaimed using a filtration distillation process that produced dry still bottoms which, until about 1982" -- I'm going to skip the parenthetical -- "or 1984 and 1985, were disposed of on site generally by filling potholes in a nearby alleyway."

So do you agree that on this cat- -- this description in chapter F, the septic soil -- tank soil absorption system around ABC Cleaners was a primary pathway of contaminants from the dry cleaning operations?

A Yeah. Probably. Yes.

Q Okay. And are you aware based on -- you know, does it follow from what this paragraph said that ATSDR knew that ABC One-Hour Cleaners still waste was disposed of outside until 1982 or 1984 or 1985?

A In terms of location that doesn't make any difference for us.

Q But that -- that -- that is what ATSDR knew about disposal practices; correct?

A It seems so, yeah.

MR. DEAN: Objection to form.

BY MS. O'LEARY:

Q Okay. If the -- does the time when ABC

Cleaners stopped disposing of their solid still waste outside affect how the model performs in terms of accuracy?

So what I mean is if -- you know, if the ABC Cleaners stopped disposing of their solid still waste in potholes in 1982, would that be expected to reduce modeled contaminant concentrations?

MR. DEAN: Object -- object to the form.

A If you are referring to how we model the discharge from the ABC Cleaners, we looked at two different applications. One of them discharging at a point in the saturated zone --

BY MS. O'LEARY:

Q Uh-huh.

A -- that's the MT3DMS model --

Q Uh-huh.

A -- application. The other one is the discharging of the ABC Cleaners contaminants in the -- in the unsaturated zones of the aquifer. That's the TechFlowMP model.

So we looked at two different cases but both of them on a large scale map in a idealization that we have used is just a point.

Q Okay. And so that's one point. Is that

on the boundary of one of the 50 by 50-foot, like, squares --

A Yeah.

Q -- in the mesh?

A Yeah.

Q Okay. I have a question about the calibration process for mass loading at --

A Okay.

Q -- Tarawa Terrace.

So this is on page -- to start on page F30 of chapter F, which is Exhibit 9.

A Okay.

Okay.

Q All right. So there's text underneath the figure on that page.

Do you see that?

A F11?

Q No, I'm sorry.

F30.

A Yeah. F30, yeah.

Q F30. Okay.

So the text at the bottom of that page --

A Yeah.

Q -- in the column on the right-hand side near, sort of, the middle there's a sentence that

begins, "The initial mass loading rate."

Do you see that?

A Yes.

Q Okay. It says, "The initial mass loading rate applied to the model was 230 grams per day and was adjusted upward during model calibration. The final calibrated mass loading rate was 1200 grams per day."

And I was wondering why did you start with 230 grams per day?

A I think it was estimated the volume of discharge from a cleaner operation.

Q Like, an average cleaner operation or --

A No. Beginning operation -- beginning value for a calibration application.

Q Specific to a dry cleaner?

A Yeah.

Q Okay. And how did you end up at 1200 grams per day?

A Oh, we -- calibration means that. You adjust the parameter values to match the field data. So to get to the field data we observed in water treatment plant we had to increase the mass loading rates to that level.

Q Okay. And staying in chapter F, if you

can just go back to page F28?

A Okay.

Q And there's a section in the column on the right that's got the heading "Biodegradation."

Do you see that?

A F23, did you say?

Q F28?

A Twenty-eight.

Yes. Yes.

Q So under, "Biodegradation," it says, "Reductions of PCE concentration reported at water supply well TT-26 between September 1985 and July 1991, table F2, probably occurred largely by microbial mediated degradation such as reductive dechlorination."

And does that mean that biodegradation is called biodegradation because it involves microbes in the processes?

A Yes.

Q Okay. And does biodegradation rates of PCE depend on anything?

What I mean is, is the biodegradation rate of PCE always the same?

A Probably changes by temperature.

Q Okay. Would it vary by what microbes are

in the environment where the PCE is?
A I think biodegradation, referred to here, is the biodegradation of the chemical itself.
Q Right. Of -- of like --
A Right.
Q -- PCE into --
A Right.
Q -- TCE and on?
A Right.
Q Yeah. So -- so my questions are about the rate that that happens.
A Uh-huh.
Q So, you know, you mentioned temperature might affect that rate.
A Right.
Q What else would affect the biodegradation rate of PCE?
A Microbes are used sometimes to treat the contaminants. So my understanding is that the microbes in the aquifer affects the concentration values that is out there.
Q That's my last question on that area for a minute. Moving onto some questions about other parameters that were input into the Tarawa Terrace model.

First, what is bulk density?
A That's the dry density of soil.
Q Okay. And is bulk density used to calculate a retardation factor for a -- a particular chemical?
A That's correct.
Q If bulk density were calculated incorrectly, would that affect a calculation for a retardation factor?
A Yes, it does.
Q And if a bulk density value were calculated too high, would that cause a retardation factor to be higher or lower?
A If you are not changing any other parameter in that equation, it will be higher.
Q Okay. So they would vary together, bulk density and retardation factor?
A Yeah.
Q Okay.
A But there are other parameters in that equation.
Q Sure. Sure.
A Okay.
Q And then what is a distribu- -- distribution coefficient or KD?

A Okay. That describes the amount of soil that may be absorbed or -- a contaminant that may be absorbed on the soil system.

Q Ah. So it would be removed from a plume --

A Right.

Q -- by the soil?

A That's right.

Q Okay. And is it calculated by the fraction of organic carbon multiplied by an organic carbon water partition coefficient?

A That's correct.

Q So is fraction organic common -- carbon, excuse me, often called FOC?

A Yes.

Q And is the organic carbon water partition coefficient often called KOC?

A That's correct.

Q And is distribution coefficient often called KD?

A That's correct.

Q If bulk density were calculated incorrectly, would that have an impact on KD?

A No.

Q No. Okay.

If FOC were determined incorrectly, would that impact KD?

A Yes, of course.

Q Because it's multiplied by that --

A Right.

Q -- partition coefficient?

A Right.

Q And we'll stay in chapter F, I think right where -- around where we were.

Can you go to page F27, that goes to page F28?

A Yes.

Q All right. In the column on the right, the last paragraph starts, "Estimates of retardation factors."

Do you see that?

A Yes.

Q Okay. It says, "Estimates of retardation factors and distribution coefficients for PCE migration within the Tarawa Terrace aquifer or Castle Hayne aquifer are unknown, and initial estimates applied to the MT3DMS model were based on literature sources. Roberts, et al., 1986 reported retardation factors determined from a field scale investigation of PCE migration through a sand

aquifer that ranged from 2.7 to 5.9 based on the collection of high resolution synoptic data during a period of about two years.

"Retardation factors increased directly with increasing time but at a decreasing rate. Hoffmann, 1995, reported highly controlled laboratory column determination of distribution coefficients for PCE migration through gravels, sands, and silt.

"Of the approximately 150 samples analyzed the distribution coefficients for sand ranged from 0.25 to 0.76 milliliters per gram, and averaged 0.39 milliliter per gram. Corresponding values for silts ranged from 0.21 to 0.71 milliliters per gram and averaged 0.4 milliliters per gram.

And it goes on to say that, "Neither the field scale experiments reported by Roberts, et al., 1986, know that -- nor the laboratory results of Hoffmann 1995 related to Camp Lejeune or even to North Carolina, the solute investigated in both studies was PCE. And PCE migration was observed through porous media of sands and silt -- sand and sands and silts similar to Camp Lejeune."

Did I read that correctly?

A Yeah.
Q Okay. So am I understanding correctly that the ATSDR had determined estimates of KD, distribution coefficients and retardation factors within the Tarawa Terrace aquifer and Castle Hayne aquifers, were unknown?
A Yeah. That the -- from what -- what you just have read, I think it's coming from literature -- literature data.
Q Okay. So in -- in calibrating the ATSDR's Tarawa Terrace model, did ATSDR select an initial KD value from the literature values that were reported?
A That's what it seems, yes.
Q Okay. And --
A But there's also data on KD at the site, as far as I recall.
Q Is it KD or FOC data at the site?
A I don't recall completely but I think it was KD.
Q Okay. So from what we read on F27 to 28, the literature range ATSDR reported for KD averaged 0.39 milliliters per gram with a range of 0.25 to 0.76 milliliters per gram for sands.
Right?

A Uh-huh. Yeah.
Q And for silts, it was an average 0.4 milliliters per gram and a range of 0.21 to 0.71 milliliters per gram.
A Uh-huh.
Q Okay. And that literature range was from laboratory experiments on sands or silts but not related to Camp Lejeune or North Carolina.
A That's right.
Q Okay.
A That's right.
Q And after calibration, am I correct that the ATSDR selected 0.14 milliliters per gram as the KD for the Tarawa Terrace calibrated model?
MR. DEAN: Object to the form.
A Well, that seems to be the number that -- where -- where did you get that number? I don't --
BY MS. O'LEARY:
Q It wasn't in that part but I thought you might know that. That the --
A No. Not on the top of my head, no.
Q Okay. Would you agree that 0.14 milliliters per gram is lower that ten literature ranges ATSDR reported for both sands and silts?
A Uh-huh.

MR. DEAN: Object to form.
BY MS. O'LEARY:
Q For calculating KD, you had agreed that that was done by multiplying the fraction of organic carbon by that --
A Yes.
Q -- partition coefficient, KOC; is that right?
A Yes.
Q The KOC, the organic carbon water partition coefficient, is that compound specific or different for PCE than TCE?
A It's compound specific --
Q Yes.
A -- of course.
Q Of course. Okay.
And is --
A Yeah.
(Whereupon, the court reporter requests clarification.)
BY MS. O'LEARY:
Q Sorry.
Are values for the organic carbon water partition coefficient for each chemical available in literature?

A Yeah.
Q Okay. You said that you had read Alex Spiliotopoulos's report.
Did I hear you correctly?
A Yes.
Q And I -- I believe he included tables with fraction of organic carbon measurements from Camp Lejeune.
A Yes.
Q Do you know why the ATSDR didn't use those FOC estimates?
MR. DEAN: Object to the form.
A I don't know.
BY MS. O'LEARY:
Q Like, did -- did the ATSDR use those fraction organic carbon estimates when they were calculating KD for Tarawa Terrace?
A I don't know what they have done to come up with these retardation coefficients. But if that was available, I'm sure they have used it.
Q Okay. Do you -- if the fraction organic carbon data from Camp Lejeune were buried significantly --
A It -- it will -- it will vary by soil type, definitely.

Q Okay. Would that -- if it varies, would that be a reason not to use it to calculate the --

A I wouldn't know --

Q -- KD?

A -- why they have not used it if they have not used it.

Q But if you had fraction organic carbon data that varied a lot, would that cause you not to use it in determining a KD?

MR. DEAN: Object to the form of the question.

A It's -- it's a judgment call. If -- if you know enough information on what is at the site, it may be better to use it.

BY MS. O'LEARY:

Q Okay. And this -- I think you mentioned this phrase but I just wanted to check my understanding of what it is.

So you mentioned retardation factor, I believe?

A Yes.

Q What is a retardation factor?

A Due to absorption of chemicals in a soil, it acts as if -- a reduction factor of the velocity of the contaminants in the aquifer.

Q A reduction in velo- -- velocity relative to what?
A To the retardation coefficient of one.
Q Is that for water, the "one"?
A No, it's not a water issue.
It's -- it's a issue of density. It's a function of distribution coefficient and the porosity.
Q Okay.
A You may ignore retardation factor --
Q Uh-huh.
A -- or you may calculate it as ATSDR has done.
Q And if you calculate it, then that's going to be a retardation factor specific to a compound?
A The distribution coefficient is specific to a compound --
Q And --
A -- because KOC is a --
Q Right.
A -- specific to a compound.
Q And so -- and -- and distribution coefficient is used in calculating the retardation factor though; correct?

A Can you speak --
Q Yeah.
A -- louder, please?
Q A distribution coefficient is used in calculating a retardation factor; correct?
A That's correct.
Q Okay. So a particular calculated retardation factor is going to be specific to a compound; correct?
A That's correct.
Q Okay. And as K- -- KD, distribution coefficient, increases, what happens to retardation factor?
A All the other parameters kept constant --
Q Right.
A -- retardation increases.
Q Okay. And as retardation factor increases, does that mean the contaminant is moving more slowly relative to the groundwater flow --
A Yes --
Q -- speed?
A -- that's correct.
Q Okay.
MS. O'LEARY: And I want to, actually, turn to -- actually, this would

actually be a good place to stop.

MS. BOLTON: Yeah.

MS. O'LEARY: Do we know if lunch has arrived?

MS. BOLTON: I think it's here.

MS. BAUGHMAN: It's here.

MS. O'LEARY: Then we'll take a break now.

Thank you.

THE WITNESS: Okay. Thank you.

THE VIDEOGRAPHER: The time right now is 12:18 p.m. We are off the record.

(Whereupon, there was a recess taken from 12:18 p.m. to 1:00 p.m.)

THE VIDEOGRAPHER: The time right now is 1:00 p.m. We are back on the record.

MS. O'LEARY: Thank you.

BY MS. O'LEARY:

Q And Professor Aral, if you could pull back up Government Exhibit 9, the chapter F report --

A Uh-huh.

Q -- for Tarawa Terrace and then go to page F28?

A Uh-huh.
Q And in the column on the left, the first paragraph, the bottom of that paragraph, it says, "An initial distribution coefficient."
Do you see that?
A Yeah.
Q Okay. So it says, "An initial distribution coefficient of 0.4 milliliters per gram or 0.000014 cubic feet per gram was applied uniformly to all layers of MT3DMS model for all stress periods. The final calibrated value was 0.14 milliliters per gram" -- skipping the parenthetical -- "similarly applied and the calibrated retardation factor was 2.9."
So Professor Aral, having seen now that page, do you agree that in the calibrated model for the Tarawa Terrace, the -- the distribution coefficient was 0.14 milliliters per gram?
MR. DEAN: Objection to the form.
A The retardation coefficient was 2.9.
BY MS. O'LEARY:
Q Right. But do you agree the distribution coefficient was the 0.14 milliliters per gram?
MR. DEAN: Same objection.
A Yeah, but I don't recall that number. It

depends on whether it was a number related to the corrected density or earlier density, which was used.

BY MS. O'LEARY:

Q What do you mean "corrected density"?

A Well, in MT3DMS, I think there was a problem which was recognized in terms of density values, what density was not used and the other wet density was used. So it was corrected.

So I don't recall this number. If this is the corrected value, it must be correct.

Q And who corrected the bulk density value in --

A Bob Faye.

Q -- in MT3DMS?

A Bob Faye.

Q Bob Faye.

And where would you expect a record of that correction on bulk density to be in the reports?

A Was I aware of that?

MR. DEAN: Object to the form.

It's not in the report --

A Was I aware of that or how would I know that or --

BY MS. O'LEARY:
Q Well, you said that --
A What's the question?
Q Yeah. You said that Bob Faye --
A Uh-huh.
Q -- caught the bulk density error.
A Uh-huh.
Q And I asked where you would expect the fact that Bob Faye corrected bulk density to be in the ATSDR reports?
MR. DEAN: Object to the form. It's not in the reports.
A Bob density -- Bob Faye corrected the bulk density value and adjusted the distribution coefficient to the observations that he has in his hand, and the result came out to be the same retardation coefficient that you are reporting here.
BY MS. O'LEARY:
Q Retardation coefficient or distribution coefficient?
A Retardation coefficient.
Q Do you mean retardation factor?
MR. DEAN: Objection to the form.
A Retardation factor. It's the same terminology.

BY MS. O'LEARY:

Q So do you have any reason to think that what's listed in the chapter F report as the final calibration value for distribution coefficient -- so 0.14 milliliters per gram --

A I assume --

Q -- is wrong?

A -- this -- this -- I have assumed this is the correct number.

Q The zero -- 0.14 milliliters --

A Yeah.

Q -- per gram?

Okay.

A Yeah.

MR. DEAN: Object to the form. The report --

MS. O'LEARY: And --

MR. DEAN: -- is dated February 2008.

MS. O'LEARY: And I'd like to move -- this will be number 40, supplement six from the Hadnot Point reports.

It looks like this will be Government Exhibit 11.

THE WITNESS: Okay.

(Whereupon, Government's Exhibit Aral 11, Supplement Six from the Hadnot Point Reports, was marked for identification.)

THE WITNESS: Thank you.

MR. DEAN: Thank you.

BY MS. O'LEARY:

Q And Professor Aral, I'd like to go to page S6.14, so 14.

A Say that number again, please?

Q Yeah. S6.14. It will be on the bottom --

A Of which page?

Q -- left of the page.

A Okay.

Q Yeah. The page numbers start S6 on all of them.

A Yeah. One, four.

Yeah.

Q Okay. So there's a section labeled "Sorption." Under that it says, "Sorption in the HP, HB study area is assumed to be similar to sorption in the TT study area of USMCB Camp Lejeune described in Faye 2008."

"Sorption processes, i.e. adsorption and absorption for HPIA and HPLF models were represented in MT3DMS by using a linear isotherm sorption model. The input data required to simulate sorption included porosity, distribution coefficient, and soil bulk density. Constant values were assigned to the aforementioned model parameters throughout the model owing to the lack of site-specific field data. MT3DMS uses values assigned to porosity, distribution coefficient, and soil bulk density to compute a retardation factor."

And then we'll stop there.

So Processor Aral, do you agree that data sorption in MT3DMS -- or excuse me. Let me back that up.

Do you agree that MT3DMS was used in both Tarawa Terrace and Hadnot Point/Holcomb Boulevard water models?

A Can you repeat that --

Q Yeah.

A -- question louder, please.

Q Was --

MS. BAUGHMAN: Actually, if you don't mind, I meant to put something on the record about that.

We -- we talked to Dr. Aral at the break about the fact that he can't hear you. And he's guessing at what you are asking him often because he feels he doesn't feel comfortable continuously asking you to raise your voice.

So you are risking having a record that is not reliable and I'm -- I'm -- I'm putting you on notice right now: If you don't raise your voice, he can't hear you. He doesn't feel comfortable continuously asking you so you need to raise your voice.

You are not -- when we ask you to raise your voice, you are just repeating the question and not making it louder.

BY MS. O'LEARY:

Q Professor Aral, are you uncomfortable asking me to speak more loudly?

A Yes, I am.

Q Okay. Why?

A Because I'm a person of certain values and standards. I cannot keep asking the same question to the person I'm talking to.

I expect that person to respond to my

question in the first time that they hear the question.

Q Well, if you can't understand me, please ask me to speak louder.

A Well, you may say that but I have a personality that doesn't allow me to do that.

Q So --

MS. BAUGHMAN: So our request is that you continuously raise your voice.

BY MS. O'LEARY:

Q Professor Aral, do you agree that the MT3DMS was used in both the Tarawa Terrace and Hadnot Point/Holcomb Boulevard water models?

A That's correct.

Q And do you agree that MT3DMS uses input values related to porosity, distribution coefficient, and soil bulk density?

A Yeah.

Q And do you agree, based on what it says here on page S6.14, that the ATSDR concluded that sorption in the Hadnot Point/Holcomb Boulevard study area was similar to sorption in the Tarawa Terrace study area?

A That's what it says.

Q And do you agree that MT3DMS is a model

that is trying to simulate sorption?
A I have not used MT3DMS lately so I don't remember the details of the input parameters on it.
Q I mean, the input parameters of porosity, distribution coefficient, and soil bulk density are -- are in what we just --
A Yeah. But --
Q -- read.
A -- you are talking about sorption.
Q Right.
A You asked that.
Q But those input parameters relate to sorption, don't they?
A Adsorption and sorption is the same thing? I don't think so.
Q Well, what is the difference?
Aren't they both two examples of sorption?
A No, it's not.
Q How are they different?
A One of it is absorption into the soil --
Q Uh-huh.
A -- particles, the other one is absorption -- sorption onto the surface of soil particles. There's a big difference.

Q Okay. But for -- does MT3DMS model both?
A That's what I said, I have not used MT3DMS lately. So if there's a distinction between adsorption and sorption --
Q Uh-huh.
A -- whether it addresses that, I don't remember that.
Q But what does that have to do with porosity or distribution coefficients or soil bulk density and whether those would be similar at Tarawa Terrace and Hadnot Point --
A That's correct.
Q -- Holcomb Boulevard?
A But those refer to retardation coefficient evaluation, not sorption.
Q Isn't the retardation factor trying to be a way to account for --
A It --
Q -- sorption?
A No. It accounts for adsorption.
Q Right.
A Uh-huh.
Q Okay. Did you -- why would -- or, sorry.
Going on -- still on page S6.14 at the top of the column on the right --

A Okay.

Q -- it says, "Typically, KD values are calculated based on laboratory scale experimental data that quantify partitioning behavior for a chemical in simple systems, e.g. octanol water in field data are estimates, for the amount of organic material present in the soil or aquifer material of interest.

"Model specific KD values for benzene, 0.11 liter per kilogram; TCE 0.15 liters per kilogram; and PCE, 0.3 liters per kilogram were derived by using partitioning data for each chemical. An assumed value of 0.002 for the site specific organic carbon fraction of aquifer material and refinement during the model calibration process. Final model-specific KD values are well within the range of values calculated for multiple sources of partitioning data."

So do you agree that in the calibrated model for Hadnot Point, the ATSDR used 0.3 liters per kilogram for PCE?

A This is what this report indicates. That's --

Q Do you have any --

A -- correct.

Q -- reason to think that's incorrect?
I'm sorry, I -- I interrupted you. What were you saying?
A Do I have any -- do I have any reason to believe that these numbers are incorrect?
Q Are not what the ATSDR used in the Hadnot Point model.
A Well, they -- they say that they have used it. I haven't written this report so they must have used it.
Q Okay. Is 0.3 liters per kilogram equivalent to 0.3 milliliters per gram?
A I have no idea.
Q You don't know?
A No, not on the top of my head. I need a calculator, maybe a computer to do -- to evaluate that.
Q Aren't there one thousand milliliters in a liter and one thousand grams in a kilogram?
A I'm so tired. I can't do that off the top of my head.
Q Okay. And do you know why the ATSDR decided to use a different distribution coefficient in Hadnot Point than what they had used in Tarawa Terrace, even though they had said they assumed

similar sorption?

MR. DEAN: Object to form.

A Again, you are using sorption instead of adsorption.

BY MS. O'LEARY:

Q Uh-huh.

A Sorption is a different process.

I don't know what you are referring to in terms of KD values referring to sorption.

Q Well, why did the ATSDR mention in this section on sorption --

A I --

Q -- and KD values that they felt the sorption in the two study areas was similar?

A I have not written this report so I will not be able to answer that.

Q Okay. Can we go back to the Tarawa Terrace chapter A report which is Government Exhibit 3 and go to page A41.

(Whereupon, there was a discussion off the record.)

BY MS. O'LEARY:

Q Okay. Were you involved in the analysis of degradation by-products in the Tarawa Terrace model?

A Yes. I was involved in the use of TechFlowMP model in degradation by-products.

Q Okay. In page A41, in the column on the right near the top -- this actually starts the fourth line from the top -- there's a sentence that says, "The biodegradation rate was determined from field data and the calibration process."

Do you see that?

A Yeah.

Q Does that match your understanding of how the biodegradation rate was determined in Tarawa Terrace?

A It was a calibration parameter, definitely. Probably we have started with some initial values that we expected to see in the soils of Camp Lejeune as a generic database.

So that's the starting point.

Q What do you mean from a "generic database"?

A Well, for example, there's a characterization of the aquifers in the Camp Lejeune. Different soil types has different values for these parameters. Probably we used those soil types to come up with the generic values that we started with, then calibration parameter takes

precedence and adjusts itself.

Q When you say "generic values," do you mean from measurements at the site or from, like, literature reference values?

A Its says here "biodegradation rate was determined from field data." So there must be some field data that we have used in that.

Q That would mean from Camp Lejeune?

A Yeah.

Q Okay. And --

A That's what I understand.

Q And then if you could go to the Tarawa Terrace chapter F report, which is Government Exhibit 9, and to page F28?

A Yes.

Q And there's a column on the right, and it says, "Biodegradation."

Do you see that?

That -- there's a label in the column on the right --

A Uh-huh.

Q -- that says, "Biodegradation." And then there are some, like, values listed. And I want to turn --

A Can you show me on that?

Q Yeah.
A Oh.
Q So here's biodegradation and then can you look at --
A What did you say, F20 or F28?
Q F28.
A Okay.
Yeah. Okay.
Q Okay. So in that biodegradation section, the -- the last paragraph.
A Yeah.
Q Okay. So there it says, "The PCE concentrations at water supply well TT-26 on September 25, 1985, and July 11, 1991, were 1100 and 350 micrograms per liter, respectively. And the elapsed time was 2,151 days. Applying these data to equation three yields a degradation rate of 0.00053 per day."
Do you see that section?
A Uh-huh.
Q Okay. And so trying to relate what we just read in this chapter F to what we just saw in chapter A about field data for biodegradation rate, am I understanding then that these measurements at TT-26, the September 25th, 1985 and July 11th, 1991,

those are the field data where ATSDR started with to calculate biodegradation rate?

A Probably, yeah.

Q Okay. Do you see anything in here describing a calibration process where that was refined?

MR. DEAN: Object to the form.

A In reference to this?

BY MS. O'LEARY:

Q To the biodegradation rate.

A In reference to the MT3DMS application or TechFlowMP application?

Q Well, as I look at chapter F, page F28, I don't see any dis- -- reference to whether it's MT3DMS or TechFlowMP or both.

A Yes --

Q It's just saying --

A -- exactly. But this report that you are showing me, chapter F, is PCE analysis coming from MT3DMS.

Q Uh-huh.

A You started your questioning by asking me biodegradation rates of TechFlowMP, now you are showing me chapter F --

Q Yeah.

A -- again, which is MT3DMS analysis.
Are you asking me whether we have used these numbers in TechFlowMP, or what is the question here?
Q I mean, that is an eventual question, yes. Did you --
A Okay.
Q -- use the same --
A Can you repeat that question to me now?
Q Did you also use degradation rate of 0.00053 per day in TechFlowMP?
A That --
MR. DEAN: Object to the form.
A -- that could be the starting point but it's a calibration parameter, altogether.
BY MS. O'LEARY:
Q Was that the value in the calibrated model of TechFlowMP?
A I remember biodegradation rates. Probably it was, yes.
Q Okay.
A Probably. I'm not sure.
Q And still on page F28, going -- is it -- it spans F28 to F29.
A Okay.

Q So after the sentence I already read, it says, "Potentiom metric levels shown in figures F7 and F8 indicate that while TT-26 is located on a direct advective pathway from ABC One-Hour Cleaners. This PCE mass migrates down gradiant toward and away from well TT-26. To the extent that migration of PCE mass toward and away from well TT-26 occurred at about equal rates from 1985 to 1991, the computed degradation rate of 0.00053 per day approximates a long term average degradation rate. On the other hand, if a significant quantity of the PCE degraded in the vicinity of well TT-26 was replaced by advection, then the degradation rate computed using equation three is probably a minimum rate."

Do you agree?

MR. DEAN: Object to the form.

A This --

MR. DEAN: Does he agree -- hold on a second.

Object to the form. We agree you read the paragraph correctly but you continue to read to him a -- a report that he did not participate in --

MS. O'LEARY: Yeah.

THE WITNESS: Right.

MS. O'LEARY: No, I under-
MR. DEAN: -- nor did he author.
MS. O'LEARY: I understand that.
BY MS. O'LEARY:
Q My question is, do you agree with what this report says that that biodegradation rate --
A This report --
Q -- would repre- -- would represent a minimum rate if -- if --
MR. DEAN: Objection.
BY MS. O'LEARY:
Q -- travel to and from TT-26 aren't the same?
MR. DEAN: Object to form.
A This report talks about what they have done or Bob Faye has done --
BY MS. O'LEARY:
Q Okay.
A -- on application of MT3DMS.
Q Right.
A I don't know anything about that. I wasn't a part of that modeling. I didn't write this report.
I'm on the record for that.
Q I understand that, Professor Aral. You

did, however, do the TechFlowMP --
A That's correct.
Q -- analysis and that also involved a biodegradation rate --
A That's correct.
Q -- correct?
And you said you think you did use the same biodegradation rate.
MR. DEAN: Object to form.
A I said it was a calibration parameter, as far as I recollect.
BY MS. O'LEARY:
Q Well, what value did you use at TechFlowMP?
A It must be in our reports. I --
Q Okay.
A -- don't have it here --
Q Right.
A -- on the top of my mind.
Q So --
A Yeah.
Q -- would you agree with the concept that's described in what I just read about flow --
A I --
Q -- towards and away from TT-26

affecting --
A I --
Q -- whether this biodegradation --
A I'm going to --
Q -- rate --
MR. DEAN: Objection to form.
MS. O'LEARY: Excuse me, can I finish my question?
MR. DEAN: Sure.
BY MS. O'LEARY:
Q -- whether that bio- --
MS. BAUGHMAN: Dr. Aral, make sure you let her finish the question before you answer, okay?
THE WITNESS: Yeah.
BY MS. O'LEARY:
Q Okay. So to rephrase, do you agree that flow towards and away from TT-26 is not about the same for -- for PCE and its degradation products, then the calculation that was apparently used to come up with 0.00053 would likely represent a minimum rate of biodegradation at TT-26?
MR. DEAN: Object to form.
A I -- I -- you know, you are making statements, like minimum or maximum, without any

value -- evaluation of what it is, okay?

I will not answer that question whether it was a minimum for this application. It could have been a different value for the TechFlow -- TechFlowMP application. So I cannot answer questions related to another chapter and refer my answers to a chapter which is written by me on TechFlowMP.

BY MS. O'LEARY:

Q Yeah.

A So these two models are totally different.

Q No, I -- I under- --

A You cannot -- you cannot compare the values used, the initial values used, whether it was a calibration outcome at the end or not. Those are totally different questions.

If you ask me what TechFlowMP does, how does it do it, I'm ready to answer it. But I'm not going to answer somebody else's report, somebody else's model right now.

Q So my question is not about MT3DMS and it's not --

A But you started with that.

Q This is in a chapter about that but

that's not my question, right?

A Okay.

Q My question is about the science expressed in this sentence, right?

This is not about what MT3D- -- -DMS does. It's a statement about how actual movement would affect biodegradation rate measurement calculation. That's not MT3DMS. It's about inputs that go into both MT3DMS and TechFlow.

So my question is: Do you agree with the scientific statement here about how different rates traveling of contaminants towards and away from TT-26 would impact whether the way this describes calculating a biodegradation rate is accurate?

MR. DEAN: Object to the form.

A The moment of contaminants from A to B doesn't imply or doesn't involve the calculation of biodegradation rates. The --

BY MS. O'LEARY:

Q Sure.

A -- biodegradation rates starts the calculation. The calculation ends up with the moment of the contaminants in the aquifer based on that input data, not vice versa. The flow doesn't determine the biodegradation rates.

Your question is totally out of scientific base.

Q Why?

A I explained to you. You are saying moment of contaminants in the aquifer determines the biodegradation rate. I'm saying --

Q No, that's not what I'm saying.

MR. DEAN: Object to the form.

Please let him finish his answer.

THE WITNESS: Okay.

MS. O'LEARY: Go ahead.

A That's what I understood.

And then you are saying the biodegradation rates are determined based on the flow. That's not correct.

BY MS. O'LEARY:

Q No. What this says on page --

A Can you repeat what --

Q -- on F28 --

A -- it says?

Q Yeah.

What it says on F28 --

A Yeah.

Q -- is that, "Potentiom metric levels shown on figures F7 and F8" --

A Uh-huh.
Q -- "indicate that while TT-26 is located on a direct advective pathway from ABC One-Hour Cleaners" --
A Yeah.
Q -- "thus PCE mass migrates downgradient toward and away from well TT-26. To the extent that migration of PCE mass toward and away from well TT-26 occurred at about equal rates from 1985 to 1991, the computed degradation rate of 0.00053 per day approximates a long term average degradation rate."
Do you agree with that?
MR. DEAN: I'm going to object to the form of the question. I'm going to instruct the witness -- no, I'm not.
You've asked the same question now five times. You are getting to the point of badgering the witness, okay?
MS. O'LEARY: Excuse me.
MR. DEAN: No.
MS. O'LEARY: Let me continue.
MR. DEAN: No. No. We are not --
MS. O'LEARY: No. You are limited to form and foun- and foundation. Let's

continue.

MR. DEAN: No. But I'm going to protect the witness from -- from you harassing him. You are reading to him a report he had nothing to do with and you know that --

MS. O'LEARY: Mister --

MR. DEAN: -- and he's already told you --

MS. O'LEARY: Mr. Dean, let's continue --

MR. DEAN: Let me finish. Let me finish.

MS. O'LEARY: Let's go off the record and we can talk for a few minutes.

MR. DEAN: No, we don't -- I don't want it off the record. I want this on the record --

MS. O'LEARY: Let's go off the record.

MR. DEAN: -- so the Court can read --

MS. O'LEARY: Thank you.

MS. BAUGHMAN: We are not agree to go off the record.

MR. DEAN: I want the Court to read it.

MS. O'LEARY: Well, then please stop interrupting.

MR. DEAN: I'm not interrupting.

BY MS. O'LEARY:

Q So Professor Aral, did you understand when I reread?

My question is do you agree --

MR. DEAN: Asked and answered. Move on.

MS. O'LEARY: No.

BY MS. O'LEARY:

Q Do you agree?

A Repeat the question --

Q Yeah.

A -- please?

MR. DEAN: It's the same question she's asked five, six -- eight times now.

MS. O'LEARY: Evidently, he's not clear on what it is, so --

BY MS. O'LEARY:

Q Figures F7 and F8 indicate that, "While TT-26 is located on a direct advective pathway from ABC One-Hour Cleaners" --

(Whereupon, the court reporter requests clarification.)

BY MS. O'LEARY:

Q Okay.

-- "thus PCE" --

MS. BAUGHMAN: And you need to speak louder.

BY MS. O'LEARY:

Q -- "thus PCE mass migrates downgradient toward and away from well TT-26."

A That's correct.

Q "To the extent that migration of PCE mass toward and away from well TT-26 occurred at about equal rates from 1995 to 1991, the computed degradation rate of 0.00053 per day approximates a long-term average degradation rate."

Do you agree with that?

MR. DEAN: Object to the form --

A See the --

MR. DEAN: -- of the question.

A -- the point that I don't agree is that computed biodegradation rate statement written in that report is not correct..

Biodegradation rate was evaluated first -- I mean, that reads like the water

contaminant moment determines, somehow, the biodegradation rates. The computed -- computed refers to the modeling computation.

If it refers to the computed biodegradation rate first as database and that database being used in the model results in that contaminant plume, that's a correct answer.

But that computed implies to me that the biodegradation rate was computed based on what the model results predicted.

BY MS. O'LEARY:

Q What if it --

A That --

MS. BAUGHMAN: Wait.

A -- I don't understand.

BY MS. O'LEARY:

Q Okay. What if it's referring to the two measurements at TT-26?

MR. DEAN: Object to --

BY MS. O'LEARY:

Q -- in the two points in time. So we are talking about September 1985 and July 1991.

If that's what the computed means, then do you agree?

MR. DEAN: Object to the form of the

yes. You are asking him to speculate on a report he did not prepare what that intended sentence means.

A Okay. If the -- if the computed biodegradation rate that was reported in a chapter F report, that I have no contribution to, is used in the MT3DMS model which resulted in the migration of the contaminants from ABC Cleaners towards the TT-26 plumping route, that's the correct definition. That's correct. I agree with that.

BY MS. O'LEARY:

Q Okay. So would you agree then that on the other hand, if a significant quantity of the PCE degraded in the vicinity of well TT-26 was replaced by advection, then that degradation rate computed, using equation three which is on F28, is probably a minimum rate?

MR. DEAN: Object to the form of the question.

A What does -- what does advection got to do with the biodegradation rate? Can you tell me that?

BY MS. O'LEARY:

Q Isn't it talking about how fast the different PCE and its by-products are moving --

A But --
Q -- up and downstream?
A But your statements are not scientifically correct. Please correct your question so that I can answer properly.
Q What doesn't make sense in my question?
A You are associating advection in an aquifer --
Q Uh-huh.
A -- with biodegradation rate. It has nothing to do with that.
Q I'm not trying to associate biodegradation with an advection rate. I'm trying to talk about the effect of two data points that were used for calculating a biodegradation point. Do you appreciate the difference?
A That is a totally different application of the equation three that we have seen in this report.

If you are trying to calibrate a biodegradation rate based on some observed contaminant migration, not simulation --

Q Right.
A -- then that's fine.
Q Okay. So that is what I mean. Not a

simulation --
A Okay.
Q -- I mean calculation from observed data.
A Yeah. But where is that observed data coming from?
Q Well, it -- it says here in chapter F that there were measurements in September 1985 --
A Okay.
Q -- and --
A So there's --
Q -- "Jaloo" 1991 --
A -- field study --
Q Right.
A -- which looked at -- so your question were not complete for me to answer that.
So let's start with the beginning. They have made -- ATSDR has made field studies --
Q Uh-huh.
A -- is that correct?
I mean, I'm not --
Q Well, there --
A -- supposed to start this discussion but --
Q They are -- they are reporting the two values; right?

They are reporting September --
A Is that --
Q -- 25, 1985 --
A -- field study?
Q It is what ATSDR is reporting from the field.
A So you don't know what --
MR. DEAN: Object to the form.
A -- the chapter F is saying --
MR. DEAN: Mischaracterizes --
A -- I don't know what chapter F is saying, so why are we discussing this?
BY MS. O'LEARY:
Q Well, I wanted to see if you agreed with the scientific conclusion they made based on what they reported on data.
A If there's an independent field study that ATSDR has conducted to determine the biodegradation rate, independent of MT3DMS --
Q Sure.
A -- simulations, I accept that.
Q Okay. So then do you similarly accept what the ATSDR says about if, on the other hand, a significant quantity of the PCE degraded in the vicinity of well TT-26 was replaced by advection,

then the degradation rate computed using equation three is probably a minimum rate?

MR. DEAN: Objection to the form of the question. Asked and answered 50 times.

A I -- I have no idea who wrote -- I mean, I know who wrote this report. I didn't write it so I have no idea what this is all about.

BY MS. O'LEARY:

Q Okay. And do you agree that if you have a higher biodegradation rate, that means PCE is going to degrade into TCE, and on, at a faster rate?

A Right.

Q Do you agree that a higher biodegradation rate used in the -- either MT3DMS or TechFlowMP would result in lower PCE concentrations at TT-26?

A As far as I know, MT3DMS application look at -- looked into single species model.

Q I agree.

A Okay. So why are we referring to MT3DMS in this question?

Q Because my question is just about how a higher biodegradation rate would affect PCE concentrations at TC -- at TT-26?

A It will reduce -- it will be reduced

compared to non-biodegraded -- -degraded PCE concentrations.

Q Would it be reduced compared to a -- using a lower biodegradation rate or would it be increased?

A If you change the parameters of a model, results will change.

Q Yeah. So if you put in a higher biodegradation rate --

A Yeah.

Q -- are you going to get lower PCE concentrations --

A That's correct.

Q -- at TT-26?

A That's correct.

Q And do you agree that lower PCE concentrations at TT-26 would result in lower PCE concentrations entering the Tarawa Terrace Water Treatment Plant?

A TT-26 is the main supplier of the contaminants, so if it is lowered, water treatment entry values will be lowered.

Q Okay.

MS. O'LEARY: Can we pull 28? Actually, nevermind. We'll skip

that.
BY MS. O'LEARY:
Q When you were doing the TechFlowMP model, did you run it using other biodegradation rates besides the 0.00053?
A In different applications we have used many different parameters.
Q I mean in the Tarawa Terrace model.
A We have used what we have reported.
Q Okay. Thank --
A I don't remember that number out of my mind.
MS. O'LEARY: Then can we get 20- --
A Besides, remember that it's a calibration parameter.
BY MS. O'LEARY:
Q Uh-huh.
MS. BAUGHMAN: What exhibit number is this?
MS. O'LEARY: This is Exhibit 12.
(Whereupon, Government's Exhibit Aral 12, E-mail Chain, was marked for identification.)
BY MS. O'LEARY:
Q Okay. So Professor Aral, I'm handing you

Exhibit 12. It appears to be an e-mail -- a chain of e-mails.

I'd like to start at the one that starts in the middle of the first page where it says, "From Morris Maslia."

Do you see that?

A Yeah.

Q Okay. As you look at the part of this thread that starts at the second half of 12 at -- from Morris Maslia and continues onto the second page --

A Uh-huh.

Q It says, To Jason Sauntner (phonetic), Renee Sorresoto (phonetic), Amy Krueger (phonetic), to -- and e-mails, one of which is Mustafa.Aral@ce.gatech.edu?

A Uh-huh.

Q Is that your e-mail address?

A Yes.

Q And do you recall receiving this e-mail?

A Yes.

Q Okay. And did you discuss this e-mail with Morris Maslia ever?

A Discuss?

Q Yes.

A Yes.
Q Okay. Did you ever discuss it with Robert Faye, Rob Faye?
A Uh-huh. Oh, did I --
Q Did you discuss this --
A No.
Q No? Other than Morris Maslia, have you disc- -- did you ever discuss this e-mail with anyone else during the --
A No.
Q -- water modeling?
A No.
Q Okay. And the e-mail says in the first paragraph, "In this particular case, there is apparently a discrepancy on the value of the biodegradation rate for PCE 0.006 per day and 0.004 per day."
A Uh-huh.
Q And do you recall that discrepancy in biodegradation rate for PCE?
A This wasn't a discrepancy. This was a factual -- fact finding. We are using two different models.
Q Uh-huh.
A One is MT3DMS model and the other one is

using TechFlowMP model.

It is normal to two different models calibrate to two different constants which is differing from one another in the order of 0.0001 per day.

Q Uh-huh.

A And then the issue becomes the leader of the group, which is Morris Maslia --

Q Uh-huh.

A -- who wants to go with a uniform constant to be used in both models. And since these two numbers are not significantly different --

Q Uh-huh.

A -- from another, he made that decision that a mid-value should be used and I agreed with that.

I'm sure what -- I'm sure Bob Faye agreed with that as well.

Q Okay. So then in the e-mail, the -- in the numbered list number one says, "Fate and transport results provided using the MT3DMS model, we'll use a biodegradation rate of 0.0005 per day."

Do you agree that is what happened?

A Which one are you referring to?

MR. DEAN: He's read- -- she's

reading number one.
A Okay. Number one.
BY MS. O'LEARY:
Q Yeah.
A MT3DMS, I think it's using -- see, one number is -- ends with a four, the other one with a six, so the average was five. Could that be a --
Q No, my question is just: Is 0.0005 what was used in --
A Yeah.
Q -- MT3DMS?
A At the end, yes.
Q Okay.
A Of course.
Q And is that what was used in TechFlowMP as well?
A Exactly.
Q Okay. And if we are back in the first paragraph --
A Uh-huh.
Q -- of the part from Morris Maslia?
A Yeah.
Q So the part that begins the middle of page --
A Right.

Q -- one.

I think it's the second sentence says, "In this particular case, there is" -- excuse me, the sentence after that.

"There are two different levels of sophistication of models used, MT3DMS versus TechFlowMP" -- that's what you just --

A Exactly.

Q -- said basically; right?

A Yeah.

Q "And a lack of definitive data to compare modeling results attack -- against non-detects ranging from 2-micrograms per liter to 10 micrograms per liter in my opinion do not constitute a definitive standard by which to compare modeling results."

Do you agree that there was no definitive data on biodegradation rate?

MR. DEAN: Object to the form.

A I think that was a calibration parameter. That's what I said at the beginning.

BY MS. O'LEARY:

Q Does that --

A Even if we started with a certain estimate of a beginning point, it changes based on

calibration --

Q Okay.

A -- that we are doing.

Q Does that mean you would agree there was no definitive data on the biodegradation rate?

MR. DEAN: Object to the form of the question.

A As far as I know, whether there is field data existing or not, I cannot remember it right now --

BY MS. O'LEARY:

Q Okay.

A -- but probably not.

Q And then in the e-mail, at number three --

A Number three.

Q Yeah.

Actually, excuse me, number four.

Number four is, "If you wish to compare simulated results with measured samples including ND, you can do so in a table with four columns: sample location, date, measured value, simulated value detection limit. You are free to discuss in the text any implications you see from the data, but no other quantitative analyses are to be made. I'm

abandoning the use of the geometric bias as I have concluded we just do not have the data to justify its use."

And then right after it, it says, "Each report analysis will also provide a graphical comparison such -- such as the one I'm attaching as an example. I'm providing both tiff and jpeg file formats. In your respective graphs, you can plot simulated PCE versus time for a specific condition, e.g., calibrated early arrival, late arrival, etc., and overlay that with the measured data only."

A Uh-huh.

Q And what did you understand as the directions that Morris Maslia was giving in this e-mail bout not making quantitative comparisons using non-detects?

A I -- I will think from five, first of all, he's giving instructions to his team as to use a plot to --

Q Uh-huh.

A -- generate a plot to see how the two results are comparing with each other.

In terms of number four, what was your question in reference to that?

Q What were the directions --

A What direction --
Q -- you were receiving from this about using no quantitative comparisons with non-detects?
A I think he -- Morris is referring to some graphical analysis of the results with or without detects.
Other than that, I don't remember the content of this number four.
Q Okay. Did you understand number five in this list as prohibiting graphical displays that overlaid simulated --
A Yeah.
Q -- concentrations using different biodegradation rates?
A Right. He's asking different biodegradation rates and plotting the results to --
Q Wasn't he --
A -- compare.
Q Isn't he saying everyone is using 0.0005 as their biodegradation rate?
A No, before it gets to that stage --
Q Right.
A -- I think he was suggesting that his team to look into this.
Q How -- how is he suggesting that?

A He's suggesting to abandon -- abandon the other way of comparing the results, which is the -- I don't remember what that is now -- the -- some graphical geometric bias representation.

So he's suggesting to check the graphical comparison of simulated --

Q Uh-huh.

A -- results in chapter -- in item five and asks to see that comparison.

Q Right. So in five, the second sentence where it says, "In your respective graphs, you can plot simulated PCE versus time for a specific condition, e.g., calibrated early arrival, late arrival, etc." --

A Uh-huh.

Q -- "and overlay that with the measured data only."

A Yeah.

Q So does that mean you couldn't overlay that with, for example, data from runs of the simulation with --

A I --

Q -- two different --

A I --

Q -- biodegradation rates?

A I wouldn't answer that question because you are referring to what Morris has said in his position of the leader of this group and you are expecting me to interpret that. I wouldn't answer that question.

Q Did you make any graphical displays in reports you authored where you showed results of two different biodegradation rates --

A No.

Q -- in the simulated model?

A Even if we did, it didn't appear in a report. We may have looked at it.

Q Okay. And when you started calibrating the TechFlowMP model, did you start with the calibrated mass loading rate from MT3DMS, what they had used in that?

A Yeah, starting point was the same.

Q And did you use that starting point in both the unsaturated and saturated zones of TechFlow?

A We discharged that into the unsaturated zone, looked at the volatilization effects.

Q Uh-huh.

A We also considered the soil concentrations and the dilution from the soil

concentrations.
Q Uh-huh.
A That was available data for us, so that brought us to the starting point --
Q Uh-huh.
A -- of the calibration. So two -- two processes are different.
Q Sure. And when you started calibrating TechFlowMP, did you start with the biodegradation rate that had come from the calibration of the MT3DMS --
A Probably --
Q -- model?
A -- as a starting point, yes.
Q Sure. And how did the biodegradation rate change as you calibrated TechFlowMP?
A It must be in the tables that we have written in the reports.
Q Okay.
A I don't remember now.
Q You don't remember?
A Yeah.
Q Is biodegradation in the saturated zone anaerobically driven?
A Yeah.

Q Is biodegradation in the unsaturated zone aerobically driven?
A That's correct.
Q Okay. How do they compare? Is anaerobic biodegradation, for example, bigger or smaller than aerobic?
A Aerobic will be bigger --
Q And --
A -- volatilization.
Q Oh, I wanted to ask just specifically about biodegradation.
A Biodegradation.
Q So not losses, but -- but just biodegradation.
A Okay.
Q Is anaerobic -- anaerobically-driven or aerobically-driven biodegradation faster?
A You cannot say "driven" because it depends on the length of the unsaturated zone --
Q Uh-huh.
A -- and then the saturated zone. The -- this is a time-dependent process.
How long does it stay in the unsaturated zone is the driver actually. If you put a contaminant in the unsaturated zone, it passes

through in --

Q Uh-huh.

A -- seconds. It will be a different driving mechanism than if it stays there for days, months, etc. --

Q Right.

A -- because of the lower rates of migration. Of course that will be a different driver.

Q But what if it was in the two zones for the same amount of time? So if we were comparing apples to apples --

A Uh-huh.

Q -- if we were looking at the same amount of time in saturated and the same amount of time in unsaturated, and so we're looking at aerobically and anaerobically driven?

A Yeah.

Q Which one is faster?

A You are trying to speculate -- me to speculate on that. I --

Q But I'm wondering if you know?

A No, I'm not going to answer that because I have to run it and see it.

Q So you don't know, like, reference --

A No.
Q -- scale?
A I don't have a reference in my mind.
MS. O'LEARY: Okay. Can we look at 27, please?
(Whereupon, there was a discussion off the record.)
MS. BAUGHMAN: He means by that, be careful to let her finish her question before you answer.
COURT REPORTER: And the answer finish. There's a lot of overlap.
MS. O'LEARY: Yeah. You know what, we're actually not going to talk about 27.
BY MS. O'LEARY:
Q So moving on, I have questions --
THE WITNESS: What is 27?
MS. O'LEARY: It's an e-mail. But I'm not going to ask you anything about it, so I'm not going to introduce it.
BY MS. O'LEARY:
Q So I have questions for you now about pumping schedules at Tarawa Terrace, and I have just some questions for you about the -- the way water

supply wells work and are maintained.

So if I say where a well is screened, do you understand what I'm talking about?

A Uh-huh.

Q What is where a well is screened mean to you?

A That's where the water enters into the well hole.

Q Okay. And are you familiar with the concept of crusting on a screen from mineral deposits?

A It may happen, yes.

Q Okay. Does that cause blocking then of the screen?

A The capacity of the well reduces by that.

Q Is that, like, just phys- -- you know, basic physics? You get blocks --

A It's not physics.

Q -- from the minerals?

A It's a natural process.

Q Isn't everything physics in basis?

A Not really.

Q Not really?

Do you -- are you familiar with issue with wells being -- blockage of the screen from the

growth of algae or bacteria?

A Yeah.

Q And what -- well, you've already answered for the mineral crusting.

You said that that reduces well capacity; is that right?

A Right.

Q Does blockage of a screen from algae or bacteria growth also lessen well capacity?

A Of course, yes.

Q And how -- is it possible to try and fix mineral crusting that has happened on a -- on a well screen?

A You mean reduce that well capacity reduction?

Q Well --

A What --

Q -- reduce the crusting to try and increase capacity?

A I don't think so. I mean, you can reflush the well just to flush out the accumulated amounts in there and then restart pumping.

Q Okay.

A That's a way of --

Q And is --

A -- treating the problem.
Q Okay. So you can treat the problem by, you said, flushing?
A Yeah.
Q Okay. Can you -- what if you are dealing with -- or can you in- -- inject with, like, an acid to try and remove a mineral crust?
A That's not within my expertise --
Q Okay.
A -- area. That's a field study application.
Q And what about, like, the algae or bac- -- bacteria that are blocking a screen, can you try and fix that?
A That's also not in my expertise area.
Q Okay. If -- for the flushing that you mentioned --
A Yeah.
Q -- how long does that take to do?
A That's not in my expertise area.
Q Okay. How are the pumps in -- in water supply wells, how are they cooled?
A How are they what?
Q Cooled?
A Cooled?

Q Yeah. The pumps themselves?
A I have no idea. I mean, that's a field study.
Q Okay.
MS. O'LEARY: Can we pull number one, please?
(Whereupon, there was a discussion off the record.)
MS. O'LEARY: All right. This will be Government Exhibit 13, Professor Aral.
(Whereupon, Government's Exhibit Aral 13, Excerpt from Expert Panel Transcript from March 28, 2005, was marked for identification.)
THE WITNESS: Uh-huh.
BY MS. O'LEARY:
Q And this is an excerpt from an expert panel transcript from March 28th, 2005.
Are you familiar with this expert panel?
A Yeah. I have attended some, too; probably most of them.
Q Okay. And this panel was reviewing water modeling efforts of ATSDR at Camp Lejeune; right?
A That's what it says, yeah.
Q Okay. So can you go to -- it will be

marked as page 140?
A What?
Q It should say 140 in the top right corner.
A I have three pages in mine.
Q But one of them should be 140?
A Oh, okay.
MS. BAUGHMAN: That --
A Yeah, okay.
MS. O'LEARY: Yeah.
A Yeah.
BY MS. O'LEARY:
Q Okay. So on that page, starting at line nine, there's something from Dr. Walski.
Do you know who Dr. Walski is?
A Yeah, I know him.
Q Was he a member of this expert panel?
A Yes.
Q Okay. And there's also -- it mentions a Mr. Faye.
Is that the same Bob Faye?
A I assume so, yeah.
Q Okay. So at line nine, it says Dr. Walski said, "The fraction -- the fraction of the time was 26 on. Is it run, like, 80 percent of

the time or did it run 70 percent of time on average?"

And Mr. Faye said, "That I really don't know, Tom. All I know that it probably rotated."

And Dr. Walski said, "Okay. So --"

And Mr. Faye said, "And so didn't run a hundred percent of the time."

And you -- you mentioned that you had been at this panel; is that correct?

A That doesn't mean that I understand what they are talking about.

Q Well, would you -- you don't know what they are talking about?

A No, I don't know what they are talking about.

Q So you don't know if they are talking about how much TT-26 was run?

A No idea.

Q Okay. I think we looked at this earlier, but do you agree that the ATSDR model showed TT-26 as pumping unless there was a documented -- documentation that it was out of service?

A You mean actually it was pumping at a lower rate or at a period that it was modeled in the contaminant transport model?

Q I mean in the model, it was assumed to always be pumping, albeit at --

A Yeah, yeah, yeah.

Q -- varied amounts --

A Yeah, yeah.

Q -- unless it was documented that it wasn't pumping?

A Yeah, I understand what you are referring to.

Yes, the -- all the models -- all the pumping wells were assumed when they were running, pumping. Within a month --

Q Uh-huh.

A -- they were pumping throughout the month. If they are not -- if they are offline for three, four days --

Q Uh-huh.

A -- we didn't reflect that in the modeling analysis because we have a time period of one month sequentially to run one after the other.

We cannot get into a time interval and adjust pumping conditions. That's not possible.

Q Was it ever considered to try and reconstruct a maintenance schedule at the wells?

A Do I have information on that?

Q Right.
A No, I don't.
Q Okay. Do you agree that assuming that TT-26 was pumping, unless documents showed it wasn't, was a con- -- a more conservative assumption than, for example, assuming that it had a maintenance schedule?
MR. DEAN: Objection. Form. Assumes facts not in evidence.
MS. BAUGHMAN: Also, I think you need to speak louder. I don't think he's hearing you.
THE WITNESS: Yeah.
BY MS. O'LEARY:
Q Would you like me to repeat the question?
A Can you repeat the question, please?
Q Sure. Do you agree that assuming the TT-26 was pumping unless documents show that it wasn't was a more conservative assumption than modeling a maintenance schedule for TT-26?
A Conserv- --
MR. DEAN: Same objection.
A Conservative in what sense? Increased contaminant levels will be transferred to the water treatment plant --

BY MS. O'LEARY:

Q Right.

A -- is that what you are implying?

Q Right.

A Yes, that would be the case.

Q Okay. Okay. Can we go to chapter F again for a minute, ATSDR?

A I would like to be on record that I have not written this report, didn't run the simulations, and I'm not ready to answer the questions that may be coming up.

Q Okay. If we go -- I understand you did not write the chapter F.

If we go to page F 33 --

A Yes.

Q There's a table and then there's some text on the bottom right column. And in that text, it says -- kind of in the middle of the top paragraph, it says, "A geometric bias that compares."

Do you see that?

A Yeah.

Q Okay.

"A geometric bias that compares simulated and observed concentrations also was computed. An

inclusive bias was computed using all 19 paired data at water supply wells and equaled 5.9. A selected bias also was computed that excluded paired data at water supply well TT-23 and equaled 3.9. Both results indicate that simulated PCE concentrations moderately to substantially over-predicted observed concentrations at water supply wells."

So in reading that, do you understand this to mean that ATSDR calculated geometric bias for Tarawa Terrace in two ways, one that did not include non- -- which did not include non-detects?

A Yes.

Q Is that correct?

MR. DEAN: Object -- object to form.

A Yes.

BY MS. O'LEARY:

Q And then it -- they -- in that calculation of geometric bias for the Tarawa Terrace model, they did it in two ways: one where they included TT-23 and one where they did not?

A Uh-huh. Yes.

Q Do you know why the ATSDR calculated geometric bias with and without water supply well TT-23?

A Is it reported in this chapter F report,

that -- that statement?
Q I --
A Is it coming from this chapter?
Q I mean, I think -- I think I just read it, that it said --
MS. BAUGHMAN: He can't hear you, that's why.
MS. O'LEARY: Yeah.
A I -- I think you're looking at the different text than reading from the chapter. That's why I'm having problems. You are not reading from the chapter. You are reading from your notes.
BY MS. O'LEARY:
Q That's a snip of the same thing.
A Yeah, but I don't know that. It's -- it's your choice.
Q Right. Do you have F 30- -- page F 33 in front of you?
A Yeah, I do.
Q Okay. So in there, right, it says, "a selected bias also was computed that excluded paired data at water supply well TT-23"?
A Yes.
Q Okay. So my question is: Do you know why the ATSDR calculated a geometric bias with and

without TT-23?

A Probably the TC -- TT-23 was operating at a much shorter period of time. Whatever the data is coming from that, probably they don't want to include. I have no idea.

I think this report that you are referring to is not written by me. I have no idea what the -- the author wanted to say at that point in reference to these questions you are asking, so...

Q Okay. Do you agree that the Tarawa Terrace model moderately to substantially over-predicted observed concentrations at water supply wells?

A I think you should look at the results in an ensemble analysis of statistics rather than looking at point values of a well at a certain time, comparing it with the observations made at a certain time or at a similar time at the site.

So the analysis doesn't -- although ATSDR -- -DR provided all kinds of tables, the analysis was based on statistical analysis, not point-wise comparisons.

Q That statistical analysis is the geometric bias; right?

A No, the statistical analysis is based on the uncertainty analysis, whether the model falls into that range, whether the application is consistent with that uncertainty range, whether the sensitivity analysis is associated with that parameter reflects that --

Q Sure.

A -- in the model.

I mean, there are so many other aspects of uncertainty or statistical analysis rather than just looking at a scatter diagram that I am seeing here.

Q I understand that.

But isn't geometric bias part of that statistical --

MR. DEAN: Objection.

A Not necessarily.

MR. DEAN: Hold on. Hold on.

BY MS. O'LEARY:

Q -- analysis?

MR. DEAN: Hold on. Object to the form. Asked and answered.

MS. O'LEARY: Well, it wasn't answered.

BY MS. O'LEARY:
Q Sorry, what were you saying Professor Aral?
MR. DEAN: He told you he couldn't answer it.
MS. O'LEARY: He did not say that.
A Okay. I said it in record. I said it -- that.
I didn't write this report. I'm not answering any questions that is coming from somebody else's statements in this report.
BY MS. O'LEARY:
Q Yeah.
A And a scatter report -- a diagram like that may be used or may not be used. I'm not insisting that it should be used.
BY MS. O'LEARY:
Q So if we go to Exhibit 3, which is the chapter A report --
A Chapter A report. Okay.
Q -- to page 25?
A Page?
Q A 25.
A Okay.
Q Oh, actually, we can skip this. Never

mind. We don't have to go through that.
A Okay.
Q Okay. On -- back to chapter F page 33, so where we were.
A Okay. Chapter F.
Q Yeah, I want to talk to you --
A I repeat my on-the-record statement on that.
Q I just have questions about the data in this table. So Table F 13 --
A Page?
Page --
Q So we are on F 33.
A Okay. Okay.
Q So I just want to make sure I'm understanding the data in this table correctly.
A Uh-huh.
Q This is showing simulated -- so from the model -- PCE concentrations at water supply wells and then matching those up with observed concentrations of PCE in the water supply wells in Tarawa Terrace; is that correct?
A That's what it seems so.
Q Okay. And then it's showing in the column at the right, the calibration target range;

is that correct?
A Yeah.
Q So if I look at the section on TT-23, am I correct in -- in understanding this is showing that all 11 samples over-predicted PCE concentrations in the simulation versus the observed for TT-23?
A Repeat that question for --
Q Yeah.
A And loud, please?
Q For TT-23 in figure F 13 --
A Yes.
Q -- am I correct in understanding that the simulated PCE concentrations were higher for all 11 of the TT-23 entries?
A Yes. They were all higher, but they were in the calibration range as well.
Q Well, for TT-23, actually, didn't ten of 11 of them fail the calibration range?
A If I recall --
Q Not ten of 11, excuse me.
A I mean, the range goes from 11 to 117.
Q Yeah.
A Any way.
Q Okay.

A Yeah.
Q And if we look at TT-26 --
A Yes.
Q -- and am I correct that five over-predicted the PCE concentrations? Five of eight?
A Five zero eight?
Q Five of them were over- --
A Oh.
Q -- predictions of a total of eight; is that correct?
A Yeah.
Q And looks like several failed the calibration range --
MR. DEAN: Object.
BY MS. O'LEARY:
Q -- as well; is that correct?
MR. DEAN: Object to the form of the question.
A I -- I am on record saying that we don't look at calibration conditions based on one well at a time and compare the observed and the simulated values at one point in time. We look at the overall ensemble analysis --

BY MS. O'LEARY:

Q Yeah.

A -- of the statistics --

Q Yeah.

A -- of that representation.

So what you are doing right now is bringing back to me one data at a time comparison.

I would not do that.

Q But Professor Aral, I mean, you've already said -- agreed that -- earlier that this table is --

A That table is --

Q -- all of the values that were used --

A -- correct.

Q -- for calibration?

A That table is for you to look at and see the results.

Q Right.

A Analysis of the results is a total different story.

Q But --

A You do it statistically. You do it --

Q Yeah.

A -- in a different methodology.

Q Yeah. So this Table F 13, though, is --

is the comparison of all of the values --
A This is not --
Q -- used for calibration?
A It is not the comparison. It is for you to see what numbers are there. We are looking at or using in a statistical sense, probably they are going to refer to this table.
Q Uh-huh.
A These numbers or the statistics that we came up with is coming from this table. That's it.
Other than that, this table just for the information to be sent out to the other person to see what it is.
MS. O'LEARY: Can we go to 26?
A Page 26.
MR. DEAN: No.
BY MS. O'LEARY:
Q No, it's going to be a new exhibit.
A Okay.
Q You don't have it yet.
A Oh, okay.
Q That was for Ms. Horan to grab the right document?
A Okay.
(Whereupon, there was a discussion

off the record.)

MR. DEAN: Yeah, we should have put this on the record earlier. But when we are referring to an exhibit, the number we are using is the number we call out as the exhibit number in the deposition --

MS. O'LEARY: Yeah.

MR. DEAN: -- for the record.

MS. O'LEARY: Thank you.

(Whereupon, Government's Exhibit Aral 14, E-mail from Mustafa Aral to Jerome Ensminger, was marked for identification.)

BY MS. O'LEARY:

Q And so I've just handed Professor Aral what's marked as Government Exhibit -- is it 14?

MS. HORAN: Yup.

MS. O'LEARY: And then for the record, this is not a Bates-stamped copy, but the Bates is CLJA_ATSDR_ --

(Whereupon, the court reporter requests clarification.)

BY MS. O'LEARY:

Q Yeah.

-- -A_ATSDR_BOVE-0000018710 and then the

next page is -- ends in -11?

MS. BOLTON: I hate to do this, but can you just repeat just the final numbers --

MS. O'LEARY: Just the numbers?

MS. BOLTON: Yeah.

MS. O'LEARY: -18710 to -11 -- you know, to -11.

MS. BOLTON: Okay.

MS. BAUGHMAN: There were five zeros first?

MS. O'LEARY: Yes.

Okay.

BY MS. O'LEARY:

Q And Professor Aral, this looks to be an e-mail from you to Jerome Ensminger; is that correct?

A That's correct.

Q Do you recall this e-mail?

A Yeah. No, it's coming from me, definitely.

Q Okay. So -- and the subject --

A Okay.

Q -- is --

A Yeah, I remember this.

Q You do? Okay.
A Yeah.
Q It says the subject is testimony from John Nuckholls?
Who --
A Yes, yes, yes.
Q Who is John Nuckholls?
A One of the members of the expert panel.
Q The expert panel for 2005 or for --
A I don't --
Q -- 2009?
A One of them. I'm not sure.
Q Okay. And who is --
A I -- I think he was on the NRC report panel? Or did we have a panel? I'm not sure.
Q Okay.
A Anyway, he was on the NRC report.
Q And who is Jerome Ensminger?
Who is Jerome Ensminger?
A I think one of the plaintiffs; right?
Yeah.
Q You think he's a plaintiff? Okay.
This e-mail, though, is from -- it looks like it's from October 6th, 2009.
Do you have any reason to think that date

is incorrect?

A The date on it is -- seems to be correct; yeah.

Q Okay. And -- in October of 2009, how did you know Jerome Ensminger?

A I met him in probably 2005 in one of the ATSDR meetings. I told you that --

Q Yeah.

A -- at the beginning.

Q And at the beginning here, the first line, it says, "After a quick read, the following points strike me as not coming clean in his overall testimony."

A Yes.

Q Whose testimony are you talking about? Is that John Nuckolls' testimony?

A I think so, yeah.

Q And what was he testifying about?

A I think the expert panel was suggesting that ATSDR should use simpler models rather than complex models --

Q Uh-huh.

A -- to finish up the project and don't spend too much time on calibration.

MR. DEAN: Why don't you take time

and take a look at the e-mail.

THE WITNESS: I -- I know this e-mail.

MR. DEAN: Okay.

BY MS. O'LEARY:

Q Okay. So Professor Aral, I have a question for you on the paragraph that's numbered three.

A Yeah.

Q And it says, "His" -- I'm starting at the -- there's a line that says, "Having said that," kind of in the middle; do you see that?

A Yeah.

Q Okay. It says, "Having said that, in historical reconstruction methodology verifications are made by extending the historical predictions to the present day timeframe to see if the model that predicts the past ties to the present day conditions smoothly.

"In this verification process, the data used are the observed data in the present day. The verification in this case is the prediction of the present day with the use of the same model. This verification was done in the TT-modeling study and the results indicate that the models predicted the

past -- predicting the past was successfully predicting the present when extended to the present day within certain acceptable bounds of error."

And do you agree that in historical reconstruction methodology, verifications are made by -- can be made by extending the historical prediction to the present day timeframe to see if the model that predicts the past ties to the present day conditions smoothly?

A First of all, this modeling sequence that we are working with has four stages.

Q Uh-huh.

A Unstressed conditions in the ground waters, stressed conditions in the ground water.

For those two model applications, we have a lot of data. So those models are -- are calibrated, recalibrated looking at the data and so forth.

When we move to the third stage, which is the contaminant --

Q Uh-huh.

A -- transport model, there's no data, okay, at the field during the period of the historical --

Q Uh-huh.

A -- reconstruction.

However, having said that, if the first two models like stress/unstressed conditions in the aquifer is properly calibrated, most of the processes in the contaminant transport model is already available to us to run the model. Whether those -- those are advection conditions, diffusion conditions --

Q Uh-huh.

A -- it comes from the previous two models.

Q Sure, sure.

A In other words, if there's velocity, the velocity field is determined. If the velocity is determined, the diffusion constants are determined.

So what is missing -- what is missing is the retardation coefficients that we would use that we have discussed earlier or biodegradation rates that we have used earlier.

And I think there were several databases that was available to us towards the end of the period of the contaminant transport calibration. We have used that database. That's the 36 number that we were talking about. All of it was used to calibrate the contaminant transport analysis.

And when we come to the final stage, the

models one, two, three --

Q Uh-huh.

A -- was verified using the water treatment plant database, which is the present day conditions that I'm referring there in that e-mail. And that was used to verify the model.

Q Okay. I just want to make sure I understand which present day conditions.

Present day contaminant concentrations or --

A Present day contaminant concentrations, which is coming from in an independent data set, which is the water treatment plant data set which occurred probably after 1987 -- I'm not sure exactly -- but went onto '89 or something like that.

Q So when was this -- I'm not understanding why it's called "present day" if it's the 1980s and this is from 2009.

A Oh, we are predicting -- making predictions until 1987 or '89. That's all we are doing. Present day means to us 1987 or '89, not when this --

Q Oh --

A We are not referring to this 2009.

Q Okay. So do you mean to the -- the

present day is like the time of calibration data?
A Exactly.
Q Okay. I understand. Thank you.
A Yeah.
There's a -- okay. Go ahead.
(Whereupon, there was a discussion off the record.)
MS. O'LEARY: Do we need to take a break?
THE VIDEOGRAPHER: No. No. It's just that you dropped it.
MS. O'LEARY: Oh. Thanks.
And I'd like to move onto -- this will be chapter H, which is 62.
You can set aside 14.
(Whereupon, Government's Exhibit Aral 15, Tarawa Terrace Chapter H Report, was marked for identification.)
THE WITNESS: No, I need the other one.
MS. O'LEARY: You're right.
BY MS. O'LEARY:
Q Okay. So Professor Aral, you have now what's Government Exhibit 15. It's a copy of the Tarawa Terrace chapter H report.

Am I correct that you -- you did author this report?

A Yes.

Q All right. Can you go to page H 3?

A Yes.

Q And this is in a section called "A Review of ATSDR's Tarawa Terrace Study Background."

And the column on the left, the -- the last paragraph, it starts saying, "Using hydrogeologic data."

Do you see that?

A Yes.

Q Okay. Then about midway through that, there's a sentence that begins, "Due to."

Do you see that?

"Due to the nature"?

A Yeah.

Q Okay. So it says, "Due to the nature of historical reconstruction, uncertainties are associated with reconstructed information, which in turn cause uncertainties in resulting exposure analyses. Uncertainties in the exposure outcome can have a significant effect on the epidemiological study. In particular, the uncertainty caused by the groundwater pumping schedule used in the simulations

has been pointed out to be important. Therefore, in this study there's an evaluation of the variation in PCE concentrations and arrival times of the maximum contaminant level" -- skipping the parentheses -- "at water supply wells and the water treatment plant. The variation could be caused by changes in groundwater pumping rates at water supply wells."

So a few questions about that.

First, do you still agree with that?

A Yes, I do.

Q Okay. And who was it who pointed out that uncertainty caused by the groundwater pumping schedule is important?

A Expert panel members.

Q And why did they say it was important?

A Because changes in pumping rates obviously is going to -- going to effect the arrival times of contaminants to pumping wells.

Q Why does changes in pumping rates cause change in contaminant arrival levels?

A Because the driver is the contaminant -- pumping well rates for the plume migration.

Q Okay.

A If it changes, the plume will change.

Q Okay. And did you then do a study to

evaluate variation in PCE concentrations and the arrival times of MCLs at the water supply wells --

(Whereupon, the court reporter requests clarification.)

BY MS. O'LEARY:

Q Agree -- did you do a study to evaluate variation in PCE concentrations and arrival times at the MCL at water supply wells and the water treatment plant at Tarawa Terrace?

A That's right.

Q Okay. And if you go -- still in -- at the same Exhibit 15, the chapter H report -- can you go to --

A Chapter A?

Q H.

No, the same -- the same one, H.

MR. DEAN: H.

A Okay.

BY MS. O'LEARY:

Q Page H 1?

A Page one?

Q Yup.

A Yes.

Q Okay. So this is in -- labeled the abstract?

A Uh-huh.

Q And in the column on the right, the paragraph that starts, "During the historical reconstruction study."

It's kind of in the middle.

It says, "A major cause for and contribution to this uncertainty are the pumping schedules which are discussed in other report chapters. The focus of this chapter report, therefore, is on the uncertainty associated with pumping schedules. The study discussed in this chapter includes the development of a simulation and optimization procedure identified as PS Ops" --

Is that how you would say that?

A Yeah.

Q Yeah.

-- "which combines simulation models and optimization techniques to optimize pumping schedules for maximum or minimum contaminant concentrations at the water treatment plant. Based on optimized pumping schedules, variations of PCE concentration and the maximum contaminant level arrival time at water supply wells and the water treatment plant are evaluated. Results of this study indicate that variation of pumping schedules

may cause significant changes in the contaminant concentration levels and MCL arrival times at the water treatment plant."

Do you agree that a major cause for and contribution to uncertainty is the pumping schedule in Tarawa Terrace?

MR. DEAN: Object to the form.

A We have identified that major statement later in the chapter showing the uncertain -- uncertainty band --

BY MS. O'LEARY:

Q Uh-huh.

A -- changes when it is -- when the pumping schedules are optimized and different schedules are used in an application. So won't get stuck on that major word, just look at the statistics at the end.

Q And Professor Aral, we'll get there. I just -- do you disagree with what you wrote about the major --

A No, I don't --

Q -- cause --

A -- I don't disagree.

Q Okay. And PS Ops, I want to try and make sure I understand what it did.

So it does a simulation and optimization

for ranking the wells; is that correct?
A No, not ranking.
Q Well --
A It is -- it answers the following question quite clearly: How many different ways we can combine --
Q Uh-huh.
A -- all these pumping wells to meet the demand at Camp Lejeune site which will give us a totally different outcome than the mean --
Q Uh-huh.
A -- concentrations that we used to get with a fixed schedule.
Q Okay.
A That answers that question.
Q Yeah. And does it -- to do that, does it use a rank and assigned method to maximize or minimize or more optimize the arrival time of contaminants at water supply wells?
A It's -- it's emphasizing the arrival times. Is it going to come to the -- the contaminant is going to arrive --
Q Uh-huh.
A -- at a certain date earlier --
Q Sure.

A -- than what was predicted.
So it just combines all that -- those conditions in an optimization model.
Q Right. And is the way it does that with --
A Yeah.
Q -- a rank and assignment of the wells?
A Yeah, a rank and assignment is a solution process for an optimization --
Q Okay.
A -- model.
Q In -- was TT-26 ranked first for optimization among the Tarawa Terrace wells?
A I don't remember. Probably it --
(Whereupon, the court reporter requests clarification.)
BY MS. O'LEARY:
Q Was TT-26 ranked first for optimization among the Tarawa Terrace wells?
A I don't remember that.
Q Okay.
A It must be in the record of this report.
Q Can you go to H 23?
All right.
Actually, let's go on to H 29.

A Okay.
Q Looking at figure H 21.
Do you see figure H 21?
A Uh-huh.
Q Okay. Do you agree that figure H 21 shows the simulated PCE concentrations at the Tarawa Terrace Water Treatment Plant when the results of minimum schedule one are run on PS Ops in the dashed line?
A Uh-huh.
Q And do you agree that the minimum schedule one was to run a late PCE arrival time at the Tarawa Terrace Water Treatment Plant?
A Uh-huh.
Q Okay. And do you agree that the solid pink line is the calibrated Tarawa Terrace model?
A Yeah.
Q Okay. And so the -- what has -- sort of being modeled as happening for the dashed pink line is that that pumping of Tarawa Terrace 26, TT-26 was minimized as much as it could be and still meet demand at the water plant?
A Exactly.
Q Is that right? Okay.
A Exactly.

Q And so for the dashed line run, other than pumping, were all of the other parameters the same as in the calibrated model?
A Yes.
Q Okay. So is the difference in magnitude between the dashed pink line and the solid pink line representing the difference in PCE concentration from the calibrated model and what it could theoretically be minimized at?
A Theoretically is the right word.
Q Yeah.
A Okay.
Q Right. So -- would you -- but that would be theoretically possible?
A Impossible. Exactly.
Q Okay. And am I, in looking at figure H 21, understanding correctly that it shows that if TT-26 were minimized as much as were theoretically possible --
A Yes.
Q -- to meet demand, then the ATSDR's model would otherwise not simulate any PCE contamination in the water supplied by the Tarawa Terrace Water Treatment Plant between about January of 1960-something and January of 1972?

A That's correct.
Q Okay. And --
A But that's not theoretically possible. Because TT-26 is operating.
Q Sure. And I -- I want to go on next to H 38 --
A Okay.
Q -- and ask about another run that I think is -- is what you are talking about.
A Okay. That's fine.
Q So if we look at figure H 33 and --
A Figure on what page now?
Q H 38?
A H 38. Okay.
Q And then figure H 33?
A Okay.
Q And it says that it's the simulated PCE concentrations at the water treatment plant under the original schedule, solid line, minimum schedule one, and minimum schedule two, dashed lines.
A Uh-huh.
Q And so is minimum schedule two, is that where it's optimized to have a late PCE arrival time with the restriction that TT-26 had to pump at least 25 percent --

A Yes.
Q -- of its pumping --
A Yes.
Q -- capacity?
A Exactly.
Q And why did you do the minimum schedule two run where TT-26 has to pump at least 25 percent of the time?
A Well, because that was more realistic in reference to what we were observing as how TT-26 contributed to water treatment --
Q Okay.
A -- plant.
Q So more realistic in how it was --
A More realistic.
Q -- pumping?
A Yeah.
Q Okay. And in looking at figure H 33, is the -- the dashed line that has closer together dashes, is that the simulated PCE levels at the water treatment plant when that minimum schedule two is on? So the one where TT-26 is pumping at -- at -- at least 25 percent --
A Right.
Q -- capacity?

A If you extend that -- if you can see that dashed line extended to 1985, that will be the water treatment plant.

Q Okay. And then is it true then that the difference between the tightly dashed line, the minimum schedule two line, and the solid dashed line, that's the difference in PCE concentration from the calibrated model and then the minimum schedule two where --

A TT- --

Q TT-- --

A -- twenty-six.

Q -- twenty-six is minimized but not below 25 percent?

A Right. Exactly.

Q Okay. So this analysis of these minimum pumping schedules is in chapter H.

And my question is: Why is this pumping uncertainty analysis in chapter H and not chapter I where the other uncertainty analyses are?

A Because we didn't look at the variations of the other parameters in this uncertainty analysis. We only looked at the pumping schedule uncertain.

Q In chapter I where the --

MS. O'LEARY: We can get 63.
We don't have it yet.
THE WITNESS: Oh, okay.
MS. O'LEARY: I'm getting it.
Sorry.
THE WITNESS: Uh-huh.
(Whereupon, Government's Exhibit Aral 16, Chapter I Report, was marked for identification.)

BY MS. O'LEARY:

Q All right. This will be Exhibit -- Government Exhibit 16, so the chapter I report.
So in chapter I, I want to go to page I 55?

A Yes.

Q Okay. There's a figure I 29; is that what you're seeing?

A Yeah.

Q Okay. So I 29's label says it's the "concentrations of PCE in finished water at the water treatment plant derived from scenario one where pumping uncertainty was excluded and scenario two where pumping uncertainty was included in the probabilistic analysis using Monte Carlo as simulation at Tarawa Terrace."

So the -- the Monte Carlo simulation, was that a probabilistic --

A Yes.

Q -- evaluation of uncertainty?

A Yes.

Q Okay. And to do that in the Monte Carlo simulations, did that involve model -- varying model input parameters?

A Yeah.

Q Okay. And so --

A I have a diagram to show which parameters.

Q In your report?

A In the uncertainty analysis in my experts report.

Q Yeah. And for what figure I 29 shows in terms of the pumping scenario -- from scenario one and two with pumping uncertainty included and not included, that pumping variation, that's different pumping variation than what was in chapter H; correct?

A In what sense?

Q Like in, like, scenario one and scenario two for pumping --

A I think you are seeing the scenario

two --

Q Well --

A No. No. No. That's not correct.

This result now that you are seeing in this chapter --

Q In chapter I?

A In chapter I.

-- includes uncertainty analysis of pumping schedule variations --

Q Uh-huh.

A -- including uncertainty analysis of pump -- parameter conditions together.

Q Right. But the pumping variation in chapter I is not the same pumping variation --

A No.

Q -- of chapter H; right?

A No. No, no, it's not.

Q Okay.

A We are looking at maximum/minimum conditions that we looked at earlier. This -- this is the pumping uncertainty standard variations with respect to statistical analysis --

Q Okay.

A -- that is reasonably what it is at the site.

Q And for the -- the variation in pumping that went into chapter I, that range, how was that range of parameters inputs selected?

A Okay. That's a question. I have to go back and read that. I don't have an answer on top of my head.

I think we looked at the distributions of possible pumping rate schedule changes. I mean, I have to read this whole report.

I -- I don't have an answer to that --

Q Okay.

A -- right away.

Q But it's different than chapter H?

A It is different, yeah.

Q And were the ranges of parameter inputs for the chapter I Monte Carlo simulations, were those the theoretical limits of parameters?

A As far as we know from the site data, I think they were.

Q In how -- in what way were -- would they be the theoretical limits?

A Not theoretical. Whatever we have observed at the site in terms of hydraulic conductivities, in terms of other parameters, we came up with that range in uncertainty analysis as

the range to be used.

Q Okay. So does that mean then that for the Monte Carlo simulations, did the Monte Carlo simulations explore the theoretical range of possible solutions --

A Yes.

Q -- at Tarawa Terrace?

A We put probability distribution on a parameter within the range that it is defined. Monte Carlo analysis picks up data from that probability density function --

Q Sure.

A -- combines it with another parameter for its -- or from its probability density function, combines all that into the model --

Q Uh-huh.

A -- runs the model. You get one point on the slide.

Q But did the Monte Carlo simulation in- -- involve simulating every possible combination of parameters --

A No.

Q -- within the --

A That would have --

Q -- ranges selected?

A -- been a hundred years to run.
Q Okay. But then how is it -- how is the Monte Carlo simulation then showing the theoretical range --
A Okay.
Q -- of possible solutions?
A There's a method for that. That -- in hyperacute modeling.
I think we ended up using only 810 simulations from the PDFs database. And then I believe some of them dried out some of the wells. I believe it was 300 or so.
So what is remaining for us to analyze is about 520 or so database to construct this uncertainty analysis.
Q Yeah. But, I mean, that would mean then you are not looking at the theoretical range of --
MR. DEAN: Object to the form.
A No.
BY MS. O'LEARY:
Q -- possible solutions?
A That -- that doesn't mean that.
The question here to ask is how many Monte Carlo simulations --
Q Uh-huh.

A -- is required to run a reasonable uncertainty analysis. In a case like this, the answer is 400.

Q But that's not my question.

A Yeah.

Q Not what's reasonable.

My question is whether the Monte Carlo simulation that was run for Tarawa Terrace explored the -- like, the universe of possible solutions?

A The universe of the possible situations that was bound by the database that we chose for each parameter.

Q Okay. And but that -- those bounds of parameters were not, like, the theoretical limits; those were selected from the site -- available site data?

A Yeah.

Q Okay.

A It is based on site data.

Q And then within the Monte Carlo simulation, it didn't -- it didn't test every possible combination of parameters?

A It wouldn't be a Monte Carlo analysis then.

Q Well, it would be another way of --

A It would be --
Q -- looking at uncertainty?
A -- running all the direct simulations for all the points on the PDF. That's an impossible act.
Q And so that's not what was done?
A How can we do it?
Q Okay. And so in figure I 29 --
A Uh-huh.
Q -- there's --
A Yeah.
Q -- areas between -- both for scenario one and scenario two, the --
A Yeah.
Q -- you know, pumping variation and no pumping variation.

There's an area between lines that says it's the range of concentrations representing 95 percent of Monte Carlo simulations.

Do you agree that that range representing 95 percent of Monte Carlo simulations for Tarawa Terrace is not equivalent to the 95 percent range of the universe of possible --

MR. DEAN: Object.

BY MS. O'LEARY:
Q -- mean historical contaminant concentrations --
MR. DEAN: Object --
MS. O'LEARY: -- at Tarawa Terrace.
MR. DEAN: Object to the form of the question.
A Okay. 95 percent within the bound of the PDF distribution that we have selected for that parameter is identified or selected by the method itself randomly. We are not assigning select this, select that, select -- no.
Randomly -- random -- random numbers are generated. Based on those random numbers, it goes and picks up some number some -- from some PDF distribution --
BY MS. O'LEARY:
Q Uh-huh.
A -- for some parameter matches up with another parameter PDF distribution number, puts them into the model, and then --
Q Yeah.
A -- then runs it.
Q Do you agree that the -- the total size of the universe of possible solutions to modeling

Tarawa Terrace is unknown?

A What do you mean by "universe"?

Q Like all of the ways that the model could have been set up, that all of the ways that the contaminants could have moved through time, that the size of that range is unknown?

MR. DEAN: Object to the form.

A So you are referring to that -- that statement to me means, Don't do a statistical analysis and just do all the possible points on a PDF function --

BY MS. O'LEARY:

Q Well --

A -- and run it through.

Q I think what I'm more trying to understand is how the Monte Carlo simulation and the confidence interval --

A Okay.

Q -- that's reported relates to the theoretical range --

A Okay.

Q -- of possible outcomes.

A I think the best way to answer is if you have a sample of 500 data point matchings from different PDF functions, the representation of that

outcome is 98.5 percent accurate with respect to the mean value that we have generated as a deterministic result.

Q But that's only within the parameter ranges that you evaluated; right?

A Well, it's the beginning of analysis. You cannot go back and question --

Q Yeah.

A -- what you started with.

Q Well, my question is about how that relates to not within the modeling world, but how that relates to what could have been possible in the real world?

MR. DEAN: Object to the form of the question.

A Okay. What you are referring to is you have not selected the proper bounds on the parameters that you inputted PDF functions. That's what you are telling me.

BY MS. O'LEARY:

Q Well, no.

A The universe means --

Q I'm asking how they relate?

A -- that to me.

Q No, I mean theoretically in the real

world, not in the parameter range that you select.

MR. DEAN: Object to the form of the question. There's no such thing as theoretically in the real world.

A Look, we decided to statist- -- to do a statistical analysis. The statistical analysis follows a standard procedure to be used in an application. And that standard -- standard -- standard procedure is very simple, it's not complex.

BY MS. O'LEARY:

Q Uh-huh.

A It's very simple. It says, Give us the bounds of each parameter you think represents the conditions at the site.

Q Uh-huh.

A That's number one.

Then fit a probability density function within that range to represent the distribution of that parameter. That represents the conditions at the site.

The third stage. You go and throw dice or -- or flip a coin, it becomes a random number. It goes back into the PDF function, picks one number out of that and another number out of the other PDF, combines that. That's the statistical procedure.

You cannot -- once you decide to do this, you cannot divert and ask questions. What you are doing, is it representing the universe?

No, we are modeling the universe.

MS. O'LEARY: And I can go on to 42. This will be a Hadnot Point --

A Okay.

MS. O'LEARY: -- summary.

Actually, do you have that already?

MS. BAUGHMAN: You did mark a summary --

MS. O'LEARY: Yeah, I think we marked -- let me find that one.

MS. HORAN: I have it as Exhibit 4.

MS. O'LEARY: Exhibit 4 should be hopefully in this stack here.

THE WITNESS: Okay.

Okay.

BY MS. O'LEARY:

Q There you go. It's rather thick.

A Chapter A.

Q Yeah, chapter A and then just to page iii in the forward?

A Four --

Q Iii.

A Iii. Okay.
Q Oh, in the forward, yeah.
A Wait a minute.
Are there two reports in here or --
Q No, it should be right near the beginning, Professor Aral.
I think it might have been before that.
A Iii. Okay. I see it. Forward.
Q Okay. Yeah. So it says in the first paragraph, "The Agency for Toxic Substances and Disease Registry, an agency of the U.S. Department of Health and Human Services, is conducting epidemiological studies to evaluate" --
A Yeah, we read this earlier.
Q Well, we read it in Tarawa Terrace.
A Oh, did we?
Q Yeah.
A This is what?
Q This is Hadnot Point.
A Oh, really? Okay.
Q Yeah.
A Okay. Good.
Q So -- "was conducting epidemiological studies to evaluate the potential for health effects from exposure to volatile organic compounds such as

tetrachloroethylene, trichloroethylene, and benzene in drinking finished water at U.S. Marine Corp Base Camp Lejeune, North Carolina. Historical exposure data needed for the epidemiological studies are limited. To obtain estimates of historical exposures, ATSDR is using" --

(Whereupon, the court reporter requests clarification.)

BY MS. O'LEARY:

Q -- "ATSDR is using water modeling techniques" --

(Whereupon, the court reporter requests clarification.)

BY MS. O'LEARY:

-- "data needed for the epidemiological studies are limited. To obtain estimates of historical exposures, ATSDR is using water modeling techniques and the process of historical reconstruction to quantify concentrations of particular contaminants in finished water and to compute the level and duration of human exposure to contaminated drinking water."

Were you aware when you were working on the Hadnot Point water -- water modeling of this purpose stated in the forward?

A I wasn't aware of the details of this purpose, but I was aware of the fact that this study was going to be followed by an epi study.

Q An epidemiology --

A Yeah.

Q -- study?

Okay. And still in the Hadnot Point chapter A, so Exhibit 4, if you could go to page A 62?

A Okay.

Yes.

Q And the top left, the first paragraph of A 62 where it begins, "Using reconstructed"?

Do you see that?

A A 6 --

Q I think you're --

A Sixty-two.

Q -- on the right page.

A 62, yeah. On the top left?

A Yeah.

Q Okay. So it says, "Using reconstructed simulated water supply well concentrations previously discussed, monthly mean concentrations of PCE, TCE, 1,2-TDCE, VC, and benzene were estimated for finished water at the Hadnot Point water

treatment plant. These estimates were computed using a materials mass balance model simple mixing to compute the flow-weighed mean concentrations of VOCs as described earlier in this section on computation of contaminated finished water concentrations."

So does -- is it the case that the ATSDR only modeled at Hadnot Point Holcomb Boulevard PCE, TCE, 1,2-TDCE, VC, and benzene?

A What's the last one?

Q Benzene?

A Oh, benzene? Yes.

Q Okay. And you aren't offering opinions about historical concentrations of any other compounds at the Hadnot Point or Holcomb Boulevard areas.

A Not --

Q Is that correct?

MR. DEAN: Object to the form.

BY MS. O'LEARY:

Q Is that correct?

A Not other than these listed.

Q So --

A Yeah.

Q -- trichloroethylene,

tetrachloroethylene --

A Yeah.

Q -- dichloroethylene, vinyl chloride, and benzene?

A Yes.

Q Okay. And in that same page where it says, "These estimates were" -- so still this is A 62?

A Okay.

Q It said, "These estimates were computed using a materials mass balance model simple mixing."

Do you agree that -- that Hadnot Point model also did not include a calculation for loss of contaminants in the water treatment plant?

A As far as our analysis go, no.

Q What do you mean "our analysis"?

A I mean the water -- water modeling analysis --

Q Oh, okay.

A -- that we have done. Yeah.

Q So water modeling did not involve a calculation for contaminant losses in the water --

A That's --

Q -- treatment plant?

A -- correct.

Q And we are going to set aside this one for a bit.

MS. O'LEARY: And can we get -- this will be 39.

There we go.

THE WITNESS: Are we done with this?

MS. O'LEARY: We are done with that one, yes.

THE WITNESS: Okay.

(Whereupon, Government's Exhibit Aral 17, Chapter A Supplement Two for Hadnot Point, was marked for identification.)

BY MS. O'LEARY:

Q Thank you.

So Professor Aral, this is Government Exhibit 17?

A Okay.

Q Professor Aral, this looks like a copy of the chapter A supplement two for Hadnot Point.

Is that what it looks like to you?

A Yeah.

Q And am I correct in understanding that you are an author on this --

A Yes.

Q -- chapter?

All right. I have a few quick questions for you --

A Uh-huh.

Q -- on page S2.74?

A Yes.

Q Okay. And -- I'm on the wrong page. There we go.

I want to look at figure S2.99; do you see that figure?

A 299, yes.

Q Okay. It says, "Estimated monthly operating days for well HP-634."

Do you agree that figure S2.99 shows the number of days per month that HP-634 was modeled as pumping in the ATSDR's calibrated model for Hadnot Point?

A As a outcome of the modeling sequence that we have used, that seems to be the case. But it's not daily. I think it's monthly.

Q Sure. So --

A Okay.

Q -- so the -- so it -- well, the scale on the left says days?

A Is it?

Oh, day.
No, number of days --
Q So then the line would represent total number of days per month.
So the time scale would be monthly?
A Yes.
Q And then --
A Yes.
Q -- it's showing its days?
A Yes.
Q Okay.
A Monthly versus days, yeah.
Q And do you agree that figure S 2.99 shows that in the calibrated HP model, HP-634 was not modeled as pumping after January of 1985?
A Yes.
Q Okay. All right. That's my only question on that. But we'll stay in -- well, maybe. We are going to --
MR. DEAN: Can we take a break?
MS. O'LEARY: Sure.
MR. DEAN: Are you okay with that?
MS. O'LEARY: Yeah, that's fine.
THE VIDEOGRAPHER: The time right now is 2:59 p.m. We are off the record.

(Whereupon, there was a recess taken from 2:59 p.m. to 3:12 p.m.)

THE VIDEOGRAPHER: Time right now is 3:12 p.m. We are back on the record.

BY MS. O'LEARY:

Q Professor Aral, I have a few more questions for you in the Hadnot Point supplement two.

So this is Exhibit 17 -- Government 17?

A Okay.

Q And could you go to page S 2.2.

All right?

A Uh-huh.

Q I think that is one --

A Two.two -- oh, 2.4, I'm sorry.

Yeah.

Q Okay. So in the data availability data sources section, so the column on the right?

A Uh-huh.

Q It says, "Four types of data sources pertinent to water supply well operational records and water treatment plant raw water records are used in the supplement. These are: one, daily operational records for January 1998 to June 2008" -- and skipping the parenthesis --

"number two, Camp Lejeune historic drinking water consolidated document repository records; three, Camp Lejeune water documents; and four, U.S. geological survey well inventory documents."

A Uh-huh.

Q "Using these data sources, operational chronologies for 96 wells supplying groundwater, raw water to the Hadnot Point Water Treatment Plant and Holcomb Boulevard Water Treatment Plant were developed."

And so Professor Aral, why did operational chronologies for these 96 wells have to be developed?

A I was not involved in data collection, so I have no idea what this is telling us about.

Q Okay. Then we can go on to page S2.12.

And so just to start out, were operational histories reconstructed for the Hadnot Point water supply wells?

A Can you repeat that question, louder please?

Q Sure. Were operational histories reconstructed for the Hadnot Point water supply wells?

A I don't -- I don't remember that.

Q Okay. So on S2.12 in that first paragraph on the top left?

A Uh-huh.

Q It says, "Similar to the training" -- or after that, actually, a couple sentences.

It says, "Because some wells did not physically exist during the training period, surrogate wells were selected to represent these untrained wells."

So do you know what the training period is a reference to?

A I have to read this paragraph here.

Q Sure.

A "Similar to..."

Looks like they are trying to come up with a operational well history on the site as to when they were operated, when they were not operating. That's what this refers to.

Q Okay.

A Yeah.

Q Were you involved in a -- like, a training process for the Hadnot Point wells?

A No.

Q Okay. And then we can set aside this supplement --

A Okay.
Q -- two from Hadnot Point and go back to Exhibit 4, the Hadnot Point chapter A, to page 80 -- 80 -- excuse me -- A 84?
A Okay.
Q And so Professor Aral, A 84, this section is titled "Trichloroethylene Source Release Date Sensitivity Analysis."
Were you involved in the trichloroethylene source release date sensitivity analysis at Hadnot Point?
A No, I don't think so.
Q You were not?
A I don't remember that.
I mean, which area is this on Hadnot Point --
Q Hadnot Point --
A -- industrial area or the landfill area or which one?
Q So the source release date sensitivity analysis --
A Yeah.
Q -- I think it involved both?
A Both?
Q Yeah.

A No, I'm -- I don't remember this.
Q Okay. Can you take a look at the next page, A 85?
A Uh-huh.
Q There's a figure, A 37 -- actually, sorry. Just a minute.
I'll come back to that. I think we can set aside actually the chapter A for Hadnot Point.
MS. O'LEARY: And can we get -- it will be 40. It will be Hadnot Point supplement six.
MS. HORAN: I believe that's Exhibit 11.
MS. O'LEARY: That's Exhibit 11. Okay.
BY MS. O'LEARY:
Q Professor Aral, could you grab Exhibit 11?
A Exhibit 11?
MS. O'LEARY: Oh, yes. There it is.
THE WITNESS: Yeah. It's there.
BY MS. O'LEARY:
Q Okay. So on Exhibit 11, page S6.17.
A Again, this is a supplement that I wasn't an author on.

Q No?
Okay.
A Okay.
Q So actually, going one page -- rather than S6.17, S6.16. So just the page before.
Do you see a table S6.5?
A Okay.
Q And it says it's calibrated contaminant fate transport model parameter values used to describe contaminant sources in the Hadnot Point industrial area and Hadnot Point landfill area, Hadnot Point Holcomb Boulevard study area.
Were you involved in selecting the calibrated contaminant, like, mass loading rates?
A Which is presented in this report?
Q No. In general, at Hadnot Point?
A But we are looking at this report.
Is that in this report? That's what I'm asking. Is that database is in this report?
If it is not, I would like to go back to the database that was used later on in another study and see if I was the author on that.
Q Oh, so -- so you're saying you're not sure if you were involved in --
A I'm involved --

Q -- that?
A -- in it. But I'm looking at a table --
Q Uh-huh.
A -- which I have not prepared.
And I'm not ready to answer questions on it, because I was not involved in writing this report.
Q Okay. So, I -- I mean, I think this is the report where these contaminant mass loading rates are reported in the Hadnot Point reports.
A But some other group did it. There's a different group in every task, and they write whatever they write.
If I have used it in another study related to this industrial area or landfill area, let's go to that report and discuss it there.
Q Well, I guess that's what I'm asking you.
Did you use -- in the areas you worked on, did you use the --
A I would --
Q -- the fate --
A -- like to --
Q -- and transport --
A -- go back --
Q -- buckles?

A -- to the report that I wrote, listed these numbers. Then, I would say, Yes, I have used it.

It may be totally "inrelevant" -- irrelevant to my application. I don't know.

BY MS. O'LEARY:

Q Okay.

MS. O'LEARY: Can we get -- this will be -- we can set aside 11, Exhibit 11.

And can we get 25?

THE WITNESS: Okay.

MS. O'LEARY: You don't have it yet, Professor Aral.

THE WITNESS: Okay.

MS. O'LEARY: It will end up being, I think, Government Exhibit 18.

THE WITNESS: Okay.

(Whereupon, Government's Exhibit Aral 18, E-mail String Between Robert Faye and Mustafa Mehmet Aral, was marked for identification.)

MS. O'LEARY: Yup.

And I have some questions about calibration of Hadnot Point.

THE WITNESS: Okay.
MS. O'LEARY: There you go.
THE WITNESS: Okay.
BY MS. O'LEARY:
Q Professor Aral, Government Exhibit 18 appears to be an e-mail from you to Robert Faye from September 21st of 2011.
Do you recognize this e-mail?
A Yeah. It's from me.
Q Do you remember it?
MS. BAUGHMAN: You should take your time to read it first.
THE WITNESS: Yeah. I'm reading it.
BY MS. O'LEARY:
Q Professor Aral, are you -- what page are you on reading?
A I'm reading the whole e-mail sequence.
Q Okay. I thought you had mentioned that you did re- -- you did recognize this e-mail?
MR. DEAN: He did, but we --
A Yeah. But this was ten -- how many years ago?
BY MS. O'LEARY:
Q Okay. Would you like --
A I have to read the whole thing to

answer --

Q Yeah. Would --

A -- questions.

Q -- you like to go off record so you can read it?

And we can --

MR. DEAN: No.

BY MS. O'LEARY:

Q -- come back on record when you're ready?

MR. DEAN: No. Keep the record rolling. But --

MS. O'LEARY: No. We --

MR. DEAN: -- if it's --

MS. O'LEARY: -- can -- we can take a break --

MR. DEAN: No. It's --

MS. O'LEARY: -- if you need to read all of the pages.

So let's go off the --

MR. DEAN: No. No.

MS. O'LEARY: -- record, please.

MR. DEAN: Absolutely do not stop the videotape rolling. You can stop transcribing if you'd like.

But he's going to continue to read

it. You're the one that asked him a- -- about the e-mail. He has a right to read it.

There's nothing that suggests that we have to turn off the record every time you present him with an exhibit, which he has a right --

MS. O'LEARY: Yes. But --

MR. DEAN: -- to read --

MS. O'LEARY: -- he's -- he's --

MR. DEAN: -- and stop --

MS. O'LEARY: -- already said --

MR. DEAN: -- the transcript.

MS. O'LEARY: -- he recognized the e-mail.

So Professor Aral, I'm fine to go off record for you to read every word --

MR. DEAN: No.

MS. O'LEARY: -- and not on the record.

So are you ready to proceed --

MR. DEAN: He can --

MS. O'LEARY: -- or not?

MR. DEAN: -- keep reading, but we'll keep the record running.

A Can you tell me which part of this --
BY MS. O'LEARY:
Q Sure.
A -- your question --
Q Yeah?
A -- is all about?
Q Sure.
A I can have a focus on that.
Q Yeah. So I have questions for you about page one and page two.
A Okay. So what is your question?
Q So on page two, there's an e-mail from you to Robert Faye that's dated September 20th --
A Uh-huh.
Q -- 2011.
The subject says, Re: TCE landfill data. And in the paragraph there, it's addressed to Bob.
Is that to Robert Faye?
A That's to Bob -- yeah. Bob Faye.
Q Okay. So, kind of, in the middle, there's a sentence that begins, Here, I'm not referring to CT application we did two years ago.
Do you see that?
A Yeah.
Q And it says, We did -- we did what we had

to do. The outcome of our assumption seems to yield pretty good answers, given what we did not know or how little we know at the time and how little we included in our overall analysis to come to that conclusion. I am interested in hearing your thoughts on the calibration targets for GW fate and transport models.

So just background, "CT" is that control theory application?

A Yeah.

Q And when you say "GW," is that groundwater?

A GW, groundwater.

MS. BAUGHMAN: Is -- isn't -- isn't "CT" calibration target?

THE WITNESS: Well, it can be that, too, referring to calibration targets. Yeah.

MS. BAUGHMAN: Because the --

THE WITNESS: That's right.

MS. BAUGHMAN: -- prior e-mail --

THE WITNESS: That's correct.

MS. BAUGHMAN: -- is all about that.

THE WITNESS: It's calibration --

BY MS. O'LEARY:

Q All right. This is about tal- -- calibration targets?

A Correct.

Q You are not referring to calibration target application you did two years ago?

A Calibration targets -- probably, I'm referring to Tarawa Terrace.

MR. DEAN: Object to the form of the question.

MS. BAUGHMAN: I -- I really think you need to read the prior e-mail on -- on -- from Bob Faye to you right before this e-mail, or you might understand the context.

BY MS. O'LEARY:

Q Well, Professor, hadn't you already read page three?

A The first e-mail is from me to Bob.

Q Uh-huh.

A Apparently, we had a meeting or a conversation on -- or during which I have asked him some calibration targets that he has or he may not have in his mind.

So that's the start of the discussion.

He answers --

MS. BAUGHMAN: Wait. Wait. Wait. What -- you've got to -- she needs to ask you a question. Okay? You're just -- you're just explaining the e-mail. Wait for a question.

BY MS. O'LEARY:

Q Pro- --

MS. BAUGHMAN: But make sure you've read the whole --

BY MS. O'LEARY:

Q So Pro- --

MS. BAUGHMAN: -- chain first.

BY MS. O'LEARY:

Q Professor Aral, let me just ask my specific questions, and this --

A Please.

Q -- might go better.

So do you agree that this e-mail --

A And loud --

Q -- thread -- the --

A -- please.

Q -- one -- yeah.

Do you agree that that e-mail on

September 20th, 2011, from you to Robert Faye -- so the one on page two --

A (The witness nods head.)

Q -- that this e-mail is about calibration targets for TCE at HP651?

A In page two?

Q Yes.

A Uh-huh.

Q You agree?

MR. DEAN: Object to the form of the question.

A Can you repeat that --

BY MS. O'LEARY:

Q Yeah.

A -- what are --

Q You agree that e-mail is about -- about calibration targets for TCE at Hadnot -- HP651, the well?

A Okay. Which page is this that you're --

Q Two.

A -- reading?

Q Right here, in the --

A Second page?

Q Yes.

A From me to Bob?

Q That's right.
A Okay.
Okay. What is your question again?
Q All right. When you said, We did what we had to do, what did you mean?
What is it that you had --
A We change --
Q -- to do?
A -- we chose a proper calibration target, and we went about applying it.
Q Okay. And you said, The outcome of our assumptions seems to yield pretty good answers given that we did not know or how little we knew at the time and how little we included in our overall analysis to come to that conclusion.
What is -- what do you mean by the "outcome of our assumptions"?
A I think we made some assumptions to choose a calibration target, and it worked out in the final analysis in the sense that our modeling application yielded good results. And I think I'm referring to Tarawa Terrace there.
Q Uh-huh.
A So I'm suggesting, maybe, why don't we use the same approach, come up with a proper

calibration target, and go at it?

Q And the way you did it at Tarawa --

A Right.

Q -- Terrace, do it at Hadnot Point?

A Right.

Q Okay. And then, on page one of this e-mail -- so the page one of Exhibit 18 --

A Uh-huh.

Q -- in the e-mail from Robert Faye to you and others that's dated September 20th, 2011, do you see that one?

A Yup.

Q It says, Hi, folks. First, it seems to me, the overall model calibration strategy has always been and should be to apply defensible methods to simulate field observations.

Second, our models only grossly approximate real-world physics, chemistry, and biology.

Third, the feed -- field data represent a snapshot in time during one day, whereas our model simulate average monthly conditions. It seems to me that an effective and a ap- -- appropriate approach to model calibration must integrate these realities into the -- into a practical strategy.

And then, there's one more sentence.

But do you agree with what Robert Faye said, that the ATSDR's HP models only grossly approximate real-world physics, chemistry, and biology?

MR. DEAN: Object to the form of the question.

A No.

I think what he's trying to do, if I -- I don't recall -- recall this e-mail sequence. But he may be suggesting different calibration targets than what we have used at Tarawa Terrace.

And probably, I'm insisting that what we did at Tara- -- Tarawa Terrace worked for us. So let's continue with the same approach, same targets, and it will work for this case, as well.

BY MS. O'LEARY:

Q Why is it that the models are not grossly approximating real-world physics, chemistry, and biology?

A Well --

MR. DEAN: Object to the form of the question.

That's not his e-mail.

THE WITNESS: Yeah.

MR. DEAN: That's Bob Faye's e-mail.
THE WITNESS: Yeah.
MS. O'LEARY: That I -- I understand that. And --
MR. DEAN: Okay. Well --
MS. O'LEARY: -- I asked --
MR. DEAN: -- you're implying --
MS. O'LEARY: -- him if --
MR. DEAN: -- that he --
MS. O'LEARY: -- he agreed.
MR. DEAN: -- said that. You're implying to him --
MS. BAUGHMAN: He did -- he did not agree.
MS. O'LEARY: All right. And I'm asking him, Why?

BY MS. O'LEARY:

Q Why is it that the models don't grossly --
A Well, because --
Q -- approximate real-world --
A -- the -- the --
Q -- physics -- I'm --
A -- models we --
Q -- sorry. Sorry --

A -- are using --
Q -- Professor Aral.
A Okay.
Q -- don't grossly approximate real-world physics, chemistry, and biology?
MR. DEAN: Object to the form.
A I don't agree with that.
BY MS. O'LEARY:
Q Right.
Why? Why don't you agree?
A Because our models are good models.
Q But, I mean, can't a model be good and still be only a gross approximation?
A No, it wouldn't be --
Q Why not?
A -- if it is done -- if it is done well, calibrated well, the model represents the assumptions you have initially introduced into it and predicts what those initial assumptions -- assumptions you have mathematically correctly.
Q Mathematically correctly, though.
But, I mean, we're talking about how it compares to the real world. Right?
The real world isn't in, for example --
A Well, then --

Q -- seven layers.
A -- it --
Q And that's what the model had. Correct?
A Yes. That they plot --
Q And then, the --
A Yeah. Go ahead.
Q The real world's not in 50 by 50 squares. But that's what the model had. Right?
A Right.
Q And the real world has variable biodegradation rates based on changing parameters throughout the distance between a contaminant source and the wells.
And the model didn't have that. Right?
A The model we have worked with is an approximation of the environment we are working in -- with.
And we are satisfied with the representation of that environment within that model, and we are trying to go through the discussion of how far should we go further in time spent in calibrating this model --
Q Uh-huh.
A -- to best fit what we have observed at the field?

So this is not a question of whether the model represents the field conditions correctly or grossly. That's not the question.

The question is what we have assumed in building this model represents the field -- or -- or the -- the -- the environment approximately, but correctly in terms of our understanding at the beginning. Okay?

So when we start there, we cannot argue whether the results are gross or exact.

Q Because you just don't know?

A No.

We know a bound of analysis based on uncertainty, that it should reflect the -- the field conditions within a certain degree of accuracy.

Q But only within the -- the range of parameters you chose to look at for the field --

MR. DEAN: Object to the form.

BY MS. O'LEARY:

Q -- parameters; correct?

A We are modeling. We cannot use all the range of field parameters that is available to us.

Q Okay. You can set aside Exhibit 18. And if you could find Exhibit 4, the Hadnot Point Chapter A?

MR. DEAN: Supplement two?
MS. O'LEARY: No. Chapter A. Exhibit four.
MS. BAUGHMAN: That would be Exhibit four. Yeah.
MR. DEAN: Oh.
THE WITNESS: Uh-huh.
MR. DEAN: Yeah.

BY MS. O'LEARY:

Q And could you go to page A46?

And so there's a figure there, Figure A18. And its label says, Reconstructed Simulated and Measured Concentrations of Trichloroethylene and Selected Water Supply Wells Within the Hadnot Point Industrial Area.

A Uh-huh.

Q So --

A That's figure eight, 18 -- A18.

Q A18. Yes.

A Yeah.

Q Do you agree that this Figure A18 shows the calibrated model values plotted with some measured values at HP well 601, 602, 608, and 634?

A Yeah. That's what the titles say.

Q Do you agree that the Figure A18 shows

some of the measured values at those wells, but not the non-detections?

A Uh-huh.

Q Okay. And so any non-detections are not on these -- on these graphs?

A I have no idea.

You are just referring to four figures, four wells, and then, asking a universal question as --

Q No. I --

A -- to all --

Q -- mean, for --

A -- the wells.

Q -- no. I mean, for these four wells, the non-detections are not --

A I don't --

Q -- shown?

A -- know.

Q Okay.

A I don't remember that.

MS. O'LEARY: Can we get number 43? And I'm -- I'm going to have you -- I'm going to need you to compare. So if you could keep Exhibit --

THE WITNESS: Okay.

MS. O'LEARY: -- 4 nearby.
This will be Government Exhibit 19.
(Whereupon, Government's Exhibit Aral 19, Chapter C at Hadnot Point, was marked for identification.)
THE WITNESS: Uh-huh.
BY MS. O'LEARY:
Q And can you go to page C95?
A C95?
Q Yup.
Okay. Professor, are you on page C95?
And you should be looking at a Table C7?
A Yes.
Q Okay. So that table says it's a summary of analyses of PCE, TCE, DCE of various kinds and vinyl chloride in samples collected in Hadnot Point water treatment plant water supply wells.
So I'd like you to look at HP634, and look at the TCE column.
A Uh-huh.
Q And there are, looks like, four non-detections.
Do you see those?
A Yes.
Q Okay. So there are four non-detections

of TCE at HP634, for example.

But if we go back to Exhibit 4, which is the Chapter A, at that figure A18 on page A46, for wells 634, there are no non-detections on that chart. Is that correct?

A 634?

Non-detects are not shown in here as a data point.

Q Yeah. Okay. You can set aside Exhibit 19, which was the Chapter C at Hadnot Point.

A Chapter what?

Q You can set aside --

A Okay.

Q -- Exhibit 19.

A Okay.

Q So Chapter -- Exhibit 4 please keep. And you can set aside --

A Okay.

Q -- Exhibit 19.

And can you go in Exhibit 4, Chapter A, to page A51?

A Yes.

Q All right. So there's a figure A20 that says --

A Yeah.

Q -- it's reconstructed, simulated, and measured concentrations of benzene at selected water supply wells at Hadnot Point industrial area, Hadnot Point Holcomb Boulevard study.

And it's showing three wells, HP 602, HP 603, and HP 608.

And were you involved at all -- or are you aware of the data on benzene detections at the Hadnot Point water treatment plant?

A Well, it says "TechFlowMP." So I must be involved.

Q Okay. So -- and are you, then, familiar with the benzene detections at the wells in Hadnot Point?

A These are the data points that we had, apparently, on benzene on these wells.

Q Okay. Do you agree that these figures show calibrated model benzene concentrations at these three wells -- HP 602, 603, and 608, as well as some measured values?

A Yup.

Q Okay. If I look at well HP 603, I don't see any measured values.

Do you know why that is?

A I don't know.

There must be no data on that.
Q Why do you think there must be no data on that?
A Well, we didn't put data points on that figure.
Q Okay. Can you pull back up Exhibit 19, the Chapter C for Hadnot Point?
A Yes.
Q And go to page C98.
A Okay.
Q So if you look at -- now, this -- there's a Table C8.
A Uh-huh.
Q And it says, Summary of Analyses for Benzene, Toluene, Ethylbenzene, and Total Xylene in Water Samples Collected in Hadnot Point Water Supply Wells.
And do you see the entries for HP 603 in the column for benzene?
A Uh-huh.
Q All right. Do you see that there are seven entries for benzene, and they're all non-detections?
A Yes.
Q Okay. So does that mean that in --

A These plots didn't include non-detects.
Q You didn't include the non-detects --
A Correct.
Q -- in well HP 603?
A Yeah.
Q Okay. So I --
MR. DEAN: Objection to form.
They don't show up on log scales anyway.
A Uh-huh.
BY MS. O'LEARY:
Q So if you look at -- back at page A51, that --
A Uh-huh.
Q -- figure A20?
A Uh-huh.
Q For H -- well HP603, what does the red line represent?
A 603?
Q 603. I'm sorry. I might have said something wrong.
603?
A Yeah. Okay.
Q What does the red line represent?
A The simulated benzene concentrations at

this well location.
Q Okay. And does the -- am I correct in understanding this shows the simulated benzene concentrations at -- at well HP603 at some point exceeded a hundred micrograms per liter?
A It shows that.
Q But then when we looked at the table in chapter C --
A Uh-huh.
Q -- there were only nondetections at well HP603?
A That's correct.
Q Okay.
A But again, you are making the mistake of comparing point values at a point in time and a point in space with the overall calibration of a model.
Q Uh-huh.
A You are confused in that.
Q Can we go to page A81?
A A81?
Q Yup. So same -- same exhibit.
A Okay.
MR. DEAN: Oh, A.
MS. O'LEARY: A, yeah.

A A81?
BY MS. O'LEARY:
Q Yeah. And the --
MR. DEAN: A81.
BY MS. O'LEARY:
Q -- column on the left --
A Yeah.
Q -- and as I send [sic] this -- the first sentence starts, "As previously discussed."
But, "Simulated results for water supply well HP602 provide reasonable agreement with field data, whereas simulated results for water supply well HP603 are inconsistent with field data. Therefore, sensitivity analyses were conducted to assess the effect of varying contaminant, source, area, size, location, and release date on reconstructed benzene concentrations at water supply well HP603 and at the HP water treatment plant.
"Additionally, the sensitivity analysis included assessing the effect of the contribution of benzene contaminated groundwater from well HP603 on benzene concentrations in finished water at the Hadnot Point water treatment plant."
Now, were you involved in this sensitivity analysis on HP603?

A Yes, I was.
Q Okay. Am I understanding from what I just read on A81 that the ATSDR recognized the simulated results for water supply well HP603 as inconsistent with field data?
A That's what it says, yeah.
Q Okay. And still on --
A We established that --
Q Uh-huh.
A -- in our prior discussion.
Q And if you go onto the next page, just A82, there's a description of a -- of the sensitivity analysis that was done.
And am I correct in understanding that in the sensitivity analysis, they determined that varying the source concentrations caused only small improvement at --
A A- --
Q -- while 603 --
A -- -83 is only figures and you are --
Q A --
A -- referring to --
(Whereupon, the court reporter requests clarification)
A A -- A83 is only page for figures. You

are actually referring to A -- A82.
BY MS. O'LEARY:
Q A 82.
A Okay.
Q Yeah.
A Okay.
Q At the top.
A Uh-huh.
Q I can read what it says.
It says, "Sensitivity analysis results for varying assigned source concentration value from a calibrated value of 17,000 micrograms per liter, and source release date from the calibrated release date of January 1st, 1964, are listed in table A25. These results indicate a small improvement in reconstructed benzene concentrations while HP603 compared to calibrated results."
So am I correctly understanding that the sensitivity analysis found only small improvement in HP603 by varying source concentrations?
A The sensitivity analysis looks at the effect of the variations of a certain parameter on the results. So in this case, actually, we are changing the source concentrations to see if it has an effect on the 603 -- well 603.

And we are concluding that the change in source concentrations does not effect that much.

Q Okay. And -- and going on after that, it says, "Perhaps more important however, in the context of the overall project, is that the effect of these contaminant source variations on finished water benzene concentrations at the HP water treatment plant is minimal."

Do you agree it's more important in the context of the overall water modeling project at Hadnot Point that the contaminant source variations of the sensitivity analys- -- analysis on finished water on benzene concentrations at the Hadnot Point water treatment plant is minimal?

MR. DEAN: Object to the form of the question.

A Yeah.

BY MS. O'LEARY:

Q Okay.

A I think it says that, yes.

Q And to -- and then its goes on to say, "To assess the contribution of reconstructed benzene contaminated groundwater from water supply well HP603 to finished water concentrations at the Hadnot Point water treatment plant, the mixing model

results were derived by removing the flow and contaminant mass contribution from well HP603.

And then it says "The reconstructed benzene concentration results shown in figure A36 indicate that the contribution from benzene contaminated water supply well HP603 to finished water concentrations at the HP water treatment plant was minimal."

And then --

A Yeah.

Q Do you agree?

A What -- yeah.

What we are saying is if we change the source date it has also minimal effect.

Q Okay. And if -- if HP603 does not have a big effect on the water treatment plant calibration, then does that mean that the calibrated model is drawing most of the benzene from different wells?

A Not the calibrated model. The water treatment plant is receiving contaminants from different wells, yeah.

Q Right.

A Yeah.

Q So if -- if -- so the specific well, HP603, has a changing source loading on that well

has a minimal effect on the water treatment plant levels, then does that mean in the model the source of the benzene is primarily other wells, not 603?

A No, that -- that's not what it says.

It says changes in the source value doesn't effect the water treatment plant concentrations. It doesn't say that the source at this well doesn't effect.

Q Well, isn't that what they varied, was the strength of the source at 603?

A No. There is a source. Let's --

Q Sure.

A -- say a hundred milligrams per liter, that's going to water treatment plant.

Now, if you make it 110 or 90, it doesn't make any change on the water treatment plant. But there is still hundred milligrams of contaminant in that --

Q Uh-huh.

A -- well.

Okay? I mean, the changing effects is not important but the source is still there, whatever it is.

Q Isn't the uncertainty analysis to see what happens when you vary the source strength?

A Yeah. But you are asking me if you take the 603 out --

Q Yeah.

A -- it's not going to change the water too. That's not true.

What I'm trying to tell you is there's a source which contributes to water treatment plant concentrations. A hundred milligrams, maybe ten milligrams of it goes to water treatment plant.

Q Uh-huh.

A Now, if you make the source or change the source value to 120 or 80, still ten goes to the water treatment plant.

Conclusion is not if you take 603 out, still there's no change in the water treatment plant. No.

Ten milligrams you are taking out now from the water treatment plant by taking out 603 totally.

Q Okay. You can set aside chapter A and we are going to go back to supplement six, which was Exhibit 11.

A Exhibit 11.

Q And to page S645.

Actually, to -- yeah. S645, that's

correct.

A Okay.

Q Okay. So in the column on the right, the second paragraph begins, "For contaminant fate and transport modeling reported herein. However insufficient -- however insufficient water quality data existed to conduct a statistical analysis for assessment of model calibration fit. In addition, specific data pertinent to the timing of initial deposition of the contaminants in the ground or subsurface chronologies of waste disposal operations, such as dates and times when contaminants were deposited in the HPLF or descriptions of the temporal variation in contaminant concentrations in the subsurface generally are not available.

It goes on, "Determining these types of source identification and characterization data became part of the historical reconstruction process whereby the contaminant fate and transport model was used to test source locations, varying concentrations, and beginning and ending dates for leakage and migration of source contaminants to the subsurface and underlying groundwater flow system."

Were you involved in that process of

determining the types of source identification and characterization data?

A No. I'm not an author on this report so I wouldn't know what is the procedure -- what are the procedures they have used and I don't remember --

Q Okay.

A -- this paragraph.

Q Okay. And were you involved in the process of testing source locations by varying concentrations and beginning and ending dates?

A That -- this is -- let's see. In the landfill area.

We referred to that earlier in one of the other exhibits that we tested the start and ending dates of the wells. It didn't have any effect. We tested the source concentration magnitudes, it didn't effect.

So is this the same well or is this a different site? I -- I have no idea what we are talking about.

Q I mean, this chapter is about all of the wells.

A The previous --

Q At Hadnot Point.

A -- chapter was on benzene application only? Is that what we discussed a minute ago?

Q So we were talking about chapter A, which is the summary of findings and chapter C, which is about occurrence of all --

A No -- no.

Q -- contaminants.

A We were looking at some figures that nondetects were used or not used and we were talking about sensitivity analysis we used, just to see if the source concentration changed or if the time of application of the contaminant at the site changes. It didn't change anything.

So you ask me the question, if you take this well off will there be any change in the water treatment plant?

I answered the question as, "yes."

Now we are coming to this supplement --

Q To supplement six.

A -- six.

Is this -- I -- I'm not familiar with this chapter. I haven't authored it.

Are these paragraphs referring to what we have discussed a minute ago, which I have summarized?

Do you know that or --
Q I don't know.
A I don't know it either.
Q Okay.
A So --
Q Are you offering opinions about the calibration assessment of Hadnot Point?
A I'm offering opinions on a paragraph that you wrote or read -- read on this chapter.
Q So supplement six is called, "Characterization and simulation of fate and transport of selected volatile organic compounds in the vicinities of the Hadnot Point industrial area and landfill."
Were you involved in any of those processes?
A No. I'm not an author on this report so I have no idea what's in this report.
Q Okay. So are you offering no opinions on anything contained in supplement six?
MR. DEAN: Object to the form.
A If I'm not an author the only thing I did, probably, I reviewed it.
BY MS. O'LEARY:
Q Okay. Are you offering any opinions

about mass loading at Hadnot Point?

A At certain sites I'm looking at benzene mass loadings that I have described a minute ago that it did effect it didn't effect and so forth. So I have an opinion on that but I don't have an opinion on this supplement six.

Q On benzene, let's start there. Were you involved in -- are you offering opinions, I mean, on the appropriateness of the calibrated value --

A Yeah.

Q -- for mass loading?

A Yeah. That study -- benzene study was done with TechFlowMP.

Q Okay. Are you offering opinions about the quality of the calibrated values of mass loading of the other contaminants at Hadnot Point?

A If my -- if -- if that is a study which I have done and I was involved in writing the report, yes, I'm going to offer an opinion on it. But the reference, the Exhibit 11 is written by some other group at ATSDR.

I'm not the author so I'm not going to offer an opinion on that.

Q If we stay on supplement six and page S645, where we were, still in the column on the

right --

A Six. Just a moment.

Exhibit six or --

Q No. It's Exhibit 11.

A Yes.

Q What we were on.

A And you are going back to the --

Q -- to S6.

A -- supplement that I'm not an author, I'm not an involved participant. Maybe I have just reviewed it and you are going to ask me a question --

Q Yes --

A -- about it again.

Q -- I have questions about it --

A Okay.

Q -- about S640.45.

So it said --

A 645?

Q Yeah. The column on the right --

A Yeah.

Q -- the third paragraph says, "Conducting a robust uncertainty analysis using Monte Carlo analysis requires simulating thousands of realizations. When using available computational

equipment, the HPIA and HPLF models have a simulation time of about six to eight hours for each simulation. The lengthy simulation times and the substantial data limitations therefore make a comprehensive uncertainty analysis computationally prohibitive based on available resources and time limitations. Thus the ranges values presented in the sensitivity analysis section of this report assess a limited number of input and output model parameter.

"The results, i.e. range of concentration presented in the sensitivity analysis reported herein should not be considered or interpreted as the results of a robust and comprehensive uncertainty analysis but do provide insight into parameters, sensitivity, and uncertainty in a qualitative sense."

Were you involved at all in an uncertainty analysis at Hadnot Point using Monte Carlo analysis?

A Yes. Not on this supplement though, on other applications, in other locations, in Tarawa Terrace, in benzene analysis. Yes.

Q But in Hadnot Point were you involved in an uncertainty analysis using Monte Carlo analysis?

A In other sites, yes.
Q What sites?
A What sites?
Q Yeah.
A Fuel farm, under storage tanks, benzene leakage, modeling of benzene using TechFlowMP. If I did the modeling I did the uncertainty analysis.
And I don't know what this is doing or what is this all about that we are looking at right now. I don't know that.
Q Can you go back one page --
A Uh-huh.
Q -- to S6.44?
A Yeah.
Q And there's a figure S6.23.
A Yes.
Q It says, "It's variations and reconstructed are simulated finished water concentrations of trichloroethylene derived using Latin hypercube sampling methodology on water supply well monthly operational schedules Hadnot Point water treatment plant, Hadnot Point-Holcomb Boulevard study area."
Do you see that?
A Yes, I see that.

Q And were you involved in the --
A I wasn't --
Q -- in this process?
A I wasn't involved in anything that you are showing me in this report, supplement six.
Q So -- so Professor Aral, you've told me that you weren't involved in supplement six but you were involved in Monte Carlo simulations at other areas of Hadnot Point.
This is where Monte Carlo simulations of from Hadnot Point are --
A I'm not the only --
Q -- report -- are reported --
A I'm not the only person who can do Monte Carlo analysis. Other teams within ATSDR can do that too.
Q Right. But --
A So at different sites we took the tasks onto us to do the simulations and then do the uncertainty analysis.
In this task, whatever this is, this is done by some other group. Anybody can do uncertainty analysis.
Q Sure.
A Yeah.

Q I don't disagree with you.

But the ones reported by the ATSDR are here in chapter A, supplement six. So where are the Monte Carlo simulations that you did on Hadnot Point? Where are they -- they reported?

A I have not done supplement six uncertainty analysis. Wherever this site is, whoever was responsible doing this simulation who did the analysis is not my group.

Q No, I understand that.

So where are the -- the simulations you did reported?

A Well, we -- we had done the benzene analysis --

Q Sure.

A -- there's a chapter on that. We did the simulations on underground storage tanks, there's a chapter on that. If we made the simulation, we are responsible of the sense -- uncertainty analysis associated with that.

If you -- if you want to go back to those chapters, I can answer all your questions.

Q Were you involved in the sensitivity or uncertainty analysis other than the benzene and the underground storage tanks?

A If -- I don't remember all the tasks that I was involved with. But if you find a report which does a simulation analysis at the different site and my name is not on the report, I have not done that study.

Q Okay. So you can set aside exhibit 11.

A Okay.

Q And I have a few questions about your -- the timeline of your involvement in the ATSDR water models and their reviews by various entities.

A Yeah.

Q So we've already talked about how you started working with ATSDR with a cooperative agreement with MESL --

A Right.

Q -- around 2000.

A Right.

Q And then you've already mentioned that there was the expert panel in 2005 that the ATSDR --

A That's correct.

Q -- convened.

Is that right?

(Whereupon, the court reporter requests clarification.)

BY MS. O'LEARY:

Q "Convened."

And at that ATSDR panel, did you know any of the panel members before it was convened?

A Can you read the names?

Q Yeah.

Barry Johnson (phonetic), Robert Clark (phonetic), David Dougherty (phonetic), Benjamin Harding (phonetic), Leonard Konikow, Eric Laball (phonetic), Peter Pomerank (phonetic), Vijay Singh (phonetic), James Uber (phonetic), and Thomas Walski.

A I know Vijay Singh. I know James Uber and I read papers from Konikow. Probably I read papers from other names that you just read --

Q Okay.

A -- but I don't know them, personally.

MS. O'LEARY: And can we grab 54, if we haven't already?

(Whereupon, Government's Exhibit Aral 20, Expert Peer Review Panel Evaluating ATSDR's Water Modeling Activities In Support of the Current Study of Childhood Birth Defects and Cancer At U.S. Marine Corps Base Camp

Lejeune, North Carolina, was marked for identification.)

BY MS. O'LEARY:

Q Professor Aral, here's --

A Uh-huh.

Q -- Exhibit 20.

A Yeah.

Q And this is -- says it's the "Expert peer review panel evaluating ATSDR's water modeling activities in support of the current study of childhood birth defects and cancer at U.S. Marine Corps Base Camp Lejeune, North Carolina."

And have you -- have you seen this development before?

A Most probably, yes.

Q Is this the report that came out after the expert review panel in 2005?

A I presume, yes.

Q Okay. I'd like to turn your attention first to page 20 -- well, I guess it's page 29.

A Seventy-nine?

Q Twenty-nine.

A Twenty-nine.

Q In section --

A Yes.

Q -- section --
A Summary of recommendations.
Q Yeah. In section 6.4.
A Okay.
Q And they -- so 6.4 says, "Data analysis, Hadnot Point area."
Oh, sorry. Can we go back to 20 -- page 29, 6.2 chronology of events?
A Okay.
Q Okay. So in that section it's: "The panel members recommended that ATSDR focus its next efforts on refining its understanding of chronological events. These need to include documenting periods of known contamination times when water distribution systems were interconnected and the start of operations at the Holcomb Boulevard water treatment plant."
So my understanding, this was a recommendation of the expert panel.
A Yes.
Q And did the ATSDR follow up on this recommendation to refine its understanding of chronological events?
A I think the answer is yes. And I think we also developed a specific application to look

into the interconnectedness of the two water treatment plants or --

Q Uh-huh.

A -- systems. We used the Markov chain analysis at that time.

MS. O'LEARY: And you can set this one aside.

Have we used one yet?

(Whereupon, the court reporter requests clarification.)

MS. O'LEARY: It was just a question, do we have one --

Exhibit 13. Would you grab Exhibit 13?

(Whereupon, there was a discussion off the record.)

THE WITNESS: Exhibit 13?

MS. O'LEARY: I guess it's just a few pages.

BY MS. O'LEARY:

Q Is that it?

A Uh-huh.

Q Yeah. There you go.

A Uh-huh.

Q And this is the -- we looked at it

before -- but this is the transcript of that expert panel.

A Okay.

Q And can we go to page 20 of the transcript? So not of the document.

MS. BAUGHMAN: We only have --

MS. O'LEARY: Not of the document, of the transcript.

So it should say "20" in the top right corner.

THE WITNESS: Twenty?

I don't see a page 20.

MS. BAUGHMAN: We don't have 20.

MR. DEAN: We don't have 20.

MS. O'LEARY: Oh, you don't have a page 20?

MS. BAUGHMAN: No.

MS. O'LEARY: All right. Then never mind. We'll skip that one then.

MS. BAUGHMAN: You want to see? It's the --

MS. HORAN: No, I believe you.

MS. O'LEARY: No, we believe you.

MS. BAUGHMAN: Okay.

MS. O'LEARY: Can we just --

MR. DEAN: Let me see that?
MS. HORAN: We believe you.
MR. DEAN: Oh, I was just giving back to --
MS. HORAN: I'll look but we believe you.
MR. DEAN: I was just giving it back to you in case you wanted to reuse this.
MS. HORAN: What?
MS. O'LEARY: Can we go back then to 54, which is the one that we had before. It's got this tan cover.
THE WITNESS: Okay.
MS. BAUGHMAN: Is that 13?
MS. HORAN: Yeah.
MR. DEAN: Okay.
MS. HORAN: He'll need it back.
MS. BAUGHMAN: What are we on now? What --
MS. O'LEARY: Well, we are pulling up this one, which is --
MS. HORAN: Exhibit 54 -- Exhibit 20?
MS. O'LEARY: -- twenty.
THE WITNESS: Exhibit 20?

MS. BAUGHMAN: We are going back to Exhibit 20?
MS. HORAN: Yes.
MS. BAUGHMAN: All right. The last one?
MS. HORAN: Yes.
MS. BAUGHMAN: What page?
MS. O'LEARY: We'll be heading for page --
THE WITNESS: Oh, my God.
MS. O'LEARY: -- 121.
THE WITNESS: Wait a minute.
MS. O'LEARY: Oh, there it is.
THE WITNESS: Yeah.
MS. O'LEARY: That's it.
THE WITNESS: 121?
MS. O'LEARY: Page 121.
MS. BAUGHMAN: Is this Exhibit 20?
MS. HORAN: It should be.
THE WITNESS: Page 121?
MS. BAUGHMAN: Yeah, but there's no page 121.
THE WITNESS: There's no such --
MS. BAUGHMAN: There's no --
MS. O'LEARY: Oh, it's section -- I

think that's the document number.

So it's section two point -- or 4.2.4, which will be --

THE WITNESS: Four point two point four.

MS. O'LEARY: There we go.

So that will be page 21.

THE WITNESS: Page 21. Okay.

Okay.

BY MS. O'LEARY:

Q And this -- so there's a section 4.2.4, suggested modeling approaches, modifications and considerations.

And in the section on groundwater, kind of in the middle there's a paragraph that begins "Dr. Walski."

Do you see that?

A Yup.

Q Can you read that paragraph?

A "Dr. Walski suggested performing an overall classification of the areas where contamination was known to occur and the areas without contamination. People in the contaminated areas will be considered exposed and those in the uncontaminated areas will be classified as

unexposed.

"He's also recommending -- he also recommended that ATSDR use modeling to concen- -- concentrate on the areas where contamination and exposure are known. As a next step, he recommended ATSDR prepare a matrix to determine a timeframe when contamination did or did not occur."

Q Okay. So at -- at the time of this expert panel in 2005, was ATSDR working primarily on Tarawa Terrace?

A Yeah.

Q And ATSDR did not ultimately decide on simpler classification systems like Dr. Walski described; is that correct?

MR. DEAN: Objection to the form.

A I think this recommendation on simple models were associated with the next phase which is Hadnot Point and Holcomb Boulevard -- Boulevard areas.

BY MS. O'LEARY:

Q Okay.

A Yeah.

Q Well, if we go down, the next line that says "Dr. Walski," so it's the last one on page 21 --

A Yeah.
Q -- Exhibit 20.
It says "Dr. Walski considered the historical pattern of contamination at Hadnot Point too complex to model because the numerous sources cannot be correlated to particular wells."
A Yeah.
Q So why was that advice not taken by the ATSDR?
A It was. It was considered.
Q Well, but they did -- they did model Hadnot Point, didn't they?
A Yeah, they did. But they didn't model the whole Hadnot Point area as we did the Tarawa Terrace area. We did --
Q What do you mean --
A We did individual sections of it where there's a contamination of benzene. We looked at the sources. We just modeled that source propagation as the main parameter.
We looked at the landfill application separately.
Q Uh-huh.
A We used simpler models in there as well. So we -- we followed all these recommendations.

Q Does that mean in the Hadnot Point-Holcomb Boulevard area water model, the groundwater contaminant fate and transport don't cover the whole area, it's just --

A No. No.

Q -- localized?

A It covers -- the groundwater flow area is done for the -- done for the whole section of Hadnot Point Holcomb, Boulevard, etc., etc.

But when you introduce the contaminant transport over that, overlay it, you just look at the benzene concentrations where the source is, like underground storage wells or spillage that occurred in certain years, so you don't look at the benzene plus the landfill area TCE concentrations at the same time.

So different applications at different sections of the model region was considered.

Q Okay. And then I have questions for you about the natural resource --

A Uh-huh.

Q -- the NRC, the National --

A Right.

Q -- Academy of Sciences --

A Right.

Q -- National Resource Council --
A Right.
Q -- because they under -- they published a report on the Camp Lejeune water studies; correct?
A That's correct.
Q And you talked about those in your expert report --
A Yes.
Q -- in this case; right?
A Yes, that's correct.
MS. O'LEARY: Let me grab that report. It's five.
(Whereupon, Government's Exhibit Aral 21, Report, was marked for identification.)
BY MS. O'LEARY:
Q Here is Government Exhibit 21, Professor Aral.
(Whereupon, there was a discussion off the record.)
BY MS. O'LEARY:
Q And Professor Aral, I'd like to go to what should be called page one.
This one starts with some Roman numerals before the main numbers.

A Page one?
Q Yup. Which is not -- not close to the first page.
A Oh.
Q It's in a little ways.
When you get there, it should say "Public summary and context" at the top.
A Yeah.
MS. BAUGHMAN: What page are we on?
MS. O'LEARY: It's page one, but that's quite a ways in.
It says, "Public summary and context" at the top.
THE WITNESS: Uh-huh.
MS. BOLTON: What's the ending Bates number?
MS. O'LEARY: Oh, yes. The ending Bates number is -452.
BY MR. DEAN:
Q So those little numbers on the bottom right.
A Yeah.
Q Okay. So in this page, it says the "Charge to the committee" --
A Uh-huh.

Q It says, "The National Research Council conducted this review in response to a request from the U.S. Navy, the department under which the Marine Corps operates. The Navy was mandated by the U.S. Congress to request a review by the NRC to address the evidence on whether adverse health outcomes are associated with past contamination of the water supply at Camp Lejeune.

"The NRC developed specific instructions for the scope of the review. It then rerecruited and appointed a committee of scientists with diverse but pertinent backgrounds and perspectives to carry out the review."

Do you have any reason to think that's inaccurate?

MR. DEAN: Object to the form of the question.

A Can you repeat that?

BY MS. O'LEARY:

Q Yeah.

Do you have any reason to think that's inaccurate, that opening paragraph?

MR. DEAN: Object to the form --

A I think it's inaccurate.

BY MS. O'LEARY:

Q You think it's what?

A Inaccurate.

Q How is it inaccurate?

A It's inaccurate because they were asked to address the evidence on whether adverse health outcomes are associated with past contamination in water supply at Camp Lejeune. They only -- what they only did, they didn't do a study to address that, they only criticized the ATSDR work.

Q Do you agree that the Navy was mandated to request the review by the NRC?

A It says that. To request a review by the NRC to address the evidence on whether adverse health outcomes are associated with past contamination of the water supply at Camp Lejeune.

So they are asking NRC to do what ATSDR did in that request.

Q Right. And that was what was mandated by Congress.

A Yeah. But they didn't do that.

Q Okay.

A They only criticized the ATSDR water modeling work.

Q You don't think a critique is a -- is a

review?
A It's -- they are not asking for a -- oh, request a review to me implies that they reviewed the whole analysis, themselves.
Q Okay. If you -- I want to turn, actually, to your report, which is --
MS. HORAN: Two.
BY MS. O'LEARY:
Q -- two, Exhibit 2.
A Exhibit 2?
Q Yes.
A Exhibit 2, Exhibit 2, Exhibit 2 -- Exhibit 8, Exhibit 7, 11, 17...
Q And I want to go to page 12, which we looked at --
A So let me first find this.
Q Oh, sorry.
A The --
Q Is that it there on the right, on that stack? Oh, no. It's not -- that's not the marked one.
Here it is, Professor Aral --
A Okay.
Q -- it's right here.
A Yup.

Q So to page 12.

Okay. So this is that bullet-pointed list that we've seen before.

And the last bullet point, where you say, "The model results show finished water at" -- excuse me.

Not the last bullet point, the second to last bullet point.

It says, "The models and techniques used by ATSDR for historical con- -- reconstruction including fundamental equations, input parameters, parameter estimates, calibration uncertainty, and sensitivity analyses were and remain reliable, scientifically valid, and state of the art procedures that are consistent with standard practices used and are generally accepted in this field."

What does it mean for the simulated -- or -- no.

What does it mean for these to be mathematically reliable, statistically accurate, and correct?

A That means the models that we are using or used, like the ones that we have developed at Georgia Tech, are mathematically correct. Meaning

the procedures that we define in mathematical terms are correctly transported into a mathematical model application without an error.

Statistically correct means the application results provide estimates of uncertainty analysis as well and the deterministic results that we are predicting is within the bounds of that uncertainty analysis.

Q Okay.

MS. O'LEARY: And I just need a few minutes break. Can we take a break right here?

THE WITNESS: Okay.

MS. O'LEARY: I need about ten minutes.

THE VIDEOGRAPHER: The time right now is 4:30 p.m. We are off the record.

(Whereupon, there was a recess taken from 4:30 p.m. to 4:41 p.m.)

THE VIDEOGRAPHER: The time right now is 4:41 p.m. We are back on the record.

THE WITNESS: Okay.

BY MS. O'LEARY:

Q Thank you, Professor Aral. So if you can

stay looking at your report, which was Exhibit 2 --
A Yes.
Q -- Government Exhibit 2, and go to page 13 --
A Yes.
Q -- where that bulleted list continues?
A Uh-huh.
Q So the first item on that -- on page 13 says, "The simulated monthly mean concentrations of TCE, PCE, 1,2-TDCE, benzene, and vinyl chloride at Tarawa Terrace, Hadnot Point, and Holcomb Boulevard included tabulated or in figures in ATSDR reports are reliable and represent, within a reasonable degree of scientific and engineering certainty, the contaminant levels in finished water at Camp Lejeune from 1953 to 1987."

MR. DEAN: Okay.

BY MS. O'LEARY:
Q What is that reasonable degree of scientific and engineering certainty for the monthly mean concentrations?
A That's -- that would be probably best described with the deterministic results being in between the uncertainty bounds of the application.
Q How does that relate to their reliability

to what the actual historical values were?
A Reliability --
MR. DEAN: Object to form.
A What -- what do you mean by reliability?
BY MS. O'LEARY:
Q So the simulated monthly mean concentrations for TCE, PCE, DCE, benzene --
A Uh-huh.
Q -- and vinyl chloride at Tarawa Terrace, Hadnot Point, and Holcomb Boulevard what is -- do you have an opinion on how close those values are to the historical values they are trying to estimate?
A Yeah.
MR. DEAN: Object. Object to form.
A Uh-huh. I looked at the final results on -- on uncertainty analysis and the mean values. I -- we can notice that at the initial phases of the simulation, the mean values are probably at the high side of the uncertainty band but between -- I don't remember exactly, but 1960s onward to 1980s -- '85, I think the mean values are right at the -- in the middle part of that uncertainty -- uncertainty band --
BY MS. O'LEARY:
Q Are the --

A -- so --
Q Are the simulated monthly mean concentrations within 10 percent of the unmeasured historical values?
MR. DEAN: Object to the form.
A Ten percent of historical values --
BY MS. O'LEARY:
Q Yeah.
A -- of what?
Q Of the contaminant concentrations.
That what the true monthly mean contaminant concentrations were --
A In the --
Q -- are the simulated values within ten percent of those?
A In a --
MR. DEAN: Object to the form.
A In a statistical sense, if you look at it from a statistical distribution, the results are within less than ten percent of the --
BY MS. O'LEARY:
Q Within what statistical sense?
MS. BAUGHMAN: He's not finished.
BY MS. O'LEARY:
Q I'm sorry. Go ahead.

A I'm -- I'm looking at the results that we are presenting within the uncertainty band and the mean deterministic results are lying just at the center of that uncertainty band.

If you are asking how does the predictions go with the observed water treatment plant concentrations, there's a significant variation on that but statistically they are on target.

Q I'm not asking about either of those. I'm asking about for the unmeasured historical mean concentrations --

MR. DEAN: Object to form.

BY MS. O'LEARY:

Q -- how close to those can you say that the simulated monthly mean values are?

A Okay. What you are asking is, what is the accuracy or model prediction results in reference to historical contamination at the site --

Q That's right.

A -- during which we didn't have any data but we needed the data for the epi study, right?

Q That's right.

A Okay.

There's no other way in mathematical

model done for the Camp Lejeune site which wrongly predicts that range but rightly predicts the water treatment plant. That cannot be developed.

Q I don't understand what you mean.

A That means the accuracy of the model within the range of the timeline where we don't have data --

Q Uh-huh.

A -- must be accurate so that we are getting to the right water distribution plant concentrations.

Q But don't -- don't you --

A That's -- that's, in a sense, what we call validation issue.

Q But aren't there multiple solutions to what the historical concentrations could have been --

A That's exact --

Q -- that arrive at the same concentrations --

A That --

Q -- that we actually know about in the 80s?

A That's exactly what I'm saying.

In the overall sense, you cannot develop

a model which totally shows a different trajectory starting from 1953, all the way to '85, totally different trajectory which matches with the water treatment plant concentrations at the level that we have matched.

There's continuity in groundwater flow. There's continuity in contaminant transport plume migration. If you are able to predict the future or present day concentrations --

Q Uh-huh.

A -- in 1987, all the other predictions dating back to 1953 must be correct or --

Q How correct?

MR. DEAN: Object to the form.

A How correct?

Statistically, that's the most rated in the uncertainty ranges associated with the variations that may be included into the model predictions which probably are referring to. And all of that is within the uncertainty bound.

BY MS. O'LEARY:

Q But you said you were not involved in chapter I, which had the analysis of much of the uncertainty in Hadnot Point.

A I'm only referring to the -- not much of

the -- I'm only referring to the work that we have done at Tarawa Terrace, the benzene concentration, landfill application, and the industrial -- not the industrial -- underground storage tanks, which we did.

Similar procedures, similar mathematical techniques are used by other groups within ATSDR, so they followed the correct procedures. And what I say to my work applies to them as well.

Q So you think that the solution that is the calibrated model for Tarawa Terrace is the uniquely best one?

A It is unique in the sense that you cannot produce a totally different trajectory of contaminant movement in the aquifers of Camp Lejeune Tarawa Terrace --

Q Uh-huh.

A -- which ends up consistently with the results that we have predicted.

Q What does totally different mean though? You said totally different.

A Totally mean -- for example, you would like to see the results being less than MCL levels in the Tarawa Terrace area throughout the region of the timeline of the study like an exponential curve

going up and reaching, finally, the water treatment plant concentrations. That's totally different, right?

Q So are you -- you are referring to the overall shape --

A Yup.

Q -- of the curve?

A Overall shape.

Q That the overall shape can't be totally different?

A Cannot be totally different.

Q Okay. But it could be different just not totally --

A It --

Q -- different?

A -- it will be different within the uncertainty bounds of the set statistical limits and the --

Q But that uncertainty bounds you've -- you've acknowledged isn't the whole universe of what could have happened at --

A We are --

Q -- the site.

A -- modeling here. We are not doing the universe application. We are just doing a model of

the universe that you are having to describe in your mind.

Q Right. So I -- my question is how to relate the model to the reality it's trying to emulate. So in that frame --

A All models are approximations to the environment.

Q Uh-huh.

A If you all agree with the assumptions we made in building this model for Camp Lejeune, we have to agree with the results of the model because there are no mathematical errors in there, there are no statistical errors in that analysis. And if the model assumptions are correct, if they are properly describing the environment approximately --

Q Uh-huh.

A -- then the results are correct.

Q But what if they don't appropriately --

MR. DEAN: Object --

BY MS. O'LEARY:

Q -- describe the environment of the model?

A Then you have --

MR. DEAN: Object to the form.

A -- the wrong model --

BY MS. O'LEARY:

Q Then you have the wrong model?

A -- in your hand.

Yeah, if you -- if you can prove that to us, we will accept the mistake.

Q Okay. Moving on from specific modeling questions, just to confirm: Did you do any water modeling at the rifle range, Camp Geiger, Marine Corps Air Station New River, Montfort Point which is also called Camp Johnson, Courthouse Bay, or Onslow Beach water distribution systems at Camp Lejeune?

A No.

Q Okay. And your report does not contain opinions about contamination in water coming from those water systems treatment plants; is that correct?

A That's correct.

Q And do you have an understanding of why no water modeling was done at rifle range, Camp Geiger, Marine Corps Air Station, New River, Montfort Point, Camp Johnson, Courthouse Bay, or Onslow Beach?

A I was not involved in that decision.

Q Okay. And I have another question about your report. It's on page 12. So near where we

were, just one page back, page 12.

A Page 12?

Q Yes.

A Uh-huh.

Q Right in -- near the top, in the 4.1 water modeling section.

A Right.

Q The second sentence says, "The use of modeling for historical reconstruction is an accepted methodology to predict past exposure or contamination levels as demonstrated both in the scientific literature." And then there are some citations. "And in site-specific studies, such as Jacksonville, Florida Naval Air Station, Tucson International Airport/Hughes Aircraft Facility, Oakridge National Lab, Hanford Site, and Toms River Dover Township."

A Yes.

Q I want to explore what you mean by a historical reconstruction being an accepted methodology within -- to predict past exposure to contamination levels and how it compares to what was done at Camp Lejeune.

MS. O'LEARY: So can we look at 52, please?

This will end up being Government Exhibit 22.

(Whereupon, Government's Exhibit Aral 22, Independent Reviewer Comments Document, was marked for identification.)

MS. O'LEARY: Here you go.

THE WITNESS: Uh-huh.

BY MS. O'LEARY:

Q Twenty-two is a document, it goes onto two pages. And the label is, "Independent reviewer comments."

And this isn't on here but I'll represent to you that the time name of this document within materials from the ATSDR was, "Aral_resp_document_2011-05-05_BallockM.docs" (phonetic).

A Wait. Wait. I -- this is the first time I'm seeing this, I think.

What is this?

Q Well, that was my question for you.

The file name had your name in it. It said it was, "Aral resp document," and then the date and then "Bollock M."

A Is -- is that name on this paper?

Q No, it was in the file name --
A Oh, the file name.
Q -- that this document came from.
And so I wondered, do you know who "Mansour Ballock ORISE fellow hydrologist" is? That's near the top in the name and title of reviewer.
A "Monsour Ballock," I don't know this name.
Q Okay.
A No. I --
Q Have you ever seen this document --
A No.
Q -- before?
A No.
Q Okay. You can --
A No.
Q -- set it aside.
MS. O'LEARY: Then can we get 36.
(Whereupon, Government's Exhibit Aral 23, Historical Reconstruction of the Water Distribution System Serving the Dover Township Area, New Jersey, January 1962 to December 1996, was marked for identification.)

BY MS. O'LEARY:

Q Professor, it looks like this will end up as Government 23.

There you go.

So this document is -- title is "Historical Reconstruction of the Water Distribution System Serving the Dover Township Area, New Jersey" --

A Uh-huh.

Q -- "January 1962 to December 1996."

A Uh-huh.

Q And are you familiar with the document that's in Exhibit --

A Yes.

Q -- 23?

A Yes.

Q What is it?

A Yes.

It has my lab's logo on it.

Q Okay. And as I look at the -- I guess it's the third page, but it doesn't have a number --

A Okay.

Q -- but it -- it appears you are listed as an author.

A Uh-huh.

Q Is that correct?

Did you -- are you one of the authors of this document?

A Yeah.

Q Okay. And can you go to the page that has the little Roman numeral four? So little iv?

A Uh-huh.

Q So in the fist paragraph in the column on the left, it -- it starts, in the last sentence, says, "In 1997, ATSDR and NJDHSS determined that an epidemiologic study was warranted and that the study would include assessments of the potential for exposure to specific drinking water sources. To assist the epidemiologic efforts, ATSDR developed a work plan to reconstruct historical characteristics of the water distribution system serving the Dover township area by using water distribution system modeling techniques.

"The numerical model chosen for this effort, EPA net two, is available in the public domain and is described in the scientific literature. To test the reliability of model simulations, water distribution system data specific to the Dover township area were needed to compare with model results. Lacking such data, a field data

collection effort was initiated to obtain pressure measurements, storage tank water levels, and system operation schedules during winter demand and peak demand operating conditions.

"Using these data, the water distribution system was -- model was calibrated to present day conditions. ATSDR released a report and a technical paper in June 2000 describing the field data collection activities and model calibration results."

Okay. So in looking in this, which is one -- this is one of the studies you cited in your report about --

A Yeah.

Q -- the established use of --

A Yeah.

Q -- of forecasting backwards --

A Yeah.

Q -- in -- in use of water models; is that correct?

A Yeah.

Q Am I understanding that in this study at Dover township area, the model involved was just the water distribution system?

Is that correct?

A That -- that's correct.
Q So there was no groundwater model in this --
A No.
Q -- is that correct?
A No.
Q And there --
A We were just using data from pumping wells.
Q Okay. And was there any contaminant fate and transport modeling?
A Yes.
Q What was the contaminant fate and --
A EPA --
Q -- transport --
A -- net --
Q -- model?
A -- two. Contaminant fate and transport in the pipelines, not in the groundwater.
Q Okay. So was there a contaminant fate and transport model in the groundwater?
A There wasn't any groundwater --
Q There --
A -- contaminant transport. But there was contaminant transport analysis in the pipelines.

Q Okay. So within the distribution system?
A Yes.
Q Okay. And then the next paragraph, still on iv, it says, "Having established the reliability of the model and the modeling approach, the model was used to examine or reconstruct plausible historical characteristics of the water distribution system. For this purpose, monthly simulations were conducted between January 1962 through December 1996 to estimate the proportionate contribution of water from points of entry well or well fields to various locations throughout the Dover township area."
A Yes.
Q So do you agree that the results from the Dover township model were a proportionate contribution and not a contaminant concentration?
A Oh, as you know, the contaminant loss within a pipeline system is always negligible. So if you put a concentration of one -- at a certain point -- milligrams per liter, it doesn't matter whether you put 200 milligrams per liter, it's proportionate. The results can be always extended to another concentration level.
Q But what was reported in the Dover township study --

A Is a character --
Q -- was the proportionate contribution --
A Yeah.
Q -- right?
A Exactly.
Q Okay. So the proportionate contribution of a particular well?
A Yeah. Yeah.
Q Okay.
A Which sites of the water distribution system received contaminants from which well.
Q Okay. In the Dover township study, am I correct that that did not include any contaminant mass loading modeling?
A No. No.
Q It --
A Whatever --
Q Meaning it did not include that?
A No, it did not.
It just looked at the -- how the water coming from wells are distributed in the water distribution system.
Q Okay. And did it involve -- it -- sorry.
It did not involve contaminant biodegradation --

A No.
Q -- modeling.
A No. I don't think so.
Q Okay. And were there fewer than ten well fields involved --
A I -- I --
Q -- in that model?
A -- have to read the report to answer that honestly.
Q Okay. And did it involve modeling anything outside of the distribution system?
A No.
Q Okay. That's all I wanted to ask you about this one.
A Okay.

MS. O'LEARY: And can we get 64?

(Whereupon, Government's Exhibit Aral 24, USGS Water Resources Investigations Report, was marked for identification.)

BY MS. O'LEARY:
Q Professor Aral, this will be Government Exhibit 24.

And -- so Professor Aral, the document -- or Exhibit 24 says it's the "Fate and transport

modeling of selected chlorinated organic compounds at hangar 1,000, U.S. Naval Air Station Jacksonville, Florida." And it says it's by the USGS Water Resources investigations report and it has its number.

A Uh-huh.

Q Is this the report you were discussing in your --

A Yes.

Q -- report when you said --

A I think so.

Q -- when you mentioned the Jacksonville Naval Air Station?

A That's correct.

Q Okay. And can you go to page two of this report, which is a few pages in?

A Uh-huh.

Q There's a section called, "Purpose and scope," in the right-hand column.

A Uh-huh.

Q And it says, "A computer model capable of simulating the groundwater flow and the fate and transport of trichloroethylene, dichloroethylene, and vinyl chloride in the groundwater at hanger 100 -- 1,000 was needed by the Navy to aid in

remedial decisions.

"The purpose of this report is to document the development of this model which simulates groundwater flow in solute transport and presents the results of the model predictions. The computer modeling effort consisted of one updating existing large scale groundwater model to simulate groundwater flow in the vicinity of hangar 1,000, establishing boundary conditions for a site specific model with the large scale model, and predicting the movement of contaminants at hangar 1,000 through solute transport simulation using the site specific model."

So do you agree that the purpose of this naval air station in Jacksonville modeling was to aid in remediation?

A Yeah.

Q And that is looking to the future? Like, using the present to look at what to do in the future, is that correct?

A I think it looked at the past contamination and how it spread over the region. If -- I don't recall exactly what it did look -- but it could have looked at the past contamination as well --

Q Oh.
A -- but the purpose was remediation.
Q Yeah. And I don't disagree about having looked at the past --
A Right.
Q -- but, I mean, the purpose was for --
A Yeah, yeah, yeah.
Q -- predicting what would happen --
A Yeah.
Q -- in the future.
A Exactly.
Q Correct?
That's the purpose on remediation, is --
A That's right.
Q -- where it's going, where should we clean up.
A Uh-huh. Uh-huh.
Q And still on -- or actually, if we could go to page 49?
A Uh-huh. Yes.
Q Okay. There's the column on the left on page 49, the second paragraph, it starts, "Simulation." "Does a simulated" -- oops, excuse me. I'm in the wrong spot. Huh.
Do you know what the time frame for the

running of the model on Jacksonville, Florida Naval Air Station was?

A I wouldn't know that.

Q Okay.

MS. O'LEARY: And that's all I wanted to ask you about that. If we could go to --

THE WITNESS: Okay.

MS. O'LEARY: -- thirty-one.

(Whereupon, Government's Exhibit Aral 25, EPA Superfund Record of Decision, Tucson International Airport Area, Arizona, was marked for identification.)

BY MS. O'LEARY:

Q There you go --

A Thank you.

Q -- Professor Aral.

MS. O'LEARY: And what's the exhibit number? Is this 25?

MS. HORAN: That's right.

BY MS. O'LEARY:

Q Okay.

A Yeah.

Q So we've got Exhibit 25. It says it's

"EPA superfund record of decision, Tucson International Airport Area" --

A Yeah.

Q -- "Arizona."

Is this what you were citing in your report in one of the area -- examples of --

A Uh-huh.

Q -- the use of --

MR. DEAN: Objection.

BY MS. O'LEARY:

Q -- historical water modeling?

A This -- this is -- if I recall this correctly, this is a site where site data was -- was used historically to determine what was going on at the site.

Q Okay.

A This reference, I put it in there implying that site data can be used, modeling can be used, statistical analysis can be used. So historical construction can be done many different ways.

Q Uh-huh. Are you familiar with this superfund record of decision?

A I remember reading it but I don't remember right now what it says.

Q Okay. Can you just go to the second page, the back of the first page?
A Okay.
Q And in the middle, there's a -- there's an abstract and it's box 16.
A Okay.
Q Okay.
MS. BAUGHMAN: Sorry. What page are you on?
MS. O'LEARY: The back of the first actual page of the document. It doesn't have a number. It's --
THE WITNESS: The ab- --
MS. O'LEARY: There are boxes on it. Yeah.
THE WITNESS: The abstract you are referring to?
MS. O'LEARY: Uh-huh.
THE WITNESS: Okay.
MR. DEAN: Can I see it for a second?
BY MS. O'LEARY:
Q Okay. So --
MS. BAUGHMAN: That's -- yeah.

BY MS. O'LEARY:

Q So the abstract says that, "The Tucson International Airport area site encompasses sections of southwest Tucson and adjoining land south of the city of Pima County, Arizona -- or the city in Pima County, Arizona.

"The site is located in the Tucson basin and includes industrial, commercial, residential and undeveloped areas as well as the Tucson International Airport, the U.S. Air Force Plant number 44, AFP 44, and part of the San Xavier Indian Reservation. The Santa Cruz River borders the site to the west.

"The groundwater system in the Tucson basin has been designated as sole source aquifer. Before the discovery of groundwater contamination in the TAA wells within the site boundaries provided water for over 47,000 people. At least 20 facilities have operated in the TAA since 1942. These include aircraft and electronics facilities which discharged waste liquids directly to surface soil.

"Fire drill training areas where uncombusted residual wastes from training operations were left in unlined pits and unlined --

(Whereupon, the court reporter requests clarification.)

BY MS. O'LEARY:

Q -- "and unlined landfills which received various wastes from several sources. The first indications of groundwater contamination in TAA appeared in the early 1950s when elevated levels of chromium were detected in municipal supply well adjacent to AFP44 in the southern portion of the site and residents in another area complained of foul smelling water from private supply wells. In 1976 the well was closed at AFP 44 by the state because of high levels of chromium.

"By 1988, additional sampling by the Air Force and EPA had indicated the presence of VOCs in the groundwater. Consequently, in 1981, the City of Tucson began closing all municipal wells that exceeded the state action level for the principle contaminant TCE and notified private well users of potential risks.

"The site was divided approximately in half along Los Reales Road with the Air Force" --

(Whereupon, the court reporter requests clarification.)

BY MS. O'LEARY:

Q "Los Reales Road with the Air Force addressing contamination to the south and EPA addressing contamination to the north.

"In 1987, the Air Force began operating its groundwater pump and treatment system using ion exchange and packed column aeration followed by reinjection into the aquifer. This rod addresses the groundwater contamination in the northern portion of the site which, together with the Air Force remedial groundwater system, constitutes the overall groundwater remedy for the site.

"The northern portion of the site has been divided into two discrete areas, A and B. Area A lies west of the airport and extends approximately three and a half miles to the northwest in the direction of groundwater flow and is generally less than a mile wide.

"Area B consists of two smaller separate areas north of the airport. It fur -- it further -- if further investigations indicate that there is soil contamination and that it is a source of continuing groundwater contamination, a rod will be developed to address soil remediation. The primary contaminants of concern effecting groundwater are

VOCs including TCE, benzene, and xylene."

So is this project also about remediation?

MR. DEAN: Object to the form. The document speaks for itself.

A Yeah, it is about remediation --

BY MS. O'LEARY:

Q Okay.

A -- but there is some population -- there's a mention of population living in the vicinity of about what, 50 -- 47,000 people.

Q Yeah.

A So I don't know how they would resolve the contaminant distribution, remediation, or they don't want to look at the health effects maybe of whatever --

Q I mean --

A Whatever --

Q Go ahead.

A Whatever the decision is for U.S. EPA or U.S. -- who is doing this? I remember --

Q So --

A This is the -- this is the record of decision. Okay.

So I think they are looking at

remediation here.

Q Is there any discussion here of historical reconstruction of a water model?

A Well, I think they -- as I said, the water modeling analysis can be done looking at model outputs, statistical outputs, or site data.

The reason I have included this reference is that this reference doesn't use modeling, it just looks at the site data and tries to understand how they can manage the system for remediation without doing a modeling. As far as I know, that's the purpose I put that in there.

Q Okay.

MS. O'LEARY: All right. That is it. I'm all finished.

Thank you, Dr. Aral --

THE WITNESS: Okay.

MS. O'LEARY: -- or Professor Aral.

THE WITNESS: Thank you.

MR. DEAN: No questions.

MS. O'LEARY: Okay.

MR. DEAN: Have a good evening.

MS. O'LEARY: Then we are done.

THE VIDEOGRAPHER: The time right now is 5:16 p.m. We are off the record.

(Thereupon, the deposition was concluded at 5:16 p.m. EST.)

C E R T I F I C A T E

I hereby certify that I am a Notary Public, in and for the State of New York, duly commissioned and qualified to administer oaths.

I further certify that the deponent named in the foregoing deposition was by me duly sworn, and thereupon testified as appears in the foregoing deposition; that said deposition was taken by me stenographically in the presence of counsel and reduced to typewriting under my direction, and the foregoing is a true and accurate transcript of the testimony.

I further certify that I am neither of counsel nor attorney to any of the parties to said suit, nor am I an employee of any party to said suit, nor of any counsel in said suit, nor am I interested in the outcome of said cause.

Witness my hand and seal as Notary Public this 10th day of February, 2025.

_____

Clifford Edwards

New York Notary ID Number: 01ED6430906
Notary commission expires: 3/28/2026

J U R A T

I have read the foregoing 381 pages and hereby acknowledge the same to be a true and correct record of the testimony.

_____

MUSTAFA MEHMET ARAL

Subscribed and sworn to

_____.

Before me this _____ day of _____,

2025.

_____

Notary Public

My Commission Expires:

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EXHIBIT 33

DEPARTMENT OF HEALTH & HUMAN SERVICES

Public Health Service

Agency for Toxic Substances
and Disease Registry
Atlanta GA 30333

February 21, 2007

Dr. Leonard F. Konikow
Research Hydrologist
U.S. Department of the Interior
Geological Survey
12201 Sunrise Valley Drive
Mail Stop 431
Reston, Virginia 20192

Dear Dr. Konikow:

On behalf of the Agency for Toxic Substances and Disease Registry (ATSDR), I would like to thank you for reviewing the following report

Simulation of Fate and Transport of Tetrachloroethylene (PCE) in Ground Water at Tarawa Terrace and Vicinity, Marine Corps Base Camp Lejeune, North Carolina, **by Robert E. Faye**

Enclosed are the author's responses to your review comments.

Please accept my thanks for assisting us in ensuring the highest caliber for our scientific investigations. Should you have any questions, please feel free to call me at telephone (404) 498-0415. I can also be contacted by electronic mail at: mmaslia@cdc.gov.

Sincerely yours,

Morris L. Maslia, P.E., DEE, D.WRE
Research Environmental Engineer

Enclosure:
Response to review comments

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Robert E. Faye and Associates, Inc.
610 High Shoals Drive
Dahlonega, Georgia 30533
Phone: 706-219-1738
Email: refaye@alltel.net

February 14, 2007

Ms. Naida Gavrelis
Eastern Research Group
110 Hartwell Avenue
Lexington, MA 02421-3136

Dear Ms. Gavrelis:

Responses to review comments by Dr. Leonard F. Konikow regarding the report "Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Potable Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-day Conditions, Chapter F: Simulation of the fate and transport of tetrachloroethylene (PCE)" are listed below in the order presented by the reviewer by letter dated July 27, 2006. The reviewer listed 5 items of major concern and then numerous page-by-page comments. The major concerns are addressed directly below followed by the page-by-page comments.

The authors wish to thank Dr. Konikow for a thorough and knowledgeable review and we are greatly appreciative of his efforts.

Sincerely,

Robert E Faye

Robert E. Faye, P. E.

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Major Concerns

1. The lumping of two aquifers and one confining unit into the surficial model layer 1:

The Tarawa Terrace aquifer and confining unit and the UpperCastle Hayne aquifer-River Bend unit are combined into model layer 1. Although the Tarawa Terrace confining unit in the vicinity of ABC One-Hour Cleaners and the STT tanks is locally somewhat competent, as evidenced by driller's comments regarding "running sands", the Tarawa Terrace aquifer and confining unit generally are thin and discontinuous in the northern part of Tarawa Terrace and vicinity. In the southern part of Tarawa Terrace, east and in the vicinity of the Tarawa Terrace shopping center, the Tarawa Terrace confining unit is difficult to distinguish, even in detailed boring logs, and the Tarawa Terrace aquifer and Upper Castle Hayne aquifer-River Bend unit appear to be vertically continuous.

Numerous water-level data in the vicinity of ABC One-Hour Cleaners, northern Tarawa Terrace, and in the southern part of Tarawa Terrace near the Tarawa Terrace shopping center indicate conclusively that (1) vertical hydraulic gradients between the Tarawa Terrace aquifer and the Upper Castle Hayne aquifer-River Bend Unit are small and inconsequential. In other words, water levels measured to a hundredth of a foot in paired observation wells open respectively to the two aquifers were the same or nearly the same during several measurement cycles; and (2) these same water-level data indicate that the water table generally occurs near the base of the Tarawa Terrace confining unit/top of the Upper Castle aquifer-River Bend unit. During or immediately following periods of significant and prolonged rainfall, the water table may temporarily reside at the base of the Tarawa Terrace aquifer. Thus the Tarawa Terrace aquifer and confining unit probably are only partially saturated much of the time. Given these field observations and lines of evidence, the authors believe that combining the 3 defined hydrogeologic units into a single model layer was hydrologically and hydraulically appropriate.

2. The use of a finite-difference method to solve the governing transport equation (which causes substantial numerical dispersion, especially if time steps are too large):

First of all the reviewer probably has no idea whether or not using a code based on finite-difference methods caused "substantial" or insubstantial numerical dispersion during solution of the Tarawa Terrace fate and transport model. Certainly, some numerical dispersion occurred; however, the degree or effects of this dispersion are unknown and, to the best of our knowledge, cannot be accurately determined. Secondly, at the beginning of the fate and transport modeling process, linked output from the flow model was applied to several transport codes, including MOC3D. All of these codes, with the exception of MT3DMS, either failed to converge or created unstable (oscillating) solutions. Thirdly, the MT3DMS model was designed with a Peclet number ($\Delta x/\alpha_L$) equal to 2.0 (Δx = 50 feet, α_L = 25 feet). A Peclet number of 2 or less generally minimizes numerical dispersion for a particular solution. Consider, as well, the Courant number ($v\Delta t/\Delta x$), which affects the occurrence of oscillations arising from the discrete approximation of the time derivative. The Courant number should equal one or less for all cells

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in all layers during all stress periods in order to control numerical oscillations. Simulated flow velocities (v) ranged between 0.01 and 1.0 feet per day at all cells in all layers except in the immediate vicinity of pumping wells, where velocities were as high as 8 feet per day. At all cells, $\Delta x = 50$ feet and $\Delta t = 28, 29, 30$ or 31 days. Thus, out of a total of approximately 27,000 cells in each model layer, the Courant number was less than one at all but a few dozen cells in the immediate vicinity of pumping wells. With respect to the calibrated flow and fate and transport models, numerical oscillations did not occur in any cell in any layer during any stress period. Furthermore, the MT3DMS code is well-documented and has been available in the public domain for about a decade. The code is well-recognized as a stable and numerically accurate solution platform.

3. The reliability of the estimate of the biodegradation rate constant based on the assumption that concentration declines observed at one location over a period of several years can be explained solely by biodegradation:

The authors never claimed that the biodegradation rate computed using field data was reliable or the sole reason for the observed decline in PCE concentration. Rather the computed rate was presented as an approximate value useful to begin model calibration. Well TT-26 is located on a direct migration/advective pathway from the PCE source at ABC One-Hour Cleaners (Figures 2, 5). To the extent that migration of PCE mass toward and away from supply well TT-26 occurred at about equal rates during 1985 to 1991, the computed degradation rate of 0.00053 per day approximates a long-term average degradation rate. On the other hand, if a significant quantity of the PCE degraded in the vicinity of supply well TT-26 was replaced by advection, then the degradation rate computed using Equation (3) is probably a minimum rate. The report does not state or indicate that the decline in PCE mass at supply well TT-23 is due entirely to biodegradation. Rather, the report indicates that the computed first-order degradation rate is an estimate used as a basis to begin model calibration.

4. The exclusion of concentration data collected in monitoring wells from the calibration basis:

Monitor well concentration data were excluded from consideration when calibrating the fate and transport model because the concentration data from monitor wells did not represent a complete or uniform mixing of solute within an intersticial volume comparable to the intersticial volume of a model cell. In other words, the scales of measurement or observation between monitor wells and model cell dimensions in terms of the volume of aquifer sampled were different by orders of magnitude. Analytical results from water-quality samples obtained from monitor wells are affected by local aquifer heterogeneities that could not be measured or accounted for when constructing the Tarawa Terrace flow and fate and transport models. On the other hand, samples obtained from operating supply wells are composite samples obtained from a large volume of the contributing aquifer or aquifers and reflect well-mixed or average conditions within the water-bearing units. Thus samples collected at supply wells conform to a considerable degree to the assumptions and limitations that apply to simulated results from the Tarawa Terrace fate and transport model.

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Consider a typical monitor well, such as well S3 and located near well TT-26. Well S3 is 39.5 feet deep, well diameter is 4 inches, and the well is screened from 19.5 to 39.5 feet. The screen is open to the base of the Tarawa Terrace aquifer and the upper part of the Upper Castle Hayne aquifer-River Bend unit. The observed depth to water ranges between about 20 and 22 feet. At a depth to water of 20 feet, the casing water volume is about 28 cubic feet. This casing volume was removed 3 to 5 times prior to obtaining a water sample for water-quality analysis. At an effective porosity of 0.2, a maximum of about 150 cubic feet of aquifer volume was sampled. In addition, this aquifer is highly heterogeneous locally and consists of silty sand and thin, discontinuous beds of clay and silt that influence the distribution of solute at a scale of inches or several feet. Such heterogeneity causes variability in transport processes, particularly advective and dispersion processes that could not be simulated using the cell and layering resolution of the fate and transport model. Hydrocone data collected in the vicinity of well S3 reflect this small-scale variability. For example, at site HC-9 at a depth of 31 feet the observed PCE concentration was 176 µg/L; at almost the same site at the same time at a depth of 36.5 feet the PCE concentration was 6.3 µg/L. Site HC-9 was located about 300 feet east of wells S3 and TT-26. At site HC-20, near wells S3 and TT-26, the PCE concentration at a depth of 34 feet was 500 µg/L; at almost the same time at a depth of 41 feet the PCE concentration was 196 µg/L. PCE concentrations determined from analyses of 2 water samples collected from well S3 were 380 and 5,400 µg/L. The hydrocone samples were collected during December 1991. Water-quality samples from well S3 were collected during April 1992 (5,400 µg/L) and September 1993 (380 µg/L). Such variability with depth and time could not be replicated using the layer geometry, cell resolution and constant loading rates applied to the Tarawa Terrace fate and transport model.

Consider next a model cell representing model layer 1 and containing well S3. The cell represents an area of 2500 square feet and an average thickness of about 40 feet, or a volume of 100,000 cubic feet. Consider also that during simulation, PCE mass available at this cell is distributed uniformly and instantaneously throughout the available intersticial volume of the cell at the end of every stress period. In other words, the simulated PCE concentration is everywhere equal within a given model cell during an individual stress period. Compare this condition to the highly variable distribution of PCE with depth noted previously at sites HC-9 and HC-20. Obviously, PCE is not distributed uniformly throughout the "real world" aquifer and PCE concentrations change by orders of magnitude over short intervals of depth. Similar or comparable variations in PCE concentration likely occurred across the screened interval of monitor well S3 and the open intervals of other monitor wells. Although mixing occurs during the sampling process, PCE concentrations obtained from well S3 reflect variability caused by local heterogeneity and relate to only a tiny percentage of the volume of a model cell. Only by the most unique and rarest of coincidences could one expect highly variable PCE concentrations within an aquifer volume of 150 cubic feet to equal or be comparable to a corresponding simulated concentration uniformly distributed throughout an aquifer volume of 100,000 cubic feet in the same area.

5. The use of a much larger mass loading rate than apparently was indicated by the field data in order to improve the model calibration:

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First of all please note that field data did not indicate a mass loading rate. The computations of PCE mass in the saturated and unsaturated zones described in the report were the result of a highly interpretive, somewhat subjective calculation using field data. With respect to the calculation of PCE mass in solution, the field data were sparse and limited to only 2 depth intervals. Secondly, the report explicitly states that the calculated mass loading rate is a *minimum* rate. Three lines of evidence were provided to support this conclusion: (1) the quantity of PCE removed from the aquifers at Tarawa Terrace supply wells during 1953 to 1985 is unknown, (2) the mass of PCE degraded to TCE during 1953 to 1985 was probably large and was not accounted for by the computation of PCE mass, and (3) similarly, the mass of PCE sorbed onto the porous media during 1953 to 1985 was also probably substantial and was not accounted for by the computation of PCE mass. These are reasonable and compelling lines of evidence to conclude that the calculated average PCE mass loading rate described in the report is a *minimum* rate; however, they were apparently ignored by the reviewer. An additional line of evidence is indicated by the discussion in #4 above wherein a high degree of variability with depth is described regarding PCE concentrations. At hydrocone sampling sites, PCE concentrations were determined at two depth intervals, frequently separated by 10 feet or more. That substantial PCE mass occurred within the zone of separation and was not accounted for when calculating the average PCE concentration between "shells" is highly probable.

The reviewer elaborates further on this concern on page 4 of his comments by introducing the issue of total versus effective porosity. The reviewer apparently believes that ground water containing PCE mass saturates the total pore space, not just the pore volume represented by connected interstices. Over time, because of the migration of PCE in solution along concentration gradients, some mass will occur within disconnected interstices; however, by definition, this mass is trapped and cannot move to wells or hydrocones to be sampled. The computation of PCE mass was obviously based on solute that was transported within the ground-water flow regime to wells or other sampling devices and thus was related to effective rather than total porosity. Effective porosity represents the volume of connected interstices that permits and facilitates the flow of ground water through a porous media. Total porosity represents the total volume of interstices, those connected and transmitting ground water and those disconnected or otherwise isolated from the ground-water flow regime. Effective porosity is always less than total porosity. By definition, ground water, including contaminated ground water, flows only through connected interstices. Some exchange of PCE mass from connected interstices to disconnected or isolated pore space possibly occurs along concentration gradients. However, the greatest concentration, by far, of PCE mass in solution is transmitted through and resides within connected interstices, particularly as flow path distance increases away from the source area and toward supply wells. Accordingly, the authors believe that using effective porosity to calculate residual PCE mass as shown in Table 11 was entirely appropriate and reasonable.

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Page-by-Page Comments

p. 17: Agree. Report corrected.

p. 22: The period of time described in the Scope of Study (January 1952 to March 1987) is correct. The Scope specifically refers to the simulation of PCE concentrations at Tarawa Terrace supply wells "for their entire period of operation, January 1952 through March 1987". For simulation purposes, Tarawa Terrace supply wells began pumping in January 1952. Pumping at supply wells was terminated in March 1987.

Fig. 1: Agree. All figures and tables and tables in the report will be published according to USGS standards.

Fig. 8: Agree. A new base for Figure 8 and similar figures will include just the contaminated area. Contours and contour fills will be well-defined and easy to read.

p. 30: Agree. The abbreviation "CLP" probably stands for "Clinical Laboratory Program", an organization/process that inspects state and Federal laboratories for purposes of certification. This abbreviation was never defined in the ABC One-Hour Cleaners OU1 and OU2 reports. We are still trying to confirm the true definition of the abbreviation as reported and will include same in the final draft of the report if we are successful.

Tables 9 and 10: Disagree. Borehole depth is the total depth of the borehole drilled prior to constructing a well. The well depth is the depth of the completed well. These terms convey pretty basic information familiar to most ground-water hydrologists and footnotes explaining same are not necessary.

p. 32 and Fig. 11: Agree. Comparing the thickness of the "Castle Hayne aquifer" shown on Figure 11 of Cardinell and others (1993) to the thickness of the Castle Hayne Formation of this study (also Figure 11) is somewhat of an "apples to oranges" comparison. Cardinell and others included most or all of the Tarawa Terrace aquifer of this study and the Upper Castle Hayne aquifer-River Bend unit of this study in their "Castle Hayne aquifer". These units are not included in the Castle Hayne Formation as defined for this study. In addition, the top of the Beaufort confining unit, which defines the base of the "Castle Hayne aquifer" of Cardinell and others (1993) and the Castle Hayne Formation of this study, is placed significantly lower in the Tarawa Terrace area by Cardinell and others (1993) than interpretations of borehole and lithologic data used for this study would suggest. The altitudes reported at the top of the Beaufort confining unit by Cardinell and others (1993 Table 3) are far below the bottom hole depth of any borehole geophysical or lithologic log available in the Tarawa Terrace area and were estimates, probably based on interpretations of surface resistivity or seismic surveys. Considerable uncertainty is attached to these data as acknowledged by Cardinell and others (1993) in their heading notes attached to their Table 3 and by questioning the depth of the top of the Beaufort confining unit shown in sections on their Plate 1. The combined effect of these

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differences would add an additional 50 to 150 feet of thickness to the contours shown on Figure 11 of this study. Of the hydrogeologic units used to define the layer geometry assigned to the Tarawa Terrace flow and fate and transport models these differences would affect only the thickness of the lower Castle Hayne aquifer, the lowermost hydrogeologic unit and layer 7 of the models. The differences described herein are also discussed in Chapter B of this study, which describes the hydrogeologic framework in the Tarawa Terrace area.

p. 40: Agree. Comprehensive water-level data were available only after contaminated ground water was discovered in the Tarawa Terrace area and various entities began remedial investigations. Consequently, only simulated potentiometric maps of pumping conditions are available. Simulated potentiometric surface maps showing pumping conditions are compared to the conceptual model in a later section of the report.

p. 42: Disagree. The reviewer appears to believe that when the report states that only one transport process was observed (biodegradation), the authors were somehow mislead and actually should have stated that several other processes (dispersion and diffusion) were also observed. Dispersion and diffusion were not observed.

p. 44, top: Agree. One stress period represented one month with the appropriate number of days assigned to the stress period as Δt. No time steps were used within stress periods. This information will be added to the report.

p. 44: Agree. The reviewer's concerns were addressed in item #1 of Major Concerns. The reviewer was possibly mislead by the maximum thickness of the Tarawa Terrace aquifer listed in Table 1 (60 feet). The maximum thickness mistakenly refers to locations southeast of Tarawa Terrace between Northeast and Wallace Creeks included in the framework report (Chapter B of this study). The maximum thickness of the Tarawa Terrace aquifer at Tarawa Terrace is about 30 feet and is 20 feet or less near the source area for PCE contamination. The thickness values listed on Table 1 were corrected.

The water table at the source area and vicinity occurs temporarily at the base of the Tarawa Terrace aquifer during periods of significant and prolonged rainfall but generally occurs at or near the top of the Upper Castle Hayne aquifer-River Bend unit. In addition the Tarawa Terrace confining unit in this area is thin and discontinuous and in the southern part of Tarawa Terrace is missing altogether. The reviewer's comment that simulated mass loading occurs directly to the River Bend unit is correct and conforms to known hydrologic conditions in the study area. Keep in mind that the scope of this study did not include simulation of flow or contaminant through the unsaturated zone. Thus, transit time through the unsaturated zone to the water table was not accounted for. With infrequent exceptions as explained previously, the porous media that overlies the River Bend unit is unsaturated. The framework report (Chapter B of this study) includes maps showing thickness and altitude at the top of the Tarawa Terrace confining unit. Additional qualitative descriptions of the Tarawa Terrace confining unit were added to the framework report.

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p. 44-45 and fig. 12: Disagree. The report states specifically that the western boundary generally conforms to the drainage divide between Frenchman and Scales Creeks. This includes the boundary segment of concern to the reviewer. Additional qualification has been added to the report.

p. 46, lines 5-10: Agree. The terms dispersion and coefficient were used incorrectly in the report where dispersivity should have been used. The text has been corrected.

p. 51: Agree. Sorption processes are unknown for this study. Consequently a statement regarding such processes that is definitive cannot be scientifically defended. Consequently, "a very weak justification was used, assuming it (linear isotherm) is the appropriate model." The parentheses are the authors.

p. 52 and 53: Agree. Unit weight and bulk density are synonymous in English units. Bulk density is the term used in the MT3DMS documentation and should be consistently used in the report. The report text has been corrected.

General comment: Most units used in this report are as reported. Occasionally, during computations such as the calculation of PCE mass, units are converted from English to metric and vice versa because the data used were originally reported in English or metric units and the results had to be presented in useful terms such as gallons or cubic feet. The rate of contaminant loading assigned to the model is reported in grams/day. Concentrations were originally simulated in grams/cubic foot. Feet were used in order to be consistent with flow model data linked to the fate and transport model. Grams were used in order to compare simulated results to observed results which are always reported in milligrams or micrograms per liter.

p. 53, para 1, last line: Agree. The calibrated retardation factor should have been reported as 3.7. The text has been corrected.

p. 56: Agree. The report should read equation 3. The text has been corrected.

p. 56 and 57: A "shell" represents a grouping of spatial data characterized by common attributes. To the best of the authors' knowledge, the term is commonly used to describe overlying GIS coverages. The term was appropriately used in the report.

Table 11: Disagree. In Table 11, the numbers are shown to the significant figures listed simply to allow the reader to check and reproduce, if necessary, the computation of PCE mass. The real test of the "accuracy and precision" intended by the authors is the final results, which are reported to 2 significant figures.

Table 11, p. 137: Agree. The units were reported incorrectly and should have been grams per liter instead of milligrams per liter. The results are reported correctly in the text.

p. 56 and 57 and Table 11: Disagree. The text clearly explains that the computations shown in

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Table 11 are performed on the volume of material computed between the upper and lower shells. The volume-weighted concentration is clearly defined as the total of sub-area weighted concentrations divided by the total of all subareas. Perhaps "volume-weighted" is a confusing term. The authors' intention in using this term was to indicate the average concentration within the volume delimited by the upper and lower shells. An attempt will be made to create a less confusing term. The thickness of porous media between the upper and lower shells was determined by interpolating the altitudes of sampling depths or the mid-points of screened intervals at specified wells (control points) located within the upper and lower shells. The results of this effort were 2 contour maps that defined the surface area and altitude of each shell. The volume of media between shells was computed by subtracting, in effect, the lower shell contour map from the upper shell contour map using GIS. The correct volume-weighted concentration was 0.0014 grams per liter. The correct concentration was reported in the text. The units on Table 11 have been corrected.

p. 46 to 59 Model input data and initial conditions: Agree. A sentence has been added to the report indicating that initial concentration arrays were assigned as zero grams/cubic foot for all layers.

p. 55 and 56 Biodegradation rate: Disagree. This criticism was previously addressed under Major Concerns, item #3. The reviewer's suggestion to simulate PCE concentrations using a degradation rate of zero and adjust the field data by simulated changes is not accepted. Adjustments to field data using such simulated changes would add additional uncertainty to an already uncertain process.

p. 57 Mass loading: Disagree. This criticism was previously addressed under Major Concerns, item #5.

p. 59 Mass loading: Disagree. See comments under Major Concerns, item #5. The reviewer seems to assign a high degree of accuracy and credibility to the PCE mass computation that is unwarranted. As explained previously, the computation of PCE mass was a highly interpretive and somewhat subjective process frequently based on questionable data. Field data applied to the PCE mass computation were limited both spatially and vertically. The computation was accomplished regardless of data limitations to provide an estimate of a minimum mass loading rate to use to begin model calibration.

The results reported for this study are reasonable within the context of limited and frequently questionable field and operations data. Legal depositions indicate that ABC One-Hour Cleaners replenished their PCE supply at a rate of two or three 55 gallon drums per month. The unit weight of PCE is approximately 100 pounds per cubic foot. Using two drums per month, or 110 gallons of PCE, ABC One-Hour Cleaners replaced about 1470 pounds or about 670,000 grams of PCE monthly. The calibrated mass loading rate applied to the model represents about 36,000 grams of PCE per month or about 5 percent of total usage. Using three drums per month, this percentage drops to 3.6 percent. These percentages represent loss not only to waste water but to filter and still residues which were disposed to the land surface in the immediate vicinity of the

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cleaners as well as spills from a 250 gallon PCE storage tank external and adjacent to the cleaners' building. Because PCE is a high-expense item, efficient use of PCE is critical to a profitable dry-cleaning operation. Thus, the calibrated mass-loading rate indirectly reflects a reasonable operational efficiency and PCE loss rate at ABC One-Hour Cleaners. A direct comparison between the mass loading rate applied to the model and total operational losses of PCE at ABC One-Hour Cleaners is not possible because the greatest loss of PCE at the cleaners, far and away, was to volatilization during the various stages of dry cleaning. Consider, as well, that PCE losses to the subsurface from the cleaning operations were originally delivered either to the land surface or to the shallow subsurface and migrated vertically through about 20 feet of unsaturated zone to the water table. Within the unsaturated zone, PCE mass was lost to aerobic degradation and retention. Accordingly, the mass loading rate applied to the MT3DMS model equates, at best, only to a minimum PCE loss rate to the subsurface and is not comparable to a total loss due to operations.

Increases in mass loading rate were accomplished during model calibration by comparing simulated results to PCE concentration data collected at Tarawa Terrace supply wells and at the Tarawa Terrace WTP. These data were available periodically only from 1982 to 1985 and again in 1991.

Whether or not 80 percent of PCE as solute is removed from the subsurface by wells and transport processes, as suggested by the reviewer, is reasonable or unreasonable cannot be resolved independent of model simulations. The hierarchical calibration process and the excellent calibration results at calibration levels 3 and 4 suggest that model simulations are indeed reasonable.

p. 59 Model calibration: Agree. The report text was corrected to remove the reference to iterative adjustments of simulation results. Adjustments to model arrays during calibration were manual, trial and error. The mass loading rate, biodegradation rate constant, and distribution coefficient were selected for adjustment during calibration because initial estimates of these parameters were considered highly uncertain. Literature descriptions of rate constants and distribution coefficients were used as general guides during calibration; however, literature sources were limited and pertinent data specific to the Camp Lejeune area or even North Carolina were not available. Effective porosity and longitudinal dispersivity were not adjusted during calibration as initial estimates of these parameters were considered reasonable. In addition, simulation results are only minimally sensitive to changes in longitudinal dispersivity.

An enhanced description of the approaches and methods of model calibration will be added to the introduction to Model Calibration.

p. 60 Level 3 calibration: Comments in this paragraph seem largely redundant to concerns expressed previously and were addressed herein in the preceding paragraph. The "conceptual" bases for calibration were, secondarily, literature descriptions of rate constants and distribution coefficients and, primarily, comparisons of simulated PCE concentrations to field data. This report does not provide and was never intended to provide (1) a daily log of calibration

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activities, (2) a catalog of thoughts and approaches leading to particular parameter adjustments, or (3) descriptions of hypothetical (conceptual implications) what ifs with respect to calibration decisions. A summary description of calibration methods and approaches is provided and is sufficient for the purposes of this report.

p. 60 Level 3 calibration: Agree. The report text has been modified to conform to the reviewer's comments. Simulated concentrations are computed for the last day of each month (stress period) and this concentration is considered representative of average conditions for the entire month.

p. 60 Level 3 calibration: Disagree. The reviewer's concerns are addressed under Major Concerns, Item #4. Monitor well data could be used for model calibration if, instead of a 50 feet per side cell dimension, model cell resolution was about 1 foot per side with respect to monitor wells and about 6 inches per side with respect to hydrocone data. Such resolution is totally impractical given the size of the model domain.

p. 60 next to last line: Agree. The text should have read "6 sides to a cell". This was a poor example used to compare scales of measurement. The example has been removed and the text modified per Item #4 of Major Concerns. The reviewer's comment regarding a 100 foot thickness that was somehow used in a unit conversion shown on Table 11 is incorrect.

Fig. 8: The title for figure 8 should read 1991-1993. The dates listed in Table 5 are correct. Data additional to those listed in Table 5 were used to generate Figure 8, thus the different time intervals.

p. 61, line 1: The calibration standard of one-half order of magnitude was selected somewhat arbitrarily and reflects the confidence level expected of calibrated model results. A literature example of exactly this approach is unknown.

p. 61, line 3: Agree. The text has been modified per Item #2 of Major Concerns.

Table 12: Agree. Table 12 has been modified.

p. 62, line 4: Agree. The report text has been corrected.

p. 62, line 8: The locations of supply wells RW-01, RW-02, and RW-03 are shown in Figure 4 and were located during a well reconnaissance prescribed for ABC One-Hour Cleaners OU1. Well RW-02 was located in a commercial building (furniture store) immediately next to ABC One-Hour Cleaners. Little is known about these wells except their location, estimates of depth and perhaps some additional construction details. Pumpage and operation data were not available. Pumpage was considered insignificant for modeling purposes and pumping was not simulated.

Fig. 14: Most concerns expressed in this paragraph were answered previously. The well location is shown in Figure 4; however, the illustration is too small to read easily. This figure

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and all other illustrations for this report are being redrafted by the USGS, which will completely resolve the reviewer's concerns.

Figs. 14-19: Agree. The final illustrations will include observed concentrations. The reviewer's comments regarding underestimates of peak concentrations are confusing. The authors have no knowledge of field observations of peak contaminant concentrations and only simulated concentrations are shown on Figures 14-19.

Vertical distribution of contaminants: Simulated contaminants were observed above detection levels as deep as model layer 5. Discussions of the vertical distribution of contaminants will be added to the report. The "lower unit" that the reviewer refers to is the Upper Castle Hayne aquifer-Lower unit, layer 3 of the model.

p. 62-64: The authors will consider graphs of pumpage assigned to model supply wells but our immediate thought is what useful or pertinent information will such graphs provide.

p. 64. bottom: The authors believe the report clearly indicates that the time in question is December 1968. Comparisons are made between simulated fate and transport simulations accomplished for December 1960 and December 1968 (Figures 20 and 21). Considerable increases in supply well pumpage directly south of ABC One-Hour Cleaners occurred during this interval and corresponding changes in hydraulic gradients and PCE plume distribution are described. Hydraulic gradients north to south in the vicinity of ABC One-Hour cleaners increased and caused a corresponding increase in flow of uncontaminated water from the general-head boundary located just north of the cleaners. This additional flow from the boundary caused additional dilution of the PCE mass in the source area between December 1960 and December 1968. Simulated flow from the head-dependent boundary during December 1960 was about 47,000 cubic feet per day. Simulated flow from the head-dependent boundary during December 1968 was about 101,000 cubic feet per day. Corresponding flows during December 1975 and December 1984 were relatively constant at about 71,000 cubic feet per day. Note as well that the simulated plume area increased by about a factor of 4 between 1960 and 1984. The dissipation of PCE mass to progressively larger areas over time and the dilution of the mass caused by corresponding increases in head-dependent boundary flow are the major causes of the progressive decrease in simulated PCE concentration in the source area. The authors do not accept the reviewer's suggestion that simulated decreases in source area concentration are the result of numerical error. Additional discussion and qualification of the information shown in Figures 20-29 will be added to the report. The reviewer's several references to 1963 are not understood.

p. 67, item 3: The reviewer is correct that a mass of PCE remained in the unsaturated zone following termination of simulated mass loading after December 1984. However, residual mass loading from the unsaturated zone could not be reasonably estimated with available data. In addition, the residual PCE mass in the unsaturated zone was considered stable and any loading from the unsaturated zone was considered inconsequential compared to the mass of PCE as solute resident in the various aquifers at Tarawa Terrace at that time. Consequently simulated

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PCE concentrations at Tarawa Terrace supply wells between January 1985 and March 1987 should be considered conservative estimates. The report text will be modified to reflect these conclusions.

p. 67: Agree. The reviewer's suggestions to add various plots of mass balance components during the entire period of simulation to the report are excellent and will be accomplished for the final report. The simulated reduction in PCE concentration at the source was certainly affected by recharge as well as boundary inflows, sorption, biodegradation, and dispersion. The suggestion to illustrate the PCE distribution during March 1987 is accepted and this illustration will be added to the final report.

The simulated PCE plume following the termination of mass loading and pumping at supply wells continued to expand in size, as expected, and plume concentrations continued to be degraded by recharge, sorption, biodegradation, and dispersion.

p. 68, line 9: Agree. The report text is misleading regarding the information presented in Table 13. The text will be modified to correct this problem.

Figure 30: That simulated results are probably not unique is being addressed by the Tarawa Terrace project by completing Monte Carlo analyses of numerous alternative distributions of hydraulic characteristic arrays and by varying individual pumping schedules at all supply wells to determine maximum and minimum breakthrough times and possible ranges in computed PCE concentrations at the Tarawa Terrace WTP.

The "lumping" of units into model layer 1 and the derivation of the mass-loading rate have been thoroughly addressed. Issues of numerical dispersion and time discretezation have been thoroughly addressed by discussing Peclet and Courant numbers characteristic of the flow and fate and transport models.

Figure 30: The decrease in PCE concentration at well TT-26 is caused by the onset of pumping at 4 new supply wells, three of which are directly south of ABC One-Hour Cleaners and well TT-26. Close examination of Figure 30 would indicate that the concentration decrease actually began in early 1962 following the onset of simulated pumping at these well in January 1962. This additional pumping diverted some PCE mass from a previous entirely southeasterly direction to a more southerly direction away from well TT-26.

p. 70, Sensitivity Analysis: No comment

p. 70, Sensitivity Analysis: The discussion of sensitivity analyses is incomplete, as the reviewer has implied in his comments. Sensitivity analyses in the modified report is based on an RMS computation of observed PCE concentrations at the Tarawa Terrace WTP and supply wells. A total of 29 paired data were available to compute the RMS for sensitivity determination.

For the record, the longitudinal dispersivity was only changed by a factor of 10, maximum.

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p. 71 & Table 7: Agree. Table 7 will be modified to include the key to reading sample depth. As a common practice, the sample depth is imbedded in the site designation. For example at site 5, the site names HC-5-25 and HC-5-40.5 indicate samples at site 5 collected at depths of 20 feet and 40.5 feet.

p. 71-72, sample anomalies: The reviewer's comments are confusing. Sampling methodologies using a hydrocone seldom deviate from site to site with depth. A hydocone point is pushed to a particular depth, a small window is opened at the exterior of the cone, a tiny sample of pore water is obtained and stored in a vile in the cone, and a few cubic inches of aquifer is sampled. Such techniques are applied over and over with little variation. The reviewer is incorrect in stating that the authors did not consider laboratory error as a possible reason for widely different analytical results. A discussion of possible errors related to a "CLP" and a mobile lab comprises a major part of information presented on page 71.

The discussion of possible analytical errors on page 72 refers only to supply wells, not hydrocone samples. Samples collected at such wells are composite samples obtained through dozens of feet of open interval. Obviously, concentration gradients over the open interval would not be evident because of mixing.

p. 74-75: Agree. A sensitivity analysis was accomplished per the reviewer's suggestion. The sensitivity of simulated concentrations to time discretization was tested by assigning one-day stress periods to the calibrated fate and transport model for the period November 1, 1984 to January 31, 1985 and comparing the concentrations simulated by the modified model to those of the calibrated model. Comparisons were made for the days November 30, 1984, December 31, 1984, and January 31, 1984. Pumpage assigned to the months of interest of the calibrated model was assigned to every day of the respective month of the modified model. Field data and the calibrated model indicated that supply wells TT-23 and TT-26 were substantially contaminated with PCE during the test period. Also, concentration gradients simulated by the calibrated model were large in the vicinity of wells TT-23 and TT-26 at this time. Concentrations simulated by the calibrated and modified models were identical prior to stress period 407 (November 1984). The PCE concentrations simulated by the modified and calibrated models during the test period at wells TT-23 and TT-26 are listed in the following table. Simulated concentrations at supply wells TT-23 and TT-26 were similar to the third or fourth significant figure at the designated times whether or not the stress period length was 1 day or 30 days or 31 days. Thus PCE concentrations simulated by the Tarawa Terrace fate and transport model were demonstrably unaffected by numerical instabilities caused by inappropriate time discretization.

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Site Name	Simulated Elapsed Time, in days	Date	**Δt = 1 day** Simulated PCE Concentration, in grams/ft^3	**Δt = 30 or 31 days** Simulated PCE Concentration, in grams/ft^3
TT-23	12,388	Nov. 30, 1984	0.007183956	0.007182317
	12,419	Dec. 31, 1984	0.007214860	0.007211736
	12,450	Jan. 31, 1985	0.007200035	0.007198663
TT-26	12,388	Nov. 30, 1984	0.02297354	0.02298510
	12,419	Dec. 31, 1984	0.02276520	0.02279888
	12,450	Jan. 31, 1985	0.02275406	0.02276190

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EXHIBIT 34

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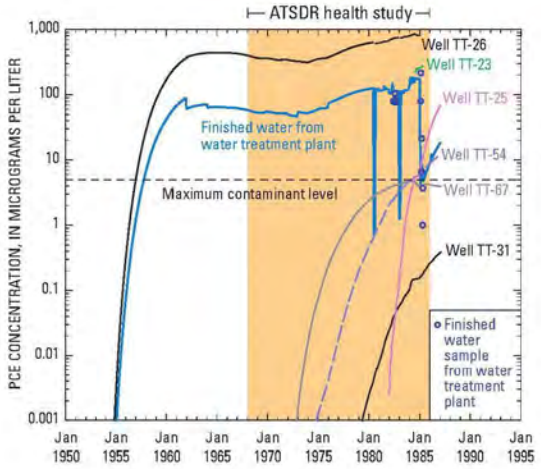
Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions

Chapter H: Effect of Groundwater Pumping Schedule Variation on Arrival of Tetrachloroethylene (PCE) at Water-Supply Wells and the Water Treatment Plant



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Front cover: Historical reconstruction process using data, information sources, and water-modeling techniques to estimate historical exposures

Maps: U.S. Marine Corps Base Camp Lejeune, North Carolina; Tarawa Terrace area showing historical water-supply wells and site of ABC One-Hour Cleaners

Photographs on left: Ground storage tank STT-39 and four high-lift pumps used to deliver finished water from tank STT-39 to Tarawa Terrace water-distribution system

Photograph on right: Equipment used to measure flow and pressure at a hydrant during field test of the present-day (2004) water-distribution system

Graph: Reconstructed historical concentrations of tetrachloroethylene (PCE) at selected water-supply wells and in finished water at Tarawa Terrace water treatment plant

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Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions

Chapter H: Effect of Groundwater Pumping Schedule Variation on Arrival of Tetrachloroethylene (PCE) at Water-Supply Wells and the Water Treatment Plant

By Jinjun Wang and Mustafa M. Aral

Agency for Toxic Substances and Disease Registry
U.S. Department of Health and Human Services
Atlanta, Georgia

February 2008

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Foreword

The Agency for Toxic Substances and Disease Registry (ATSDR), an agency of the U.S. Department of Health and Human Services, is conducting an epidemiological study to evaluate whether in utero and infant (up to 1 year of age) exposures to volatile organic compounds in contaminated drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina, were associated with specific birth defects and childhood cancers. The study includes births occurring during the period 1968–1985 to women who were pregnant while they resided in family housing at the base. During 2004, the study protocol received approval from the Centers for Disease Control and Prevention Institutional Review Board and the U.S. Office of Management and Budget.

Historical exposure data needed for the epidemiological case-control study are limited. To obtain estimates of historical exposure, ATSDR is using water-modeling techniques and the process of historical reconstruction. These methods are used to quantify concentrations of particular contaminants in finished water and to compute the level and duration of human exposure to contaminated drinking water.

Final interpretive results for Tarawa Terrace and vicinity—based on information gathering, data interpretations, and water-modeling analyses—are presented as a series of ATSDR reports. These reports provide comprehensive descriptions of information, data analyses and interpretations, and modeling results used to reconstruct historical contaminant levels in drinking water at Tarawa Terrace and vicinity. Each topical subject within the water-modeling analysis and historical reconstruction process is assigned a chapter letter. Specific topics for each chapter report are listed below:

- **Chapter A:** Summary of Findings
- **Chapter B:** Geohydrologic Framework of the Castle Hayne Aquifer System
- **Chapter C:** Simulation of Groundwater Flow
- **Chapter D:** Properties and Degradation Pathways of Common Organic Compounds in Groundwater
- **Chapter E:** Occurrence of Contaminants in Groundwater
- **Chapter F:** Simulation of the Fate and Transport of Tetrachloroethylene (PCE) in Groundwater
- **Chapter G:** Simulation of Three-Dimensional Multispecies, Multiphase Mass Transport of Tetrachloroethylene (PCE) and Associated Degradation By-Products
- **Chapter H:** Effect of Groundwater Pumping Schedule Variation on Arrival of Tetrachloroethylene (PCE) at Water-Supply Wells and the Water Treatment Plant
- **Chapter I:** Parameter Sensitivity, Uncertainty, and Variability Associated with Model Simulations of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water
- **Chapter J:** Field Tests, Data Analyses, and Simulation of the Distribution of Drinking Water
- **Chapter K:** Supplemental Information

An electronic version of this report, *Chapter H: Effect of Groundwater Pumping Schedule Variation on Arrival of Tetrachloroethylene (PCE) at Water-Supply Wells and the Water Treatment Plant*, will be made available on the ATSDR Camp Lejeune Web site at *http://www.atsdr.cdc.gov/sites/lejeune/index.html*. Readers interested solely in a summary of this report or any of the other reports should refer to *Chapter A: Summary of Findings* that also is available at the ATSDR Web site.

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Tables

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Conversion Factors

Multiply	By	To obtain
	Length	
inch	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (MG)	3,785	cubic meter (m^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
million gallons per day (MGD)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
pound, avoirdupois (lb)	4.536×10^{-4}	gram (g)

Concentration Conversion Factors

Unit	To convert to	Multiply by
microgram per liter (µg/L)	milligram per liter (mg/L)	0.001
microgram per liter (µg/L)	milligram per cubic meter (mg/m^3)	1
microgram per liter (µg/L)	microgram per cubic meter ($µg/m^3$)	1,000
parts per billion by volume (ppbv)	parts per million by volume (ppmv)	1,000

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

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Glossary and Abbreviations

ATSDR	Agency for Toxic Substances and Disease Registry
CEE	School of Civil and Environmental Engineering
CPU	central processing unit
DIS	MODFLOW discretization file
FTL	flow-transport link
GA	genetic algorithm
GB	gigabyte
GHz	gigahertz
Maximum Schedule	pumping schedule yielding the early arrival time
Minimum Schedule I	pumping schedule yielding the late arrival time with no conditions on well TT-26 schedules
Minimum Schedule II	pumping schedule yielding the late arrival time with conditions on well TT-26 schedules
MCL	maximum contaminant level
MESL	Multimedia Environmental Simulations Laboratory
OBS	concentration observation file for MT3DMS
Original Schedule	original pumping schedule used by ATSDR
PC	personal computer
PCE	tetrachloroethylene
PSOpS	Pumping Schedule Optimization System
S/O	simulation and optimization
USGS	U.S. Geological Survey
WEL	well package for MODFLOW
WTP	water treatment plant

Note: In this report, the maximum contaminant level (MCL) refers to the current MCL for tetrachloroethylene (PCE) that was set by the U.S. Environmental Protection Agency at 5 micrograms per liter, effective July 6, 1992 (40 CFR, Section 141.60, Effective Dates, July 1, 2002, ed.)

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Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions

Chapter H: Effect of Groundwater Pumping Schedule Variation on Arrival of Tetrachloroethylene (PCE) at Water-Supply Wells and the Water Treatment Plant

By Jinjun Wang[1] and Mustafa M. Aral[1]

Abstract

Two of three water-distribution systems that have historically supplied drinking water to family housing at U.S. Marine Corps Base Camp Lejeune, North Carolina, were contaminated with volatile organic compounds (VOCs). Tarawa Terrace was contaminated mostly with tetrachloroethylene (PCE), and Hadnot Point was contaminated mostly with trichloroethylene (TCE). Because scientific data relating to the harmful effects of VOCs on a child or fetus are limited, the Agency for Toxic Substances and Disease Registry (ATSDR), an agency of the U.S. Department of Health and Human Services, is conducting an epidemiological study to evaluate potential associations between in utero and infant (up to 1 year of age) exposures to VOCs in contaminated drinking water at Camp Lejeune and specific birth defects and childhood cancers. The study includes births occurring during the period 1968–1985 to women who were pregnant while they resided in family housing at Camp Lejeune. Because limited measurements of contaminant and exposure data are available to support the epidemiological study, ATSDR is using modeling techniques to reconstruct historical conditions of groundwater flow, contaminant fate and transport, and the distribution of drinking water contaminated with VOCs delivered to family housing areas. This report, Chapter H, describes the effect of groundwater pumping schedule variations on arrival times of PCE at water-supply wells and the Tarawa Terrace water treatment plant (WTP). The analyses and results presented in this chapter refer solely to Tarawa Terrace and vicinity. Future analyses and reports will present information and data about contamination of the Hadnot Point water-distribution system.

During the historical reconstruction study—described in other chapters of this report series—groundwater flow and fate and transport of contaminants at Tarawa Terrace and vicinity were simulated to evaluate the contaminant concentration at the WTP. Due to uncertainty associated with reconstructed input data used in these simulations, uncertainty may be present in simulated contaminant concentrations at water-supply wells and the WTP. As a consequence, there also may be uncertainty associated with the arrival time of the maximum contaminant level (MCL) concentration at water-supply wells and the WTP. A major cause for and contribution to this uncertainty are the pumping schedules, which are discussed in other report chapters. The focus of this chapter report, therefore, is on the uncertainty associated with pumping schedules. The study discussed in this chapter includes the development of a simulation and optimization procedure identified as PSOpS (Pumping Schedule Optimization System), which combines simulation models and optimization techniques to optimize pumping schedules for maximum or minimum contaminant concentrations at the WTP. Based on optimized pumping schedules, variations of PCE concentration and the maximum contaminant level (MCL, 5 micrograms per liter for PCE) arrival time at water-supply wells and the WTP are evaluated. Results of this study indicate that variation of pumping schedules may cause significant changes in the contaminant concentration levels and MCL arrival times at the WTP.

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Introduction

The Agency for Toxic Substances and Disease Registry (ATSDR) is conducting an epidemiological study to evaluate whether exposures (in utero and during infancy—up to 1 year of age) to volatile organic compounds (VOCs) that contaminated drinking water at the U.S. Marine Corps Base Camp Lejeune, North Carolina, were associated with specific birth defects and childhood cancers. To provide the epidemiological study with quantitative estimates of exposure, characterization of environmental contamination and the frequency and duration of exposure to contaminated drinking water is being conducted using the historical reconstruction process (Maslia et al. 2001).

The site investigation at the base concluded that groundwater was the sole source of water to the Tarawa Terrace water treatment plant (WTP).[2] The contaminant source was ABC One-Hour Cleaners (Shiver 1985), located north of the Tarawa Terrace I family housing area (Figure H1). Major contaminants at the site included tetrachloroethylene (PCE) and its degradation by-products. Contaminants released from ABC One-Hour Cleaners migrated into the groundwater system and eventually were supplied to the WTP through several water-supply wells in the Tarawa Terrace area of the base.

Based on the study of hydrogeologic and historical data of Tarawa Terrace and vicinity, the ATSDR modeling team has reconstructed and simulated multilayer groundwater flow at the site using MODFLOW, a groundwater-flow simulation model (McDonald and Harbaugh 1988). The simulation model MT3DMS (Zheng and Wang 1999) was then used to evaluate the fate and transport of contaminants in the subsurface. Based on this analysis, concentration distribution and arrival time of contaminants at the WTP were determined historically.

Due to its nature, the historical reconstruction modeling process has uncertainties associated with it; these uncertainties could have a significant effect on the epidemiological study. One uncertainty is associated with pumping schedules used in groundwater-flow simulations because there are limited historical records of pumping rates at water-supply wells. In this study, the focus is on the evaluation of the uncertainty caused by pumping schedules and its effect on simulation results. For this purpose, a methodology was developed to yield the earliest/latest contaminant arrival times at water-supply wells and the WTP associated with allowable variations in groundwater pumping schedules throughout the historical operation of the site. As it was developed in this study, this methodology uses a combination of simulations and optimization methods to adjust pumping schedules while maintaining historical total pumping demands at the water-supply wells that were identified in other chapter reports. The study presented here includes the following assumptions:

1. Tetrachloroethylene (PCE) is the only contaminant of concern at the site, although other contaminants such as degradation by-products of PCE existed in the groundwater and at the WTP. In this study, the use of the term *contaminant* implies PCE, unless otherwise specified.
2. The pumping schedule is the only variable considered to be uncertain in this analysis. Some other factors, such as hydrogeologic variables, also may cause variations in the contaminant transport process and may affect contaminant concentration and arrival time at water-supply wells and the WTP. The uncertainties associated with these variables are discussed in Chapter A (Maslia et al. 2007) and Chapter I (Maslia et al. In press 2008) and, therefore, are not considered in this study.

This study used two simulation models:

1. *MODFLOW:* A modular three-dimensional groundwater simulation model. It can be used in the solution of governing equations of multilayer groundwater-flow systems. The model uses the finite-difference method in its process, was developed by the U.S. Geological Survey, and is an open source code (McDonald and Harbaugh 1984). MODFLOW-2000 (also identified as MF2K), a fourth generation of MODFLOW, is employed in this study. In this report, all MODFLOW-related information is adopted from the report authored by Harbaugh et al. (2000) unless otherwise identified. The executable file and the source codes of MODFLOW can be downloaded from *http://water.usgs.gov/nrp/gwsoftware/modflow2000/modflow2000.html*.
2. *MT3DMS:* A modular three-dimensional multispecies contaminant transport model. It can be used in the simulation of advective, diffusive, and reactive transport of contaminants in multilayer groundwater systems (Zheng and Wang 1999). All the MT3DMS-related information in this report is obtained from reports authored by Zheng and Wang (1999) and Zheng (2005) unless otherwise identified. The version of the MT3DMS model employed in this study is version 5.1. The executable file and the source codes of MT3DMS can be downloaded from *http://hydro.geo.ua.edu/mt3d/*.

In this study, all information regarding U.S. Marine Corps Base Camp Lejeune and input data used for the models previously described are the same as used in other report chapters. Thus, there is no discussion of details of the hydrogeologic framework and the bases of these data.

The organization of this report is as follows. In the next section, a review of the study conducted by the ATSDR modeling team is provided, including a background review and a review of the simulation models used in the historical reconstruction study. A groundwater simulation and optimization procedure—identified as PSOpS (Pumping Schedule Optimization System) and developed by the researchers at the Multimedia Environmental Simulations Laboratory, Georgia Institute of Technology—is introduced in the section "Optimization of Pumping Schedules." Simulation results and a discussion of these results are presented in the section "Simulation Results and Discussion," which is followed by a "Summary of Results" section.

[2]Throughout this report (Chapter H), the water treatment plant (WTP) refers solely to the Tarawa Terrace WTP.

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A Review of ATSDR's Tarawa Terrace Study

Background

ATSDR, an agency of the U.S. Department of Health and Human Services, is currently (2007) conducting a historical reconstruction of contaminant occurrences in drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina. Camp Lejeune is located in the Coastal Plain of North Carolina, in Onslow County, south of the City of Jacksonville and about 70 miles northeast of the City of Wilmington, North Carolina (Figure H1). The purpose of the study is to determine if there is an association between exposure to contaminated drinking water and birth defects and childhood cancers in children born to women who were pregnant while living in base housing during the period 1968–1985.

Due to limited exposure data available for the period of interest (1968–1985), ATSDR has undertaken a reconstruction of historical conditions. In this series of chapter reports (A–K), ATSDR's investigation focuses solely on Tarawa Terrace and vicinity. (Future analyses and reports will present information and data about contamination of the Hadnot Point water-distribution system.) The Tarawa Terrace area is bounded on the east by Northeast Creek, and to the south by New River and Northeast Creek. On the west and north, it is bounded by the drainage boundaries of these streams. The historical reconstruction includes a groundwater system reconstruction, contaminant source characterization, and contaminant fate and transport simulation in the groundwater system and the water-distribution system serving the Tarawa Terrace area.

The ATSDR study concluded that groundwater was the sole source of water to the WTP and water-distribution system serving the Tarawa Terrace area. The source of contaminants in the groundwater was ABC One-Hour Cleaners (Shiver 1985), located to the north of several Tarawa Terrace water-supply wells (Figure H1). According to the ATSDR study, PCE was continuously released to the subsurface system at a rate of 1,200 grams per day during the period January 1953–December 1984 (Faye 2007b). PCE released from ABC One-Hour Cleaners migrated into the groundwater system and was then supplied to the WTP by water-supply wells pumping contaminated groundwater.

Using hydrogeologic data and contaminant source characterization (Faye 2007a), the ATSDR modeling team was able to simulate groundwater flow and contaminant fate and transport in the subsurface system at Tarawa Terrace and vicinity to reconstruct historical concentration levels of PCE (Faye and Valenzuela 2007; Faye 2007b). Due to the nature of historical reconstruction, uncertainties are associated with reconstructed information, which in turn cause uncertainties in resulting exposure analyses. Uncertainties in the exposure outcome can have a significant effect on the epidemiological study. In particular, the uncertainty caused by the groundwater pumping schedule used in the simulations has been pointed out to be important. Therefore, in this study, there is an evaluation of the variation in PCE concentrations and arrival times of the maximum contaminant level (MCL, 5 micrograms per liter [µg/L] for PCE) at water-supply wells and the WTP. The variation could be caused by changes in groundwater pumping rates at water-supply wells.

Introduction to Simulation Tools and Input Data

In the ATSDR study, the contaminant concentration at the WTP was evaluated by using the following steps:

1. The MODFLOW model was used to simulate groundwater flow at Tarawa Terrace area and vicinity. The MODFLOW simulation also generated a flow-transport link (FTL) file that was used in the MT3DMS simulation.
2. Using the FTL file, along with other input files, an MT3DMS simulation was conducted to obtain contaminant concentrations at water-supply wells.
3. The contaminant concentration distribution obtained from the MT3DMS simulation was used to calculate the PCE concentration at the WTP through a volumetric mixing model.

In the following sections, MODFLOW and MT3DMS models and their input files are briefly described.

MODFLOW Model and Input Data

MODFLOW is a computer program that was designed to solve the three-dimensional equation governing groundwater flow (Equation 1) by using the finite-difference method for both steady-state and transient-flow applications (McDonald and Harbaugh 1988):

$$\frac{\partial}{\partial x}(K_{xx}\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(K_{yy}\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(K_{zz}\frac{\partial h}{\partial z})+W=S_s\frac{\partial h}{\partial t}, \quad (1)$$

where

K_{xx}, K_{yy}, and K_{zz} are hydraulic conductivity values along the x-, y-, and z-coordinate axis directions (LT^{-1});
h is the piezometric head (L);
W is a volumetric flux per unit volume that represents sources and/or sinks at the site (T^{-1});
S_s is the specific storage of the porous medium (L^{-1});
t is time (T); and
x, y, z are the Cartesian coordinate directions (L).[3]

McDonald and Harbaugh (1984) developed MODFLOW. Since then it has been modified numerous times, and several versions exist in the literature. The second version is identified as MODFLOW-88 (McDonald and Harbaugh 1988). The third version is identified as MODFLOW-96 (Harbaugh and McDonald 1996a, 1996b). The latest version, which is used in this study, is identified as MODFLOW-2000 (Harbaugh et al. 2000). Also since its inception, Prudic (1989), Hill (1990), Leake and Prudic (1991), Goode and Appel (1992), Harbaugh (1992), McDonald et al. (1992), Hsieh and Freckleton (1993), Leake et al. (1994), Fenske et al. (1996),

[3]For equations in this report (Chapter H), L represents length units, T represents time units, and M represents mass units.

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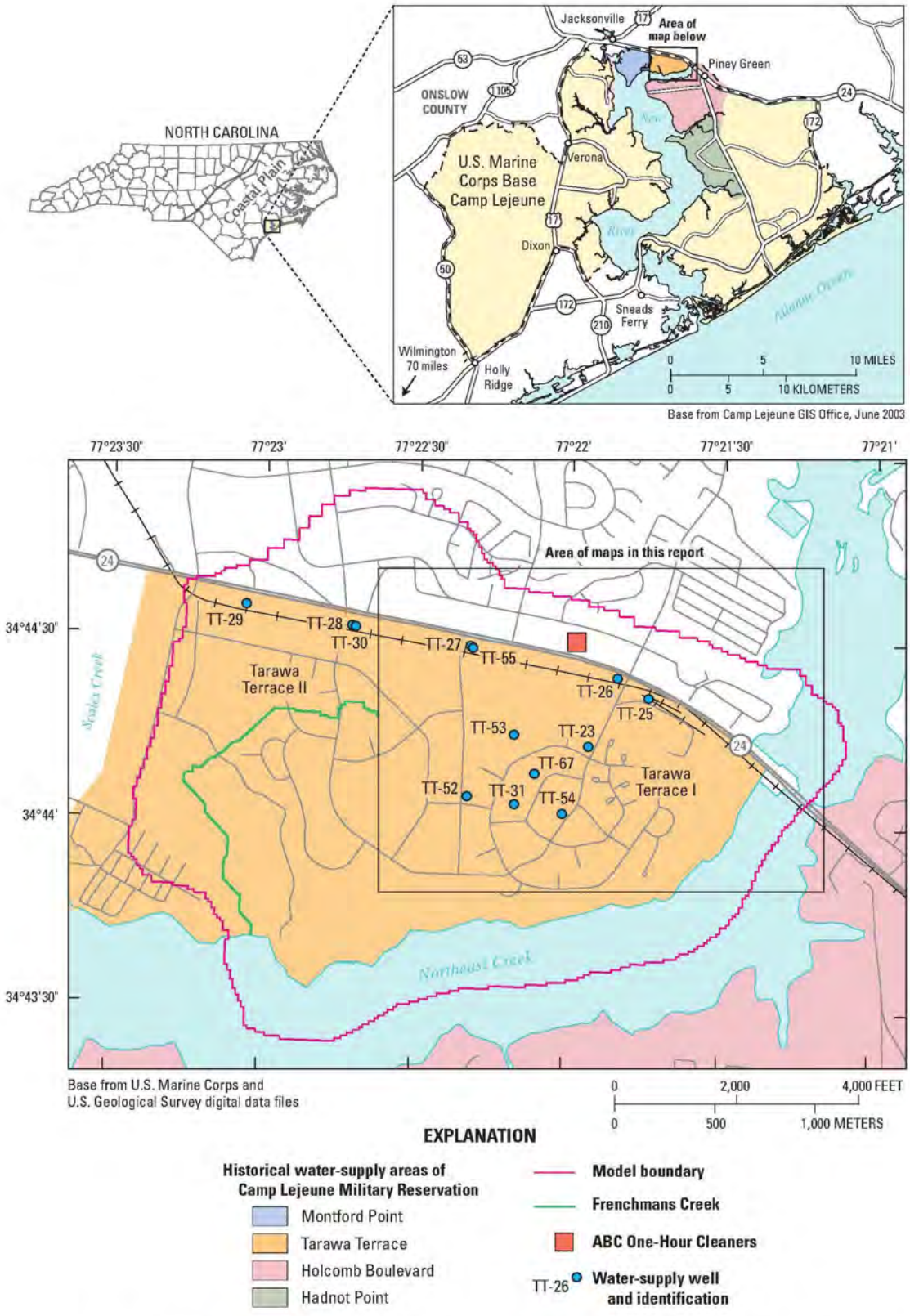

Figure H1. U.S. Marine Corps Base Camp Lejeune, water-supply wells, and ABC One-Hour Cleaners, Onslow County, North Carolina.

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Leake and Lilly (1997), and Hill et al. (2000) have made several improvements to MODFLOW.

In this study, the MODFLOW model is applied to generate an FTL file for the MT3DMS simulation. In addition, MODFLOW also is a component of the newly developed PSOpS model.

In MODFLOW simulations, a fundamental component of time discretization data is the "time step." A group of time steps is identified as a "stress period" (Harbaugh et al. 2000). In this study, from the first month of year 1951 through the last month of year 1994, each month is identified as a stress period. There are a total of 528 stress periods during the overall simulation period. January 1951 is "stress period 1," February 1951 is "stress period 2," and so forth (Appendix H1). Within a stress period, time-dependent variables, such as groundwater pumping rates of water-supply wells, are constant. Therefore, the update of the pumping schedule, as reconstructed in this study, occurs monthly.

In MODFLOW, the basic spatial simulation unit used in finite-difference calculations is called a "finite-difference cell" or "cell." In the ATSDR study, the groundwater system at Tarawa Terrace and vicinity is modeled as a zone that contains 200 rows, 270 columns, and 7 layers of cells. Thus, a total of 378,000 cells are used to idealize the three-dimensional groundwater-flow region at the site.

Input data for the MODFLOW simulation can be divided into two categories: (1) "global process input" data files and (2) "groundwater-flow process input" data files. Global process input files contain basic information that is applied to the entire simulation. As for the groundwater-flow process input files, a group of related input data are put together into a file as the input for a specific "package." For example, a discretization (DIS) file is a global process input file. It contains data such as the number of rows, columns, and layers in the model, cell widths, and so forth. In comparison, a well (WEL) file is a file that contains input data for the "Well Package," including locations and pumping rates of water-supply wells assigned to each stress period. Based on these types of classifications, MODFLOW input files, as used in the ATSDR study, are listed and are summarized in Table H1.

Table H1. Input files used for the MODFLOW simulation code, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Process	File type	Package
Global	NAM	Not applicable
	DIS	Not applicable
Groundwater flow	BAS6	Basic
	BCF6	Block-Centered Flow
	DRN	Drain
	GHB	General-Head Boundary
	OC	Output Control Option
	PCG	Preconditioned Conjugate-Gradient
	RCH	Recharge
	LMT6	Link-MT3DMS
	WEL	Well

There are two global process files used in the study:

1. *File type:* NAM
   File contents: The name and Fortran unit of each file used in the simulation
2. *File type:* DIS
   File contents: Basic discretization information, including number of rows, columns, and layers of the model; number of stress periods; confining layers information; width of each cell along rows and columns; elevation of each cell; period length, number of time steps, and the state (steady or transient) of each stress period

The following nine groundwater-flow process files also are used in the study:

1. *File type:* BAS6
   Package: Basic Package
   File contents: Boundary conditions; piezometric head value in inactive cells; initial head distribution
2. *File type:* BCF6
   Package: Block-Centered Flow Package
   File contents: Wet-dry cell information; layer-type information (whether the layer is confined or not, and how the interblock transmissivity will be calculated); transmissivities or hydraulic conductivities; horizontal anisotropy factors; primary and secondary storage coefficients; vertical hydraulic conductivities divided by thickness of cells
3. *File type:* DRN
   Package: Drain Package
   File contents: Number of drain parameters; maximum number of drain cells used in any stress period; number of parameters used in each stress period; location and elevation of each drain cell, and factors used to calculate the drain conductance in that cell
4. *File type:* GHB
   Package: General-Head Boundary Package
   File contents: Number of general-head boundary parameters; maximum number of general-head-boundary cells used in any stress period; number of parameters used in each stress period; location of each constant head cell, and the heads in the cell at the beginning and end of each stress period
5. *File type:* OC
   Package: Output Control Option
   File contents: Information on whether the computed head, drawdown, and water budget will be saved for each stress period; where to save and in what format
6. *File type:* PCG
   Package: Preconditioned Conjugate-Gradient Package
   File contents: Maximum number of outer and inner iterations; matrix conditioning method; head change criterion and residual criterion for convergence; relaxation parameter; printout interval
7. *File type:* RCH
   Package: Recharge Package
   File contents: Recharge distribution type; recharge flux (if applicable)

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8. *File type:* LMT6
   Package: Link-MT3DMS Package (Zheng et al. 2001)
   File contents: The name, unit, header, and format of the FTL file for MT3DMS simulation
9. *File type:* WEL
   Package: Well Package
   File contents: Maximum number of operating wells in each stress period; number, location, and pumping rate of each well in each stress period

MT3DMS Model and Input Data

MT3DMS is a modular three-dimensional multispecies transport model that can be used in the simulation of advective, dispersive, and reactive transport of contaminants in groundwater-flow systems (Zheng et al. 2001). In the MT3DMS model, three major classes of transport solution techniques are applied so that the best approach can be offered for various transport problems for efficiency and accuracy. These three techniques include the standard finite-difference method, the particle-tracking-based Eulerian-Lagrangian methods, and the higher-order finite-volume total-variation-diminishing (TVD) method.

The governing equation used in the MT3DMS simulation model can be given as:

$$\frac{\partial(\theta C^k)}{\partial t} = \frac{\partial}{\partial x_i}(\theta D_{ij}\frac{\partial C^k}{\partial x_j}) - \frac{\partial}{\partial x_i}(\theta v_i C^k) + q_s C_s^k + \sum R_n \quad , \quad (2)$$

where

θ is the porosity of subsurface system;
C^k is the concentration of species k in aqueous phase (ML^{-3});
t is time (T);
x_i and x_j are the distances along the three-dimensional Cartesian coordinate axis directions (L);
D_{ij} is the dispersion coefficient (L^2T^{-1});
v is pore velocity (LT^{-1});
q_s is the flow rate per unit volume of aquifer representing sinks and sources (T^{-1});
C_s^k is the concentration of species k in sink or source flux (ML^{-3}); and
$\sum R_n$ is the chemical reaction term ($ML^{-3}T^{-1}$).

In this study, MT3DMS is used to simulate the fate and transport of PCE in the groundwater system at Tarawa Terrace and vicinity. The output of MT3DMS simulation provides PCE concentration at water-supply wells.

Similar to input files of MODFLOW, input files of MT3DMS include one name file and some other input files used for various packages. These input files are described below and listed in Table H2:

1. *File type:* NAM
   File contents: The name and Fortran unit of each file employed in the simulation
2. *File type:* BTN
   Package: Basic Transport Package
   File contents: Basic model information (number of rows, columns, layers, and stress periods); number of chemical species; transport and solution options; confining layer properties; cell width along rows and columns of each cell; porosity in each cell; boundary condition information; starting concentrations of each chemical species (initial conditions); printing options; output frequency; number of observation points and their locations; mass balance output options; and stress period information
3. *File type:* ADV
   Package: Advection Package
   File contents: Advection solution option and other advective transport simulation variables, if applicable
4. *File type:* DSP
   Package: Dispersion Package
   File contents: Longitudinal dispersivities; ratio of horizontal transverse dispersivity to longitudinal dispersivity; ratio of vertical transverse dispersivity to longitudinal dispersivity; effective molecular diffusion coefficients
5. *File type:* SSM
   Package: Sink and Source Mixing Package
   File contents: Sink and source term options; maximum number of sinks and sources; concentration read-in options; concentration of evapotranspiration flux (if applicable); concentration in specified cells
6. *File type:* RCT
   Package: Chemical Reaction Package
   File contents: Type of reaction; type of kinetic reaction; bulk densities of the aquifer medium for each cell; porosities of immobile domain (if applicable); initial concentration of the sorbed phase (if applicable); sorption parameters; reaction rates
7. *File type:* GCG
   Package: Generalized Conjugate-Gradient Solver Package
   File contents: Maximum numbers of inner and outer iterations; relaxation factor; convergence criterion
8. *File type:* FTL
   Package: Flow-Transport Link Package
   File contents: Groundwater-flow-related information

Table H2. Input files used for the MT3DMS simulation code, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

File type	Package
NAM	Not applicable
BTN	Basic Transport
ADV	Advection
DSP	Dispersion
SSM	Sink/Source Mixing
RCT	Chemical Reaction
GCG	Generalized Conjugate-Gradient Solver
FTL	Flow-Transport Link

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Water-Supply Well Information

The purpose of this study is to examine the effect of updated pumping schedules on PCE concentration and the 5-µg/L arrival time at water-supply wells and the WTP. Among all input data used in this study, only groundwater pumping rates of water-supply wells are considered to be uncertain and are varied based on an optimization procedure developed in this study. Therefore, it is necessary to present detailed information about the water-supply system in the Tarawa Terrace area.

A total of 16 water-supply wells were used to supply groundwater to the WTP. Thirteen of these wells were located in the Tarawa Terrace area (Figure H1). The other three wells—identified as well #6, well #7, and well TT-45—were located outside of this area and, therefore, are not shown in Figure H1. In this study, it is assumed that well #6, well #7, and well TT-45 had zero contaminant concentration, which implies that these wells contributed only water but no contaminant mass to the WTP.

In MODFLOW and MT3DMS simulations, the location of a water-supply well is identified in terms of the coordinates of the cell (x, y, z) in which the well lies. In the simulation codes, the x, y, and z values correspond to the layer number, row number, and column number of the cells, respectively. According to well-construction logs, some wells penetrate more than one layer of aquifer. Therefore, in MODFLOW simulations, some well discharges are split into two "virtual" wells that extract water from different layers. For example, in MODFLOW input used by ATSDR, well TT-52 is split into TT-52A and TT-52B; wells TT-31 and TT-54 also are split this way. For this report chapter, wells TT-53 and TT-67 are split to satisfy their pumping capacities, with respect to dry- and wet-cell conditions observed at the cell. Locations and service periods of these 13 water-supply wells are listed in Table H3.

During the simulation period (1951–1994), pumping rates of water-supply wells varied, and some wells were out of service for some stress periods. Using historical records, pumping rates and pumping capacities of each water-supply well were generated for all stress periods.

Simulation Results of ATSDR Modeling Study

Using input files listed in Table H1, a MODFLOW simulation was performed to generate an FTL file for the follow-up MT3DMS simulation. PCE concentration distribution at water-supply wells was then obtained from an output file of MT3DMS simulation—the concentration observation (OBS) file. These results are shown in Figure H2.

In Figure H2, PCE concentrations at water-supply wells are shown during their service periods as listed in Table H3. Although 16 pumping wells were operating in the Tarawa Terrace area in ATSDR's simulation, only wells TT-26, TT-23, TT-25, TT-67, TT-54A, and TT-54B had PCE concentrations that exceeded the MCL. Among them, well TT-26 had a much longer period of exposure to PCE concentrations of greater than 5 µg/L. The PCE MCL arrival time at well TT-26 is

Table H3. Locations and service periods of water-supply wells, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[See Figure H1 for well location; well name with A, model layer 1; well name with B, model layer 3]

Well	Layer	Row	Column	Start date	End date[1]
TT-23	3	84	175	08/1984	04/1985
TT-25	3	67	194	01/1982	02/1987
TT-26	3	61	184	01/1952	01/1985
TT-27	3	52	135	01/1952	12/1961
TT-28	3	47	96	01/1952	12/1971
TT-29	3	41	61	01/1952	06/1958
TT-30	3	47	97	01/1972	01/1985
TT-31A	1	104	152	01/1973	02/1987
TT-31B	3	104	152	01/1973	02/1987
TT-52A	1	101	136	01/1962	02/1987
TT-52B	3	101	136	01/1962	02/1987
TT-53A	1	81	151	01/1962	01/1984
TT-53B	3	81	151	01/1962	01/1984
TT-54A	1	106	167	01/1962	02/1987
TT-54B	3	106	167	01/1962	02/1987
TT-55	1	53	136	01/1962	12/1971
TT-67A	1	93	158	01/1972	02/1987
TT-67B	3	93	158	01/1972	02/1987

[1]End date indicates last month and year water-supply well was pumped for model simulation. Service was terminated the following month (see Table A6 in Chapter A report, Maslia et al 2007)

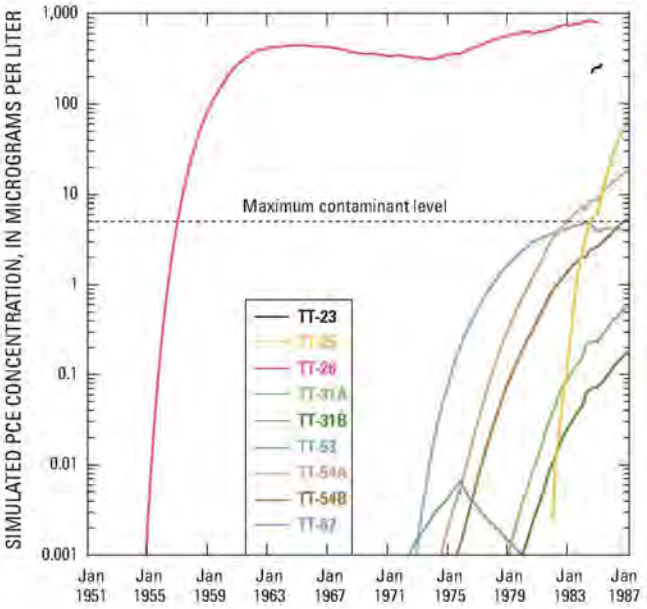

Figure H2. Simulated tetrachloroethylene (PCE) concentration at selected water-supply wells under the Original Schedule, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [TT-31A and TT-54A, model layer 1; TT-31B and TT-54B, model layer 3]

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January 1957, while the second-earliest PCE MCL arrival at a water-supply well occurred during January 1983 at well TT-54A. The PCE concentration at well TT-26 was always much greater than other water-supply wells, indicating that well TT-26 conveyed the majority of PCE mass introduced into the WTP. This is probably because of proximity of well TT-26 to the contaminant source and the well's long pumping history.

Using PCE concentration data at water-supply wells, along with their associated pumping rates, PCE concentration at the WTP is calculated by using the following mixing model:

$$C_i = \frac{\sum_{j=1}^{n} q_{ij} c_{ij}}{Q_{Ti}}, \qquad (3)$$

where

C_i is the PCE concentration at the WTP for stress period i (ML^{-3});

n is the total number of active water-supply wells for stress period i;

q_{ij} is the pumping rate of well j for stress period i (L^3T^{-1});

c_{ij} is the PCE concentration at water-supply well j for stress period i (ML^{-3}); and

Q_{Ti} is the total water demand for stress period i (L^3T^{-1}).

PCE concentration at the WTP is shown in Figure H3. It is identified as the "Original Schedule" throughout the remainder of this chapter report to distinguish it from other updated pumping schedules that were developed and are discussed in later sections. The Orignial Schedule is the pumping schedule used in other Tarawa Terrace chapter reports (Faye 2007b, Faye and Valenzuela 2007).

As shown in Figure H3, PCE concentration at the WTP first exceeded the MCL during November 1957. When this outcome is compared to results presented in Figure H2, only well TT-26 had a PCE concentration exceeding 5 µg/L by November 1957. Therefore, well TT-26 is critical in assessing the PCE MCL arrival time at the WTP.

As shown in Figure H4 for the period of interest (January 1968–December 1985),[4] the maximum PCE concentration at the WTP is 183.04 µg/L and the minimum PCE concentration is 0.72 µg/L. During this period, however, there are only 15 months when the PCE concentration at the WTP is less than 46.69 µg/L. Therefore, for most of the period of interest (201 months out of 216 months), the PCE concentration at the WTP ranges between 46.69 µg/L and 183.04 µg/L, and the average PCE concentration is about 86.39 µg/L, which is much greater than the 5 µg/L MCL for PCE.

The time periods during which the PCE concentration at the WTP is lower than 46.69 µg/L are July 1980–August 1980, January 1983–February 1983, and February 1985–December 1985. These also are time periods during which well TT-26 was out of service. As can be seen in Figure H2, during these time periods, PCE concentrations at other water-supply wells were much less than those at well TT-26. Stopping well TT-26 from supplying water to the WTP,

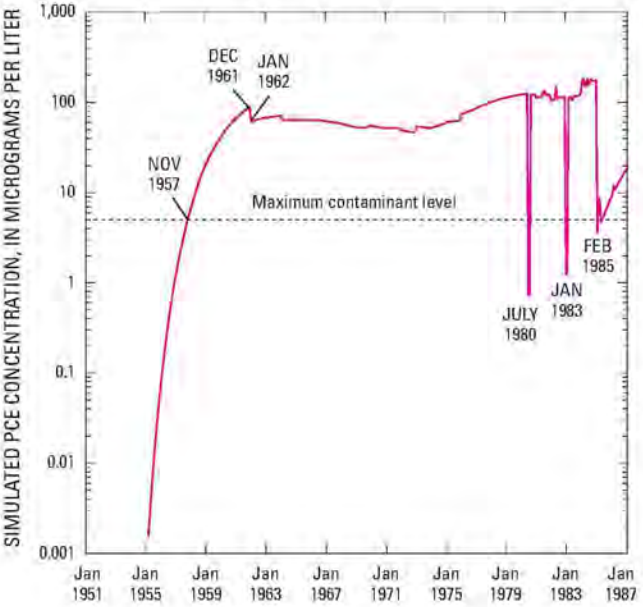

Figure H3. Simulated tetrachloroethylene (PCE) concentration at the water treatment plant under the Original Schedule, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

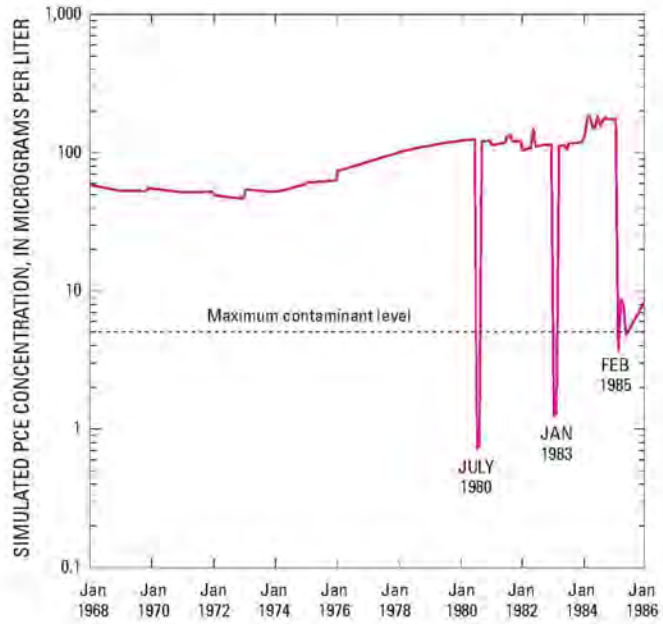

Figure H4. Simulated tetrachloroethylene (PCE) concentration at the water treatment plant under the Original Schedule, period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[4]Throughout this report (Chapter H), the "period of interest" is defined as January 1968–December 1985.

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therefore, caused the sudden PCE concentration declines as shown in Figures H3 and H4.

The reason for the PCE concentration decline at the end of 1961 (Figure H3) is similar to the one described previously. At that time, the pumping rate of well TT-26 decreased from 28,715 cubic feet per day (ft^3/day) to 18,959 ft^3/day, while the total water supplied to the WTP was unchanged (116,199 ft^3/day). Because PCE concentrations at other water-supply wells were negligible (less than 0.001 µg/L) and well TT-26 was the only source of PCE to the WTP at that time, a decrease of PCE concentration was expected at the WTP.

Optimization of Pumping Schedules

As introduced in "A Review of ATSDR's Tarawa Terrace Study," PCE concentration at the WTP was obtained through consecutive application of the following three steps:

1. Simulation of groundwater flow using the MODFLOW model.
2. Simulation of PCE fate and transport using the MT3DMS model.
3. Calculation of PCE concentration at the WTP using the MT3DMS output, pumping schedules, and the WTP mixing model.

Throughout these steps, pumping schedules are used both in MODFLOW simulation and during the calculation of PCE concentration at the WTP when using the mixing model. Moreover, as stated earlier, pumping schedules are the only uncertain variable in this study. Therefore, to evaluate the change in PCE arrival time at water-supply wells and the WTP, pumping schedules that may cause that change must be obtained first according to certain criteria. In this study, a pumping schedule optimization system (PSOpS) was developed using the simulation and optimization (S/O) approach. In PSOpS, simulation models (MODFLOW and MT3DMS) were combined with optimization techniques to generate optimal pumping schedules that would yield the "earliest" or the "latest" PCE MCL arrival times at the WTP.

Formulation of the Optimization Model

To evaluate the change of PCE arrival time at the WTP caused by a variation of pumping schedules, models must be identified to link contaminant arrival time and pumping schedules. Currently, several simulation models (or a combination of simulation models), which may be used in this analysis, are available in the literature.

Among the models, one straightforward choice is the combination of MODFLOW and MODPATH (Pollock 1994). MODPATH is a particle-tracking model that computes three-dimensional pathlines and particle arrival times at pumping wells based on the advective flow output of MODFLOW. A combination of MODFLOW and MODPATH can provide the contaminant arrival time at water-supply wells. However, several limitations in the MODPATH model restrict its use in this study. First, MODPATH only simulates the advective transport of contaminants in the groundwater system. In a MODPATH simulation, the advection of water is considered to be the only driving force of contaminant movement, while other factors that also may affect the movement of contaminants, such as diffusion and dispersion, are not considered. Second, in a MODPATH simulation, the contaminant is treated as a tracer, which implies no chemical reaction or degradation can be accounted for that might be associated with the contaminant. Third, although a MODPATH simulation can provide contaminant arrival time at a pumping well, this time is only recorded for the first contaminant particle that arrives at the well. No concentration information is associated with this simulation output. In this study, however, a more precise simulation of contaminant fate and transport is required, and the time for contaminant concentration to reach a specific level is required for exposure evaluation purposes. Considering all these restrictions, a more sophisticated model with fewer limitations (MT3DMS) was chosen instead of MODPATH. Thus, the combination of MODFLOW and MT3DMS was selected for this study.

As introduced in previous sections, MT3DMS is a subsurface contaminant fate and transport simulation model. Using an FTL file obtained from MODFLOW, MT3DMS can be run on the same groundwater system used for MODFLOW simulation. MT3DMS does not have the restrictions associated with the MODPATH model. The output file of MT3DMS provides contaminant concentrations at specified times and locations. Using this information, certain concentration levels can be evaluated as to their arrival times at water-supply wells. Other benefits of the coupled simulation of MODFLOW and MT3DMS include:

1. The contaminant concentration at the WTP can be calculated and evaluated by using the output of MT3DMS.
2. Original input files obtained from the Tarawa Terrace study can be applied directly, and only a few complementary files need to be added within the PSOpS framework.

Using the coupled simulation of MODFLOW and MT3DMS, the following steps are used to evaluate the change of PCE arrival time caused by variation in pumping schedules:

1. Optimize pumping schedules for the "earliest" and the "latest" PCE arrival times using a combination of simulation models (MODFLOW and MT3DMS) and optimization techniques (S/O).
2. Simulate the groundwater flow and the contaminant fate and transport at the site using optimal pumping schedules obtained in step 1.
3. Calculate PCE concentration at the WTP using Equation 3 and optimal pumping schedules.
4. Evaluate the "earliest" and the "latest" PCE arrival times at the WTP.

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In step 1, the optimization of pumping schedules for the "earliest" or the "latest" PCE arrival time is equivalent to optimizing the pumping schedule for the "maximum" or "minimum" PCE concentrations at the WTP because the observation of a higher concentration at the WTP implies an earlier contaminant arrival time, and vice versa. One approach to optimizing pumping at the WTP is to optimize pumping schedules for the maximum or minimum PCE concentrations for each stress period individually. After the maximum or minimum concentrations are obtained for each stress period, a relationship can be obtained between maximum or minimum concentration versus stress period (time). This approach, however, is associated with a substantial computational burden. The large scale of the simulation model—200 rows, 270 columns, 7 layers, and 528 stress periods—clearly indicates that this approach will require years of calculation time on a high-end personal computer (PC) to complete the simulations and, therefore, is unacceptable.

Another possible approach is to combine stress periods with the same characteristics (pumping rates, pumping capacities, pumping demands, recharge, and so forth) together to reduce the size of the overall model. This approach, however, would lose some detail during optimization, which implies that it would not be as precise as the original model and, thus, could affect optimization results.

Considering the computational power and memory of desktop workstations available for this study (64-bit dual-processor PCs), along with the need to obtain an acceptable result in a timely manner without losing any detail and accuracy, the optimization problem needs to be formulated in a more computationally cost-efficient manner. To create such a model, the following observations were made about the site data used in these simulations:

1. The contaminant was released continuously from the same source point (ABC One-Hour Cleaners, Figure H1).

2. Well TT-26 was the only major contaminant contributor to the WTP.

3. Well TT-26 was in operation during most of the period of interest (January 1968–December 1985).

With these observations in mind, the optimization problem is reformulated as follows: optimize each successive stress period i for a maximum or minimum PCE concentration at the WTP for stress period i while keeping all of the previously optimized pumping rates constant. In other words, in the reformulation, the pumping schedule of stress period 1 is first optimized for optimal (maximum or minimum) PCE concentration at the WTP for stress period 1. Then the pumping schedule of stress period 2 is optimized for optimal PCE concentration for stress period 2 keeping the optimization results from stress period 1 constant, and so on. In this manner, at the end of the simulation and optimization process, an optimal pumping schedule is obtained for all stress periods under which the PCE concentration at the WTP can be maximized or minimized.

The reformulated optimization problem for maximum PCE concentration at the WTP can be expressed mathematically as

$$\begin{aligned} &\underset{q_i \in R^n}{Max}\ C_i = f(q_1, \ldots, q_i) \\ &s.t. \\ &0 \le q_i \le w_i \\ &\sum_{j=1}^{n} q_{ij} = Q_{Ti} \\ &q_k = q_k^* \ (k = 1, \ldots, i-1), \end{aligned} \tag{4}$$

where

C_i is the PCE concentration at the WTP for stress period i (ML^{-3});

n is the number of active water-supply wells for stress period i;

q_i is an n-dimensional vector of pumping rates for stress period i (L^3T^{-1});

w_i is an n-dimensional vector of the upper bound of q_i for stress period i (pumping capacities) (L^3T^{-1});

q_{ij} is the pumping rate of well j for stress period i (L^3T^{-1});

Q_{Ti} is the total water demand for stress period i (L^3T^{-1}); and

q_k^* is the optimal pumping schedule for stress period k (L^3T^{-1}).

In the optimization problem given in Equation 4, $q_1, \ldots, q_{i-1}$ are known, and C_i is only a function of q_i. Thus, to obtain the maximum PCE concentration C_i, only the pumping schedule for stress period i needs to be optimized based on optimal pumping schedules for the previous stress periods. By formulating the problem in this way, the dimensions of the problem are reduced significantly, and the computational demand becomes manageable.

The optimization model for the minimum PCE concentration at the WTP is similar:

$$\begin{aligned} &\underset{q_i \in R^n}{Min}\ C_i = f(q_1, \ldots, q_i) \\ &s.t. \\ &0 \le q_i \le w_i \\ &\sum_{j=1}^{n} q_{ij} = Q_{Ti} \\ &q_k = q_k^* \ (k = 1, \ldots, i-1). \end{aligned} \tag{5}$$

Explanations used for this equation are the same as given for Equation 4.

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Equation 5 can be easily solved by using the same method as used in the solution of the optimization problem given in Equation 4 because it can be rewritten as

$$\begin{aligned} &\underset{q_i \in R^n}{Max}\ C'_i = -C_i = -f(q_1,...,q_i) \\ &s.t. \\ &0 \le q_i \le w_i \\ &\sum_{j=1}^{n} q_{ij} = Q_{Ti} \\ &q_k = q_k^* \ (k = 1,...,i-1). \end{aligned} \tag{6}$$

Therefore, in this report only the "maximization" problem given in Equation 4 is used as an example when describing the optimization method.

Selection of the Optimization Method

For optimization problems given in Equations 4 and 5, PCE concentration at the WTP is calculated by using the following governing equations:

$$\frac{\partial}{\partial x}(K_{xx}\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_{yy}\frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_{zz}\frac{\partial h}{\partial z}) + W = S_s\frac{\partial h}{\partial t}\ ; \tag{7}$$

$$\frac{\partial(\theta C^k)}{\partial t} = \frac{\partial}{\partial x_i}(\theta D_{ij}\frac{\partial C^k}{\partial x_j}) - \frac{\partial}{\partial x_i}(\theta v_i C^k) + q_s C_s^k + \sum R_n\ ; \tag{8}$$

and

$$C_i = \frac{\sum_{j=1}^{n} q_{ij} c_{ij}}{Q_{Ti}}, \tag{9}$$

For the definition of the terms used in these equations, refer to the text following Equations 1, 2, and 3. Among Equations 7–9, Equation 7 is used in the MODFLOW simulation for obtaining piezometric head distribution and groundwater-flow velocity between adjacent nodes; Equation 8 is used in the MT3DMS simulation to obtain PCE concentration distribution; and Equation 9 is used to calculate PCE concentration at the WTP.

A study of Equations 7–9 shows that optimization problems given in Equations 4 and 5 are multidimensional, nonlinear optimization problems with linear constraints, which are much harder to solve and more computationally intensive than linear optimization problems. Moreover, objective functions are nonconcave or nonconvex, which imposes more difficulty in finding a global optimal solution. Significant literature exists on optimization methods for the solution of nonlinear optimization problems. Some of these methods are introduced briefly in the following sections.

Downhill Simplex Method

The downhill simplex method is an optimization method for multidimensional nonlinear problems that does not require evaluating the derivative of the objective function but uses only the objective function values (Press et al. 1989). For an N-dimensional minimization problem, the downhill simplex method starts with $N+1$ initial points (feasible solutions), which define an initial simplex, and then moves step by step toward the optimal solution. Each step is called a "reflection." For a minimization problem, in each reflection the point of the simplex that has the largest value is found and moved through the opposite face of the simplex to a lower point, until the solution meets the termination criterion. In the downhill simplex method, although derivatives are not required, this approach is still not sufficiently efficient considering the number of objective function evaluations it requires.

Steepest Descent Method

The steepest descent method is a nonlinear optimization method that uses the derivative information of the objective function (Press et al. 1989). To solve a minimization problem by using this method, starting from an initial point, the downhill gradient is calculated at that point, and a minimization point is found along the gradient direction. The downhill gradient is calculated from that point, and another point is found along the gradient direction. By following the gradient directions on the objective function, an optimal solution can be found that meets the termination criterion.

The problem with the steepest gradient method is that iterated solutions may move in a direction of reversed gradient paths because the gradient at a new point can be perpendicular to the previous gradient. This increases the computational burden and may lead to an inefficient solution. Another problem for this method is that often the solution will be trapped in a local optimal solution.

Conjugate Gradient Method

Similar to the steepest descent method, the conjugate gradient method uses the derivative information to find the optimal solution for a nonlinear optimization problem (Press et al. 1989). This method differs from the steepest descent method in the following sense. The conjugate gradient method is improved in such a way that, for each movement toward the solution, the direction of movement is constructed to be conjugate to the old gradient. By doing this, an optimal solution can be achieved more efficiently.

Even though the conjugate gradient method is more efficient than the steepest descent method, calculation of derivatives of the objective function at each iteration step is still a heavy computational burden. Also, similar to the steepest descent method, the possibility for the solution of the conjugate gradient method to be a local optimum instead of a global optimum is very high.

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Genetic Algorithms

A genetic algorithm (GA) refers to a method of optimization that attempts to find the most optimal solution by mimicking—in a computational sense—the mechanics of natural selection and genetics (Chinneck 2006). Its application requires the solution to be expressed as a string. Using a population of strings, an objective function value can be calculated for each string for its "fitness" evaluation.

During a GA process, first an initial population is generated, and the fitness of each string is evaluated. Then, a mating pool is generated from the current population using several GA operations. For example, crossover operation (two parent strings obtained from the mating pool exchange part of their strings to form two new child strings) and mutation operation (values at some points of some strings are changed randomly) are applied to generate the new population. After the generation of a new population, the fitness of each new string is evaluated again. This evolutionary process leads to the most fit strings to remain and accumulate in the population. If the termination criterion is met, the process is stopped. Otherwise, the process will start again based on the new generation of a population.

A good aspect of GAs is that the process can yield better and better solutions without reliance on gradients. Another advantage of GAs is that they search the optimal solution globally; thus, the solution is sometimes better than those obtained from other methods mentioned previously. However, considering the computation power required for the evaluation of fitness of each string, if the computation time of the simulation tools required to solve the problem is large and if the mating pool also is large, then GAs can be more computationally demanding than the other methods discussed previously.

Based on the review given previously, it can be concluded that for a complex nonlinear optimization problem, any of the methods discussed above can be quite computationally demanding. To reduce computational demand, a new optimization method—identified as "rank-and-assign method," which will be introduced in detail in the next section—was developed uniquely for the problem discussed in this study. The few cases that cannot be solved by the rank-and-assign method are optimized by the improved gradient method.

Introduction to the Pumping Schedule Optimization System (PSOpS)

Based on the two optimization techniques (rank-and-assign and improved gradient methods) and simulation models (MODFLOW and MT3DMS), a procedure identified as PSOpS has been developed to optimize the pumping schedule for the "earliest" or the "latest" PCE arrival time at the WTP using the S/O approach. In PSOpS, MODFLOW and MT3DMS are used to simulate the groundwater flow and contaminant fate and transport conditions for derivative calculations that are necessary in the solution of the optimization problem; optimization techniques are used within the same procedure to optimize pumping schedules.

Methodology of the Pumping Schedule Optimization System

The pumping schedule adjustment necessary to achieve the maximum PCE concentration level at the WTP, which is analogous to the earliest arrival time solution, is solved by the procedure shown in Figure H5. The variables and abbreviations used in Figure H5 are defined as

Q_{Ti} total pumping demand for stress period i;

$C_i^{(k)}$ PCE concentration at the WTP for stress period i after the k^{th} iteration;

q_{ij} pumping rate of water-supply well j for stress period i;

$(\frac{\partial C_i}{\partial q_{ij}})^{(k)}$ change of PCE concentration at the WTP for stress period i caused by the unit change of q_{ij} after the k^{th} iteration;

$q_i^{(k)}$ pumping schedule vector for stress period i after the k^{th} iteration which consists of q_{ij} of all water-supply wells for stress period i;

$\nabla C_i(q_i^{(k)})$ concentration gradient vector for $q_i^{(k)}$ which consists of $(\frac{\partial C_i}{\partial q_{ij}})^{(k)}$ of all active water-supply wells for stress period i;

$\left\|\nabla C_i(q_i^{(k)})\right\|$ norm of $\nabla C_i(q_i^{(k)})$, which is the maximum absolute value of $(\frac{\partial C_i}{\partial q_{ij}})^{(k)}$;

W_i pumping capacity vector for stress period i;

$SQ_i^{(k)}$ sequence of $(\frac{\partial C_i}{\partial q_{ij}})^{(k)}$; and

ε a predefined termination criterion. If $\left\|\nabla C_i(q_i^{(k)})\right\|$ is less than ε, the pumping schedule for stress period i is considered to be optimal.

The assumptions made in PSOpS are:

1. When $\left\|\nabla C_i(q_i^{(k)})\right\|$ is less than ε, the pumping schedule for the current stress period i is optimal, and no further update is required.
2. The total pumping rate of all water-supply wells for stress period i is equal to the total pumping demand for that stress period.
3. The pumping rate in a water-supply well is always less than or equal to its pumping capacity.
4. Water-supply wells outside of the simulated region (in this case, well #6, well #7, and well TT-45) are considered as one well with zero $\frac{\partial C_i}{\partial u_{ij}}$ value. In other words, pumping rates in these wells can be adjusted, but they do not provide contaminant mass to the WTP.

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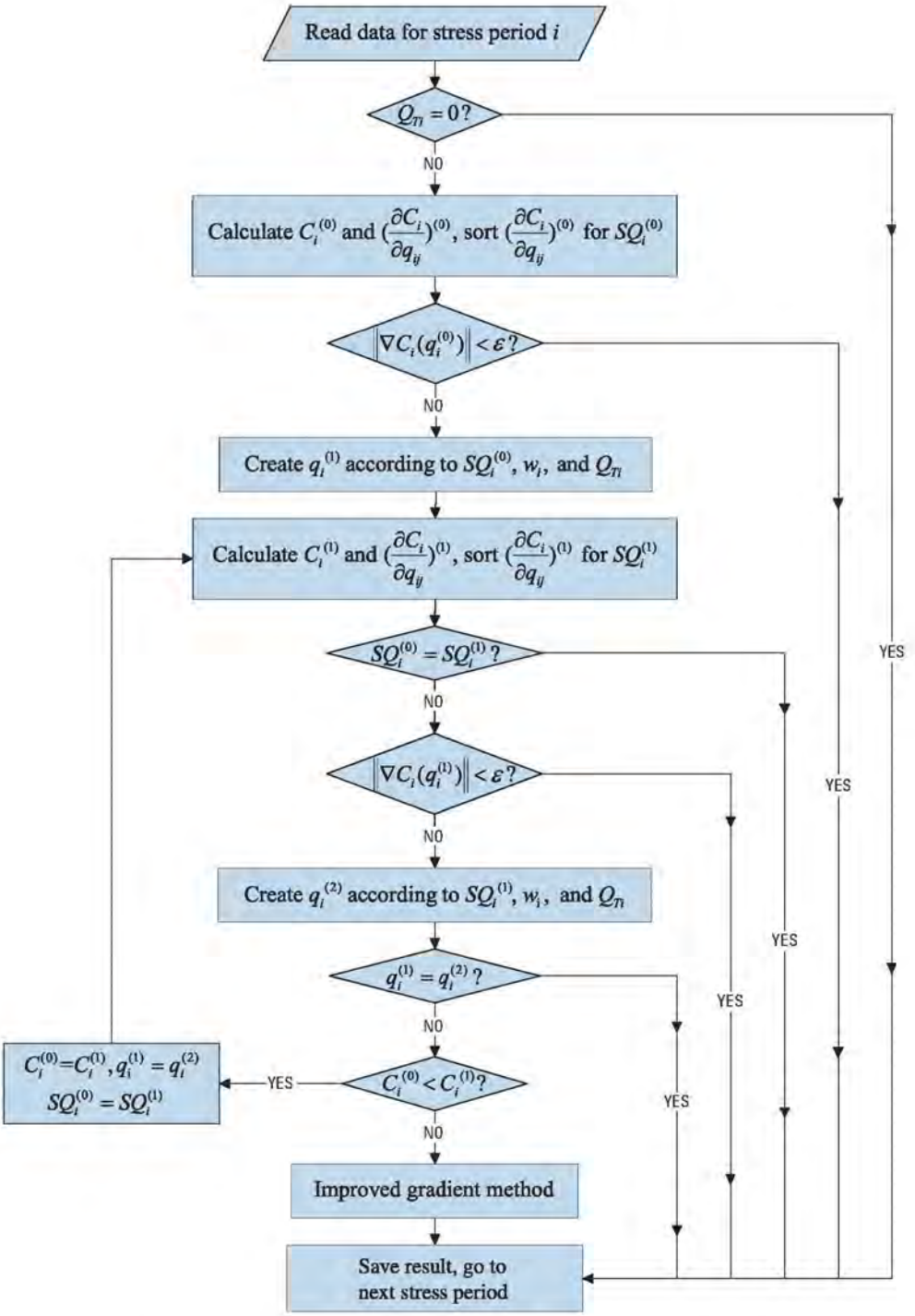

Figure H5. Flowchart of Pumping Schedule Optimization System (PSOpS).

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Following the procedure shown in Figure H5, PSOpS optimizes pumping schedules for maximum PCE concentration levels at the WTP for stress period i as outlined in the step-by-step process given below:

1. Read input data for stress period i, such as the total pumping demand (Q_{Ti}), the pumping capacities (w_i), and the initial pumping schedule ($q_i^{(0)}$).
2. If Q_{Ti} is equal to zero, no pumping schedule update is required, go to step 13; otherwise go to step 3.
3. Run MODFLOW and MT3DMS for stress period i to obtain $C_i^{(0)}$, then run MODFLOW and MT3DMS for another n times, where n is the number of active wells for stress period i, with a unit change in pumping rate to calculate the gradients $(\frac{\partial C_i}{\partial q_{ij}})^{(0)}$ for each active well. After this computation, sort the $(\frac{\partial C_i}{\partial q_{ij}})^{(0)}$ values for $SQ_i^{(0)}$.
4. If $\left\|\nabla C_i(q_i^{(0)})\right\|$ is less than ε, no update for stress period i is required, then go to step 13; otherwise go to step 5.
5. Update the pumping schedule for stress period i to $q_i^{(1)}$ using rank-and-assign method according to $SQ_i^{(0)}$, w_i, and Q_{Ti} (refer to "Rank-and-Assign Method" section for detailed information on these variables).
6. Similar to step 3, update $C_i^{(1)}$ using $q_i^{(1)}$, calculate $(\frac{\partial C_i}{\partial q_{ij}})^{(1)}$ values and sort these values to obtain $SQ_i^{(1)}$.
7. Compare $SQ_i^{(0)}$ and $SQ_i^{(1)}$. If they are the same, $q_i^{(1)}$ is the optimal pumping schedule for stress period i, then go to step 13; otherwise go to step 8.
8. If $\left\|\nabla C_i(q_i^{(1)})\right\|$ is less than ε, $q_i^{(1)}$ is the optimum, then go to step 13; otherwise go to step 9.
9. Similar to step 5, update $q_i^{(1)}$ to $q_i^{(2)}$ using the rank-and-assign method according to $SQ_i^{(1)}$, w_i, and Q_{Ti}.
10. Compare $q_i^{(1)}$ and $q_i^{(2)}$. If they are the same, then go to step 13; otherwise go to step 11.
11. Compare $C_i^{(0)}$ and $C_i^{(1)}$. If $C_i^{(0)}$ is less than $C_i^{(1)}$, use $C_i^{(1)}$, $SQ_i^{(1)}$, and $q_i^{(2)}$ to replace $C_i^{(0)}$, $SQ_i^{(0)}$, and $q_i^{(1)}$, then go to step 6 and update again; otherwise go to step 12.
12. Optimize $q_i^{(2)}$ using the improved conjugate gradient method (refer to "Improved Gradient Method" section for detailed information).
13. Run MODFLOW and MT3DMS simulations using the optimal pumping schedule for stress period i again, and save piezometric head and concentration distribution information at the end of stress period i for optimization of pumping schedule of the next stress period.

Optimization of the pumping schedule to obtain the minimum PCE concentration at the WTP is equivalent to the optimization of the pumping schedule for the maximum PCE concentration at the WTP with the objective function multiplied by minus one.

Rank-and-Assign Method

The rank-and-assign method was specifically developed for PSOpS. This method updates the pumping schedule for maximum or minimum contaminant concentration levels at the WTP based on the derivative—pumping capacity—and the total pumping demand information available for the system. The name of this method reflects the steps it follows to update the pumping schedule—it first "ranks" the gradients and then "assigns" the pumping rates to each water-supply well according to this ranking.

Steps 3–11 shown in Figure H5 describe the rank-and-assign optimization technique. In step 5, by assuming an $SQ_i^{(0)}$ with the following ranking,

$$(\frac{\partial C_i}{\partial q_{i1}})^{(0)} \geq \ldots \geq (\frac{\partial C_i}{\partial q_{ik}})^{(0)} \geq \ldots \geq (\frac{\partial C_i}{\partial q_{in}})^{(0)}, \qquad (10)$$

the procedure below is followed to assign the $q_i^{(1)}$ to yield the maximum PCE concentration at the WTP:

1. Assign the pumping capacity of the first well in $SQ_i^{(0)}$ as its pumping rate. If the total pumping demand is less than the pumping capacity of that well, assign the total pumping demand as its pumping rate, and go to step 4.
2. If the remaining pumping demand is greater than the pumping capacity of the next well in $SQ_i^{(0)}$, assign the pumping capacity of that well as its pumping rate, and repeat step 2; otherwise go to step 3.
3. Assign the remaining pumping demand as the pumping rate of the next well in $SQ_i^{(0)}$.
4. Assign zero pumping rates to all other wells that are left in the $SQ_i^{(0)}$ list.

In the rank-and-assign method, the optimized pumping schedule satisfying the condition "$SQ_i^{(0)} = SQ_i^{(1)}$" is at least a local optimum because it satisfies the Kuhn-Tucker condition (Kuhn and Tucker 1951). The Kuhn-Tucker condition is described below.

Consider the problem:

$$\begin{aligned} &\underset{x \in R^n}{Min}\, f(x) \\ &s.t. \\ &g_i(x) \leq 0 \\ &h_j(x) = 0, \end{aligned} \qquad (11)$$

where

$g_i(x)$ $(i = 1,\ldots,m)$	are the nonequality constraints;
$h_j(x)$ $(j = 1,\ldots,l)$	are the equality constraints;
m	is the number of nonequality constraints; and
l	is the number of equality constraints.

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Suppose that the objective function $f: R^n \rightarrow R$ and the constraint functions $g_i: R^n \rightarrow R$ and $h_j: R^n \rightarrow R$ are continuously differentiable at a point $x^* \in S$. If x^* is a local minimum, then constants $\lambda_i \geq 0$ $(i = 1, \ldots, m)$ and μ_j $(j = 1, \ldots, l)$ exist such that

$$\nabla f(x^*) + \sum_{i=1}^{m} \lambda_i \nabla g_i(x^*) + \sum_{j=1}^{l} \mu_j \nabla h_j(x^*) = 0$$
$$\lambda_i g_i(x^*) = 0 \text{ for all } i = 1, \ldots, m. \quad (12)$$

To prove that a solution from the rank-and-assign method satisfies the Kuhn-Tucker condition, the problem for one stress period is reformulated as:

$$\begin{aligned} &\underset{q \in R^n}{Min}\, C = -f(q) \\ &s.t. \\ &-q_i \leq 0 \ (i = 1, \ldots, n) \\ &q_i - w_i \leq 0 \ (i = 1, \ldots, n) \\ &\sum_{i=1}^{n} q_i - Q_T = 0, \end{aligned} \quad (13)$$

where

C	is the PCE concentration at the WTP;
n	is the number of active water-supply wells;
q	is an n-dimensional vector of pumping rates;
q_i	is the pumping rate of well i;
w_i	is the pumping capacity for well i; and
Q_T	is the total water demand.

The Kuhn-Tucker conditions for the problem given in Equation 13 are:

$$\begin{aligned} &-\frac{\partial f}{\partial q_i} - \lambda_i + \omega_i + \mu = 0 \ (i = 1, \ldots, n) \\ &\lambda_i q_i = 0 \ (i = 1, \ldots n) \\ &\omega_i (q_i - w_i) = 0 \ (i = 1, \ldots, n) \\ &\lambda_i \geq 0 \ (i = 1, \ldots n) \\ &\omega_i \geq 0 \ (i = 1, \ldots, n). \end{aligned} \quad (14)$$

Suppose the optimal solution from the rank-and-assign method is

$$q_i \begin{cases} = w_i \ (i = 1, \ldots, k-1) \\ \leq w_i \ (i = k) \\ = 0 \ (i = k+1, \ldots, n), \end{cases} \quad (15)$$

while the following condition is satisfied

$$\frac{\partial f}{\partial q_1} \geq \ldots \geq \frac{\partial f}{\partial q_k} \geq \ldots \geq \frac{\partial f}{\partial q_n}. \quad (16)$$

For $i \leq k$, since $q_i > 0$, to satisfy $\lambda_i \theta_i = 0$, there is

$$\lambda_i = 0 \ (i = 1, \ldots, k). \quad (17)$$

According to equation: $-\frac{\partial f}{\partial q_i} - \lambda_i + \omega_i + \mu = 0$, there is

$$\omega_i = \frac{\partial f}{\partial q_i} - \mu \ (i = 1, \ldots, k). \quad (18)$$

Let $\mu = \frac{\partial f}{\partial q_k}$, there is

$$\omega_k = 0. \quad (19)$$

Since $\frac{\partial f}{\partial q_i} \geq \frac{\partial f}{\partial q_k}$ for $i < k$, there is

$$\omega_i = \frac{\partial f}{\partial q_i} - \frac{\partial f}{\partial q_k} \geq 0 \ (i = 1, \ldots, k-1). \quad (20)$$

For $i > k$, since $q = 0$, to satisfy $\omega_i (q_i - w_i) = 0$, there must be

$$\omega_i = 0 \ (i = k+1, \ldots, n). \quad (21)$$

According to equation $-\frac{\partial C}{\partial q_i} - \lambda_i + \omega_i + \mu = 0$, there is

$$\lambda_i = \mu - \frac{\partial C}{\partial q_i} = \frac{\partial C}{\partial q_k} - \frac{\partial C}{\partial q_i} (i = k+1, \ldots, n). \quad (22)$$

Since $\frac{\partial C}{\partial q_k} \geq \frac{\partial C}{\partial q_i}$ for $i > k$, it is known that

$$\lambda_i = \frac{\partial C}{\partial q_k} - \frac{\partial C}{\partial q_i} \geq 0 \ (i = k+1, \ldots, n). \quad (23)$$

Therefore, the Kuhn-Tucker conditions are satisfied.

The Kuhn-Tucker conditions are necessary for a solution to be optimal. For an optimization problem with a convex (minimization problem) or a concave (maximization problem) objective function, the Kuhn-Tucker conditions also are sufficient for the solution to be a global optimum. However, because the objective function in this problem is nonconvex (or nonconcave), the solution obtained from the rank-and-assign method is not guaranteed to be the global optimum, which is same as the situation associated with many other nonlinear optimization methods. In this sense, the rank-and-assign method trades computational efficiency with global optimality.

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Improved Gradient Method

As shown in Figure H5, in PSOpS application, the rank-and-assign method is applied first to each stress period. If the optimal solution cannot be obtained from the rank-and-assign optimization process, an improved gradient method is used for the optimal solution. The improved gradient method is similar to the steepest descent method introduced previously. In PSOpS, the steepest descent method is further improved by two aspects: (1) reducing the dimension of the optimization problem and (2) projecting the gradient to satisfy the equality constraint.

In the improved gradient method, the ranking of active pumping wells in $SQ_i^{(0)}$ and $SQ_i^{(1)}$ obtained from the rank-and-assign method are compared, and wells with same rankings in both sequences are exempted from the optimization process. Thus, the dimension of the optimization problem can be reduced significantly along with the computational cost. For example, assume that there are five pumping wells with $SQ_i^{(0)}$ and $SQ_i^{(1)}$ as

$$SQ_i^{(0)}:(\frac{\partial C_i}{\partial q_{i1}})^{(0)} \geq (\frac{\partial C_i}{\partial q_{i2}})^{(0)} \geq (\frac{\partial C_i}{\partial q_{i3}})^{(0)} \geq (\frac{\partial C_i}{\partial q_{i4}})^{(0)} \geq (\frac{\partial C_i}{\partial q_{i5}})^{(0)} \quad (24)$$

and

$$SQ_i^{(1)}:(\frac{\partial C_i}{\partial q_{i1}})^{(1)} \geq (\frac{\partial C_i}{\partial q_{i4}})^{(1)} \geq (\frac{\partial C_i}{\partial q_{i2}})^{(1)} \geq (\frac{\partial C_i}{\partial q_{i3}})^{(1)} \geq (\frac{\partial C_i}{\partial q_{i5}})^{(1)}. \quad (25)$$

Between the two sequences given above, only wells 2, 3, and 4 have different rankings. Therefore, in the improved gradient method, only wells 2, 3, and 4 are considered as variables for optimization, and the dimension of the problem is reduced from 5 to 3, accordingly.

This variable-elimination step is logical. Using the maximization process as an example, after $SQ_i^{(0)}$ is obtained, the pumping schedule would be updated according to the procedure described in the rank-and-assign method. Then, according to Equation 25, $SQ_i^{(1)}$ indicates that well 1 still has the most potential to increase the contaminant concentration by increasing its pumping rate. However, the pumping rate in well 1 has reached its pumping capacity and cannot be increased any further. Therefore, it is exempted from optimization. The case for well 5 is similar—to increase the contaminant concentration its pumping rate is supposed to be decreased, while its pumping rate is already zero. (If the pumping rate of well 5 is not zero, then according to the description of the rank-and-assign method, we know that the pumping rates of wells 2, 3, and 4 are at their pumping capacities, respectively, and the pumping schedule cannot be updated any more.)

After eliminating water-supply wells with same rankings in both sequences, the gradient of the remaining wells is then projected to the feasible solution space by subtracting the same amount from all derivatives to make the summation of the resulting derivatives to be zero. The equality constraint of the optimization problem can be eliminated by applying this gradient projection because the process guarantees the summation of the resulting pumping rates to be constant.

The improved gradient method works through the steps shown in Figure H6. Some variables are the same as defined for Figure H5; the others are defined below.

$d^{(k)}$ The search direction of the optimal solution for the k^{th} iteration. Its dimension is the same as the dimension of the pumping rate vector.

λ_k The step size of the solution increment for the k^{th} iteration.

$\nabla^* C_i(q_i^{(k)})$ The projection of $\nabla C_i(q_i^{(k)})$ in the feasible solution space.

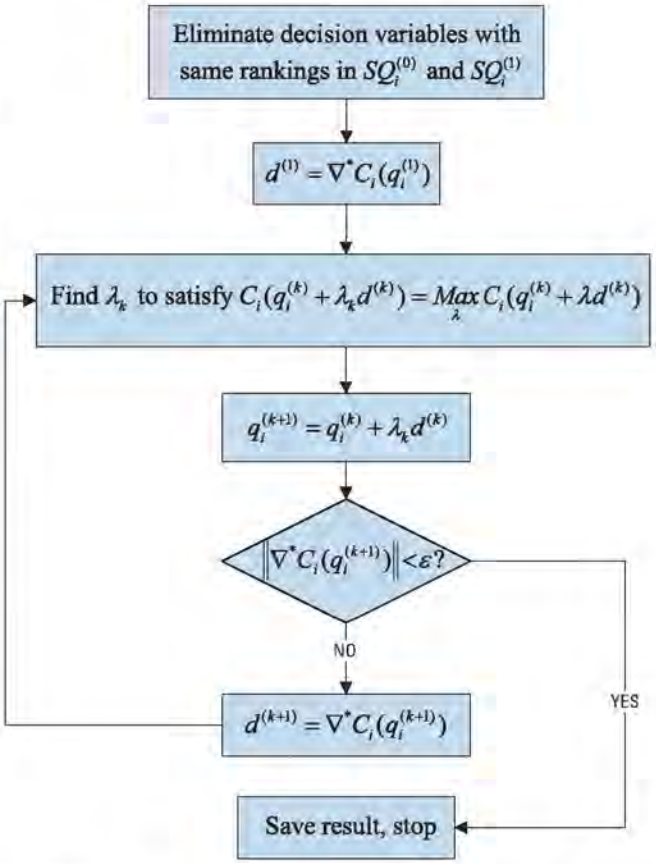

Figure H6. Flowchart of improved gradient method.

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Computational steps of the improved gradient method in obtaining the maximum PCE concentration levels at the WTP for stress period *i* are:

1. Eliminate the decision variables with the same rankings in $SQ_i^{(0)}$ and $SQ_i^{(1)}$.
2. Set $d^{(1)}$ to be equal to $\nabla^* C_i(q_i^{(1)})$.
3. Find λ_k to maximize $C_i(q_i^{(k)} + \lambda d^{(k)})$ using the one-dimensional line search method.
4. Update $q_i^{(k)}$ to $q_i^{(k+1)}$.
5. If $\left\|\nabla^* C_i(q_i^{(k+1)})\right\|$ is less than ε, and $q_i^{(k+1)}$ is the optimum, then go to step 7; otherwise go to the next step.
6. Update $d^{(k)}$ to $d^{(k+1)}$, go to step 3 for another iteration.
7. Save the optimal solution.

Improvement of Computational Efficiency

PSOpS was developed to improve the computational efficiency of the pumping schedule optimization problem. Computational efficiency has been achieved through:

1. *The reduction of the dimensions of the problem:* By reformulating the problem, only the pumping schedule of the current stress period needs to be updated to obtain the optimal contaminant concentration at the WTP. A problem that cannot be solved by the rank-and-assign technique can be solved by the improved gradient method which further reduces the dimension of the problem.
2. *The reduction of the number of iterations for the optimization:* Simulation results for this study indicate that most rank-and-assign optimizations converge within two iterations.
3. *Elimination of repeated simulations:* At the end of optimization for each stress period, the piezometric head and concentration distributions are updated and saved as the starting point of the optimization for the next stress period.

By applying PSOpS, an optimal pumping schedule for the problem can be obtained within 4–5 days on a desktop workstation with a 2 gigahertz (GHz) central processing unit (CPU) and 1 gigabyte (GB) of memory. A summary of the optimization status for maximum PCE concentration levels at the WTP is listed in Table H4. For 106 of 528 stress periods, no water was supplied to the WTP (January 1951–December 1951 and March 1987–December 1994). Among the remaining 422 stress periods, pumping schedules in 417 stress periods were updated by the rank-and-assign method, which accounts for 98.8% of the solution. This percentage indicates that the rank-and-assign method works efficiently for this problem.

Table H4. Summary of the optimization status for maximum tetrachloroethylene concentration at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Optimization status	Number of cases	Percentage
$\left\|\nabla C_i(q_i^{(0)})\right\| < \varepsilon$, no update	3	0.6
$SQ_i^{(0)} = SQ_i^{(1)}$	369	69.9
$\left\|\nabla C_i(q_i^{(1)})\right\| < \varepsilon$, no second update	7	1.3
$q_i^{(1)} = q_i^{(2)}$	41	7.8
Optimization using improved gradient method	2	0.4
No pumping and no update	106	20.0
Total	**528**	**100**

Input Data for the Pumping Schedule Optimization System

As previously discussed, PSOpS was developed based on the S/O approach. In PSOpS, the groundwater simulation model MODFLOW and the contaminant fate and transport model MT3DMS are used as the simulators. Therefore, original input files of MODFLOW and MT3DMS obtained from ATSDR's Tarawa Terrace study can be used as input for PSOpS directly. Other than these files, only three files are required to provide simulation type, pumping capacities, and total pumping demand information as given below.

1. *File type:* INFO
   File contents: Optimization type ("1" for maximization of the contaminant concentration and "2" for minimization of the contaminant concentration)
2. *File type:* PCP
   File contents: Pumping capacities of each water-supply well for each stress period
3. *File type:* TPD
   File contents: Total pumping demand for each stress period

Direct application of input files for MODFLOW and MT3DMS as input for PSOpS makes the generation of input files very efficient and convenient.

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Simulation Results and Discussion

In this study, PSOpS was run three times: the first run was to obtain the "early" PCE arrival time at the Tarawa Terrace WTP; the second run was to obtain the "late" PCE arrival time at the WTP; and the third run was to obtain the "late" PCE arrival time with a restriction that the assigned pumping rate in well TT-26 was not to be less than 25% of its pumping capacity. In all PSOpS applications, pumping rates in water-supply wells are considered to be the only unknown variables. In this report, optimal pumping schedules obtained from the three PSOpS runs are identified as "Maximum Schedule," "Minimum Schedule I," and "Minimum Schedule II." The original pumping schedule obtained from ATSDR's Tarawa Terrace analysis is identified as the "Original Schedule." In the following sections, results for these three optimized pumping schedules are discussed.

Optimization and Simulation Results for the Maximum Schedule

In the Maximum Schedule obtained from PSOpS, pumping rates are updated for 419 stress periods. Among them, pumping rates from 417 stress periods are updated by the rank-and-assign method, which reduces the computational time significantly.

According to ATSDR's Tarawa Terrace analysis, as previously discussed, water-supply wells started to pump during January 1952; ABC One-Hour Cleaners started operations during January 1953. The output of PSOpS indicates that the first 3 months of pumping during 1952 had a negligible effect on PCE concentration at the WTP after ABC One-Hour Cleaners started to release PCE into the groundwater system. Except for those three stress periods, supply well TT-26 always pumped at its maximum pumping rate (pumping capacity) in the Maximum Schedule solution. The higher (and maximum) pumping rate in well TT-26 generates a higher hydraulic gradient between the contaminant source and well TT-26. This results in faster movement of contaminants from the source to well TT-26 and, thus, an early contaminant arrival time at the pumping well and at the WTP. Pumping rates of well TT-26 under the Maximum Schedule are compared to its pumping capacities in Figure H7.

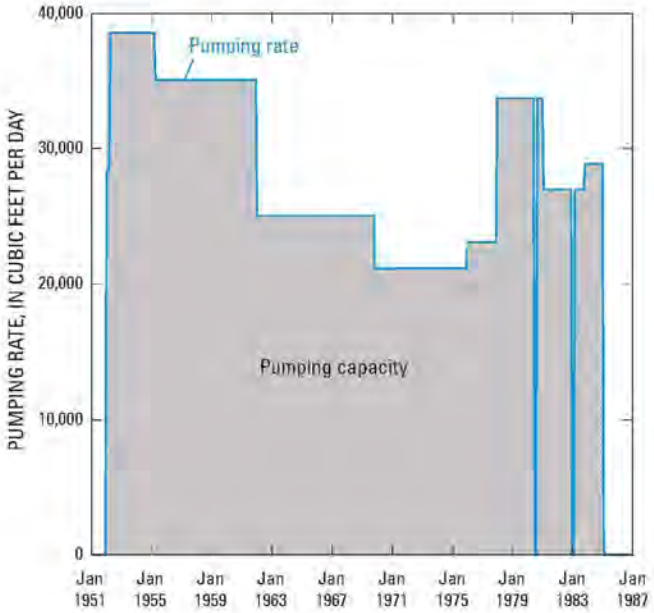

Figure H7. Pumping rate and capacity of water-supply well TT-26 under the Maximum Schedule, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

PCE Distribution in the Groundwater System

While keeping the other input data unchanged, and using the Maximum Schedule as input for the WEL package, MODFLOW and MT3DMS were used to simulate groundwater flow and PCE transport under the Maximum Schedule.

As expected, a variation in the pumping schedule changes the groundwater flow in the subsurface system. Thus, the PCE fate and transport in the aquifer domain also is changed. To illustrate this change, a comparison of the PCE distribution—for stress periods 100, 200, 300, and 400[5]—in the groundwater system at Tarawa Terrace and vicinity under the Original Schedule and the Maximum Schedule are shown in Figures H8–H10 for model layers 1, 3, and 5, respectively.

The results shown in Figures H8–H10 indicate that, when compared to the Original Schedule, the PCE contaminant plume under the Maximum Schedule is aggregated into a smaller domain and the front of the plume is directed more toward the location of water-supply well TT-26. This is because, under the Maximum Schedule, the higher pumping rate in well TT-26 creates a higher piezometric head gradient toward the location of well TT-26, which causes a faster groundwater flow toward and more contaminant mass entering into well TT-26. Therefore, a higher PCE concentration at well TT-26 is expected under the Maximum Schedule.

[5]Maps of PCE distribution always show results for stress periods 100, 200, 300, and 400. The corresponding month and year are labeled on the figures and also can be found in Appendix H1. Owing to brevity, only the stress period number will be used in the text.

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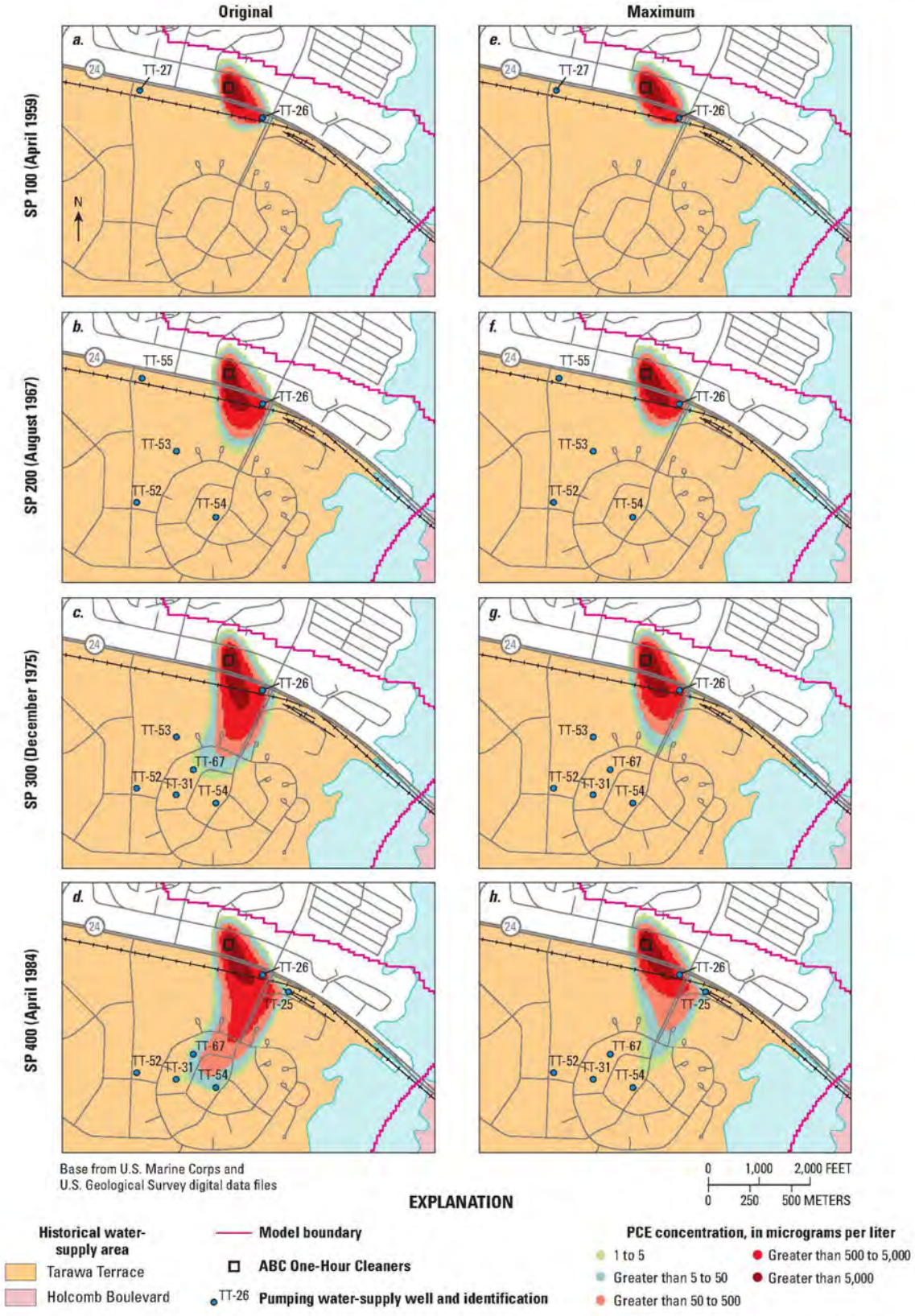

Figure H8. Comparison of tetrachloroethylene (PCE) distribution in model layer 1 under the Original Schedule for *(a)* SP 100, *(b)* SP 200, *(c)* SP 300, and *(d)* SP 400; and the Maximum Schedule for *(e)* SP 100, *(f)* SP 200, *(g)* SP 300, and *(h)* SP 400, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SP, stress period]

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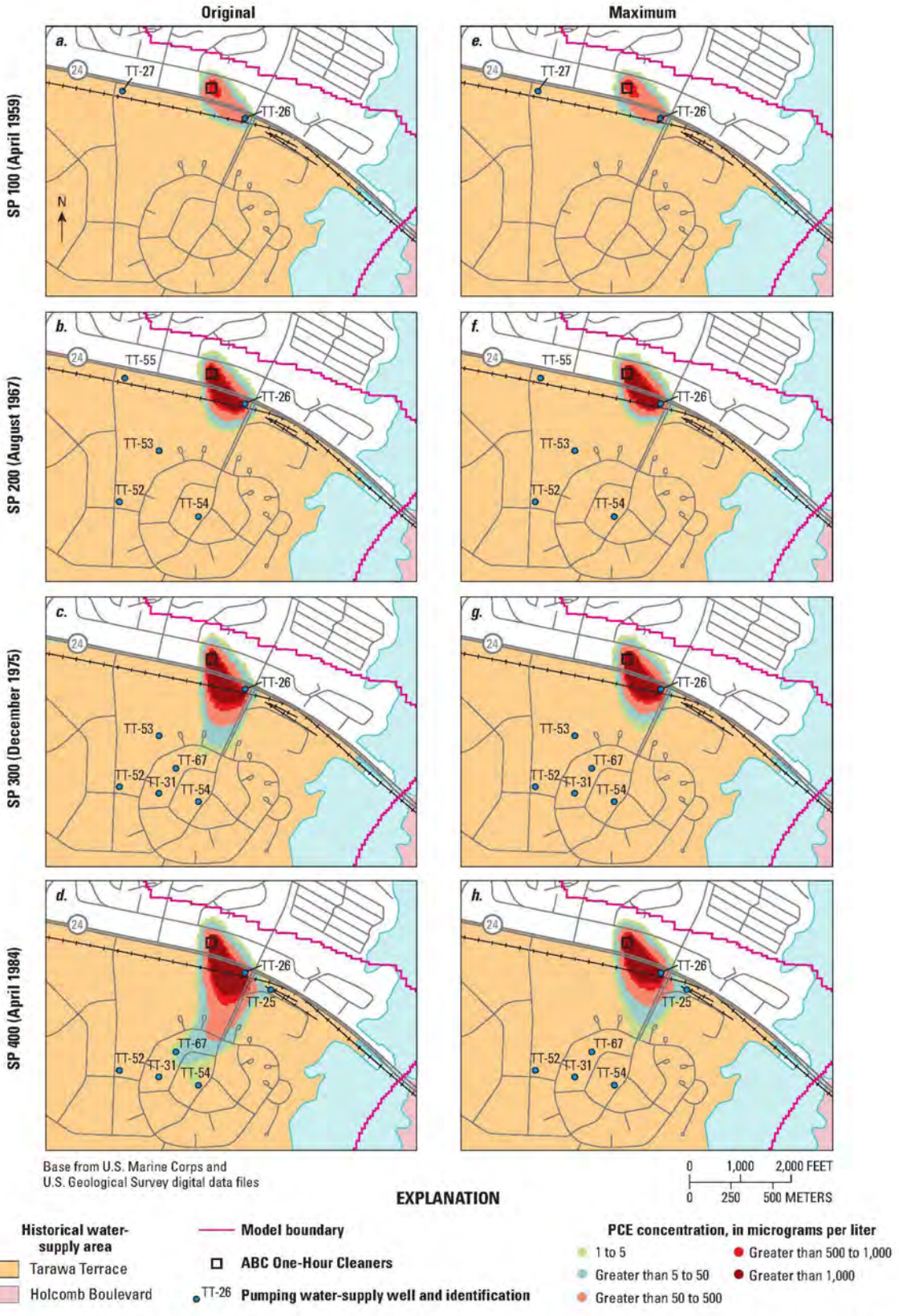

Figure H9. Comparison of tetrachloroethylene (PCE) distribution in model layer 3 under the Original Schedule for *(a)* SP 100, *(b)* SP 200, *(c)* SP 300, and *(d)* SP 400; and the Maximum Schedule for *(e)* SP 100, *(f)* SP 200, *(g)* SP 300, and *(h)* SP 400, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SP, stress period]

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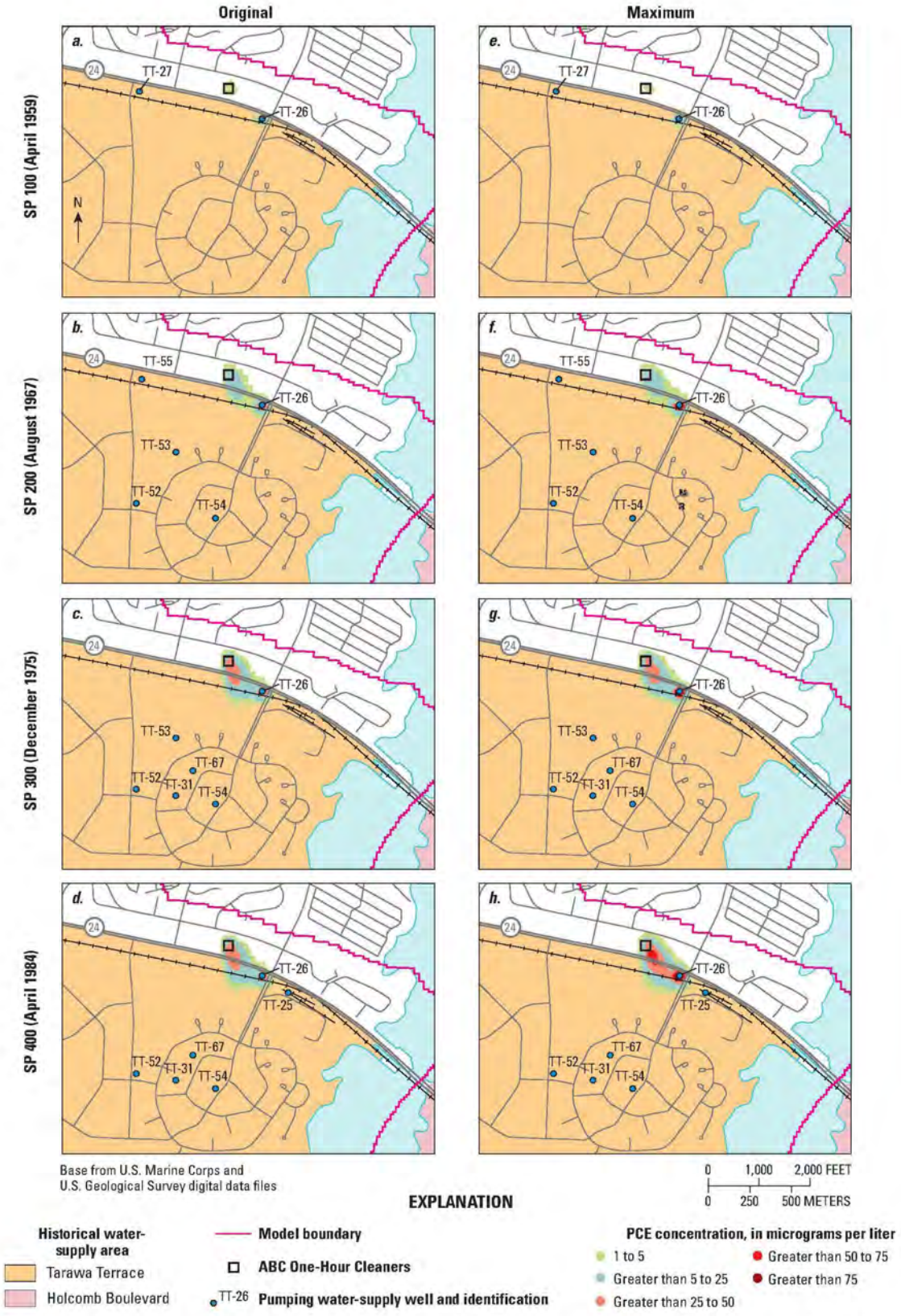

Figure H10. Comparison of tetrachloroethylene (PCE) distribution in model layer 5 under the Original Schedule for *(a)* SP 100, *(b)* SP 200, *(c)* SP 300, and *(d)* SP 400; and the Maximum Schedule for *(e)* SP 100, *(f)* SP 200, *(g)* SP 300, and *(h)* SP 400, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SP, stress period]

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PCE Concentration at Water-Supply Wells

From a concentration observation file obtained from the MT3DMS simulation, PCE concentration is acquired at water-supply wells. The results are compared to the PCE concentration distribution under the Original Schedule as shown in Figure H11.

The results presented in Figure H11 lead to the following observations for PCE concentrations at water-supply wells under the Maximum Schedule:

1. Instead of nine water-supply wells (TT-23, TT-25, TT-26, TT-31A, TT-31B, TT-53, TT-54A, TT-54B, and TT-67) that had PCE concentrations greater than 0.001 µg/L under the Original Schedule, under the Maximum Schedule there are only five pumping wells (TT-23, TT-25, TT-26, TT-54A, and TT-54B) that had PCE concentrations greater than 0.001 µg/L.
2. Throughout the simulation period, PCE concentrations at well TT-26 are always higher under the Maximum Schedule when compared to concentrations obtained under the Original Schedule. More specifically, as shown in Figure H12, PCE concentrations at well TT-26 are much higher under the Maximum Schedule when compared with the Original Schedule results during the period of interest (1968–1985).
3. PCE concentration at well TT-25 is higher under the Maximum Schedule when compared with the Original Schedule results before October 1985 and is lower after that.
4. For wells TT-23, TT-54A, and TT-54B, PCE concentrations are lower under the Maximum Schedule when compared with concentrations obtained under the Original Schedule.
5. Under the Maximum Schedule, only three water-supply wells (TT-23, TT-25, and TT-26) have PCE concentrations greater than 5 µg/L. Among them, PCE concentration in well TT-26 is much greater than the MCL throughout the period of interest. The other two wells have PCE concentrations greater than the MCL only for a very short period of time.
6. PCE concentration at well TT-26 is much greater than those obtained in other wells throughout the simulation period. Since well TT-26 always pumped at its full capacity (except for the first 3 months of 1952), it is the major water-supply well that transported contaminants into the WTP under the Maximum Schedule.

Based on the observations listed above, the difference of PCE concentrations obtained in well TT-26 using different pumping schedules is further evaluated, and the following observations can be made:

1. PCE concentration at well TT-26 reaches 5 µg/L during May 1956 under the Maximum Schedule, which is 8 months earlier than the PCE MCL arrival time under the Original Schedule (January 1957). Since well TT-26 was the major contributor of PCE to the WTP, PCE concentration at the WTP also could reach the MCL earlier under the Maximum Schedule.
2. PCE concentration at well TT-26 is much higher under the Maximum Schedule when compared to the concentration obtained under the Original Schedule during the period of interest. Between these two pumping schedules, the minimum difference of PCE concentration at well TT-26 is 169.62 µg/L, the maximum difference is 304.84 µg/L, and the average difference is 247.13 µg/L (Table H5).

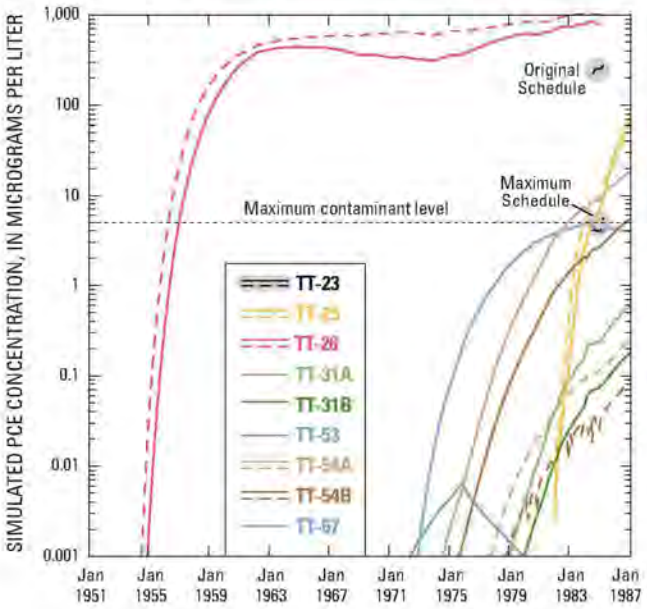

Figure H11. Simulated tetrachloroethylene (PCE) concentration at selected water-supply wells under the Original Schedule (solid line) and the Maximum Schedule (dashed line), Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [TT-31A and TT-54A, model layer 1; TT-31B and TT-54B, model layer 3]

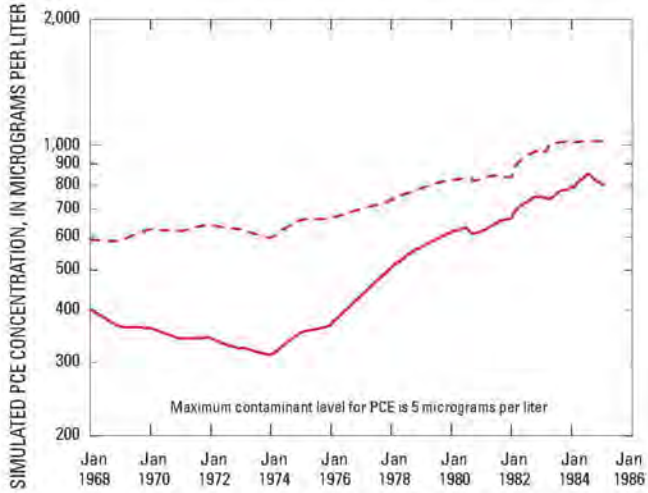

Figure H12. Simulated tetrachloroethylene (PCE) concentration at water-supply well TT-26 under the Original Schedule (solid line) and the Maximum Schedule (dashed line), period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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Table H5. Tetrachloroethylene concentration at water-supply well TT-26 under the Original Schedule and the Maximum Schedule for the period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter]

	Maximum[1] (µg/L)	Minimum[1] (µg/L)	Average (µg/L)
Original Schedule	312.62	851.19	494.36
Maximum Schedule	585.98	1,023.31	741.49
Difference	304.84	169.62	247.13

[1]Values for Original Schedule and Maximum Schedule occur during different stress periods

PCE Concentration at the Water Treatment Plant

Using the mixing model described in Equation 3, PCE concentration at the WTP under the Maximum Schedule was calculated and compared to that obtained under the Original Schedule. These comparisons are shown in Figure H13 for the entire simulation period and in Figure H14 for the period of interest (January 1968–December 1985).

Results shown in Figures H13 and H14 lead to the following observations:

1. PCE concentration at the WTP under the Maximum Schedule is significantly higher than that obtained from the Original Schedule, except for the time period after February 1985, when well TT-26 was out of service. The higher PCE concentration at the WTP is caused by the higher pumping rate and the higher PCE concentration at well TT-26 under the Maximum Schedule.
2. The higher PCE concentration at the WTP is equivalent to the earlier contaminant arrival time—PCE concentration at the WTP reached 5 µg/L during December 1956, which is 11 months earlier than the Original Schedule (November 1957).
3. There are three sudden declines in PCE concentration at the WTP under the Maximum Schedule: July 1980–August 1980, January 1983–February 1983, and February 1985–December 1985. This is similar to what was observed under the Original Schedule and also is caused by well TT-26 being out of service during these periods.

Results shown in Figures H13 and H14 also indicate that after well TT-26 was shut down during February 1985, PCE concentration at the WTP is lower than that obtained under the Original Schedule, although the absolute difference is small (less than 4 µg/L). This phenomenon is caused by the presence of lower PCE concentrations in other water-supply wells. Ten water-supply wells (TT-23, TT-25, TT-31A, TT-31B, TT-52A, TT-52B, TT-54A, TT-54B, TT-67A, and TT-67B) are still in service after February 1985 under the Maximum Schedule. Results shown in Figure H11 indicate that, besides water-supply wells with PCE concentrations lower than 0.001 µg/L and not shown in the figure, PCE concentrations in all remaining wells are lower under the Maximum Schedule when compared with results obtained under the Original Schedule for this period.

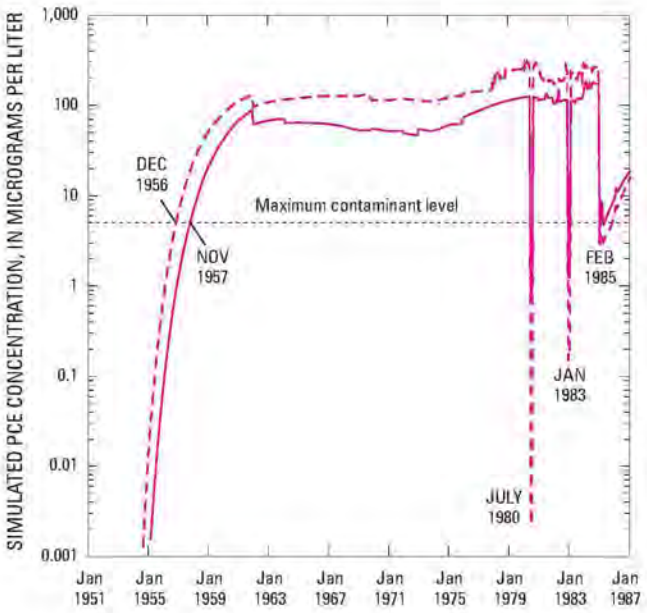

Figure H13. Simulated tetrachloroethylene (PCE) concentration at the water treatment plant under the Original Schedule (solid line) and the Maximum Schedule (dashed line), Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

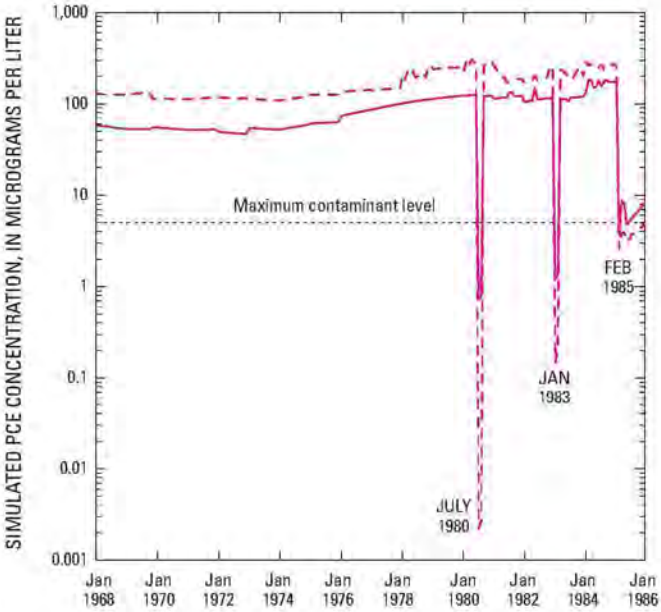

Figure H14. Simulated tetrachloroethylene (PCE) concentration at the water treatment plant under the Original Schedule (solid line) and the Maximum Schedule (dashed line), period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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Lower PCE concentrations in these 10 water-supply wells may be attributed to the following:

1. According to results shown in Figures H8–H10, the higher pumping rate in well TT-26 under the Maximum Schedule causes the PCE plume to aggregate into a smaller region, which in turn causes lower PCE concentrations at water-supply wells other than TT-26.
2. More contaminant mass is withdrawn and less mass is left in the groundwater system under the Maximum Schedule. According to the original model, 1.40×10^7 gr of PCE were released into the groundwater system January 1953–December 1984. By the time all pumping operations were terminated (February 1987), 2.45×10^6 gr of PCE were discharged through water-supply wells under the Original Schedule, while 4.59×10^6 gr of PCE were discharged under the Maximum Schedule as indicated in Table H6.

As discussed previously, there were 15 months during the period of interest when well TT-26 was out of service and PCE concentration at the WTP was less than 5 µg/L. In the other 201 months, PCE concentration at the WTP was greater than the MCL under both the Original Schedule and the Maximum Schedule. A comparison of PCE concentrations at the WTP during those 201 months is summarized in Table H7.

Table H6. Tetrachloroethylene mass withdrawn under the Original Schedule and the Maximum Schedule, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

	Total mass released (gram)	Mass withdrawn (gram)	Percentage[1]
Original Schedule	1.40×10^7	2.45×10^6	17.50
Maximum Schedule	1.40×10^7	4.59×10^6	32.78

[1]Percentage of mass withdrawn relative to total mass released

Table H7. Tetrachloroethylene concentration at the water treatment plant under the Original Schedule and the Maximum Schedule for the period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter]

	Maximum[1] (µg/L)	Minimum[1] (µg/L)	Average (µg/L)
Original Schedule	183.04	46.69	86.39
Maximum Schedule	304.66	108.76	166.07
Difference	180.75	42.67	79.68

[1]Values for Original Schedule and Maximum Schedule occur during different stress periods

Optimization and Simulation Results for Minimum Schedule I

Similar to the Maximum Schedule, PSOpS was run using Minimum Schedule I to obtain the "latest" PCE MCL arrival time at the WTP. The results obtained under Minimum Schedule I indicate that well TT-26 pumped at the lowest possible rate for most of the time period (Figure H15), which implies that well TT-26 was not put into operation unless there was no other water-supply well available to provide the required total demand. The reason for this is evident because PCE concentration at well TT-26 is significantly higher than PCE concentration in other pumping wells. For most of the simulation period, lower PCE concentration at the WTP can be realized by reducing the pumping rate of well TT-26. However, there are exceptions to this during the period of late 1970s and early 1980s, which will be discussed in the following section.

PCE Distribution in the Groundwater System

Similar to the maximum schedule results presented in Figures H8–H10, PCE distributions in the subsurface system around Tarawa Terrace and vicinity under the Original Schedule and Minimum Schedule I are compared in Figures H16–H18. The notation used in these figures is the same as used for Figures H8–H10.

Results presented in Figures H16–H18 indicate that Minimum Schedule I also causes a change of PCE distribution in the groundwater system. The contaminant plume under Minimum Schedule I is dispersed to a larger area, and the front of the plume is away from well TT-26, which is opposite to what has been observed under the Maximum Schedule. Therefore, PCE concentrations at some wells other than well TT-26 are expected to be higher, and PCE concentration at TT-26 is expected to be lower.

According to results presented in Figures H16–H18, PCE concentration near well TT-26 is still relatively high due to its closeness to the contaminant source, which causes a greater PCE concentration at well TT-26 when compared to other wells. Therefore, as discussed in previous sections, well TT-26 was pumped at the lowest possible rates for most of the time under Minimum Schedule I to lower the PCE concentration at the WTP.

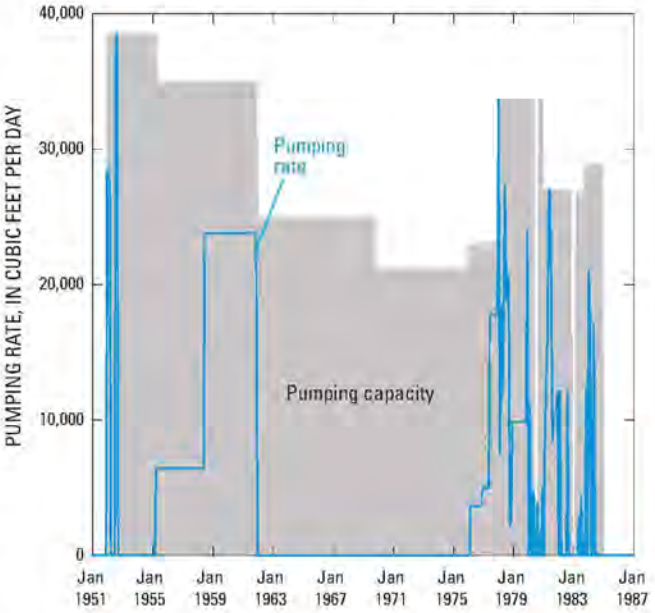

Figure H15. Pumping rate and capacity of water-supply well TT-26 under Minimum Schedule I, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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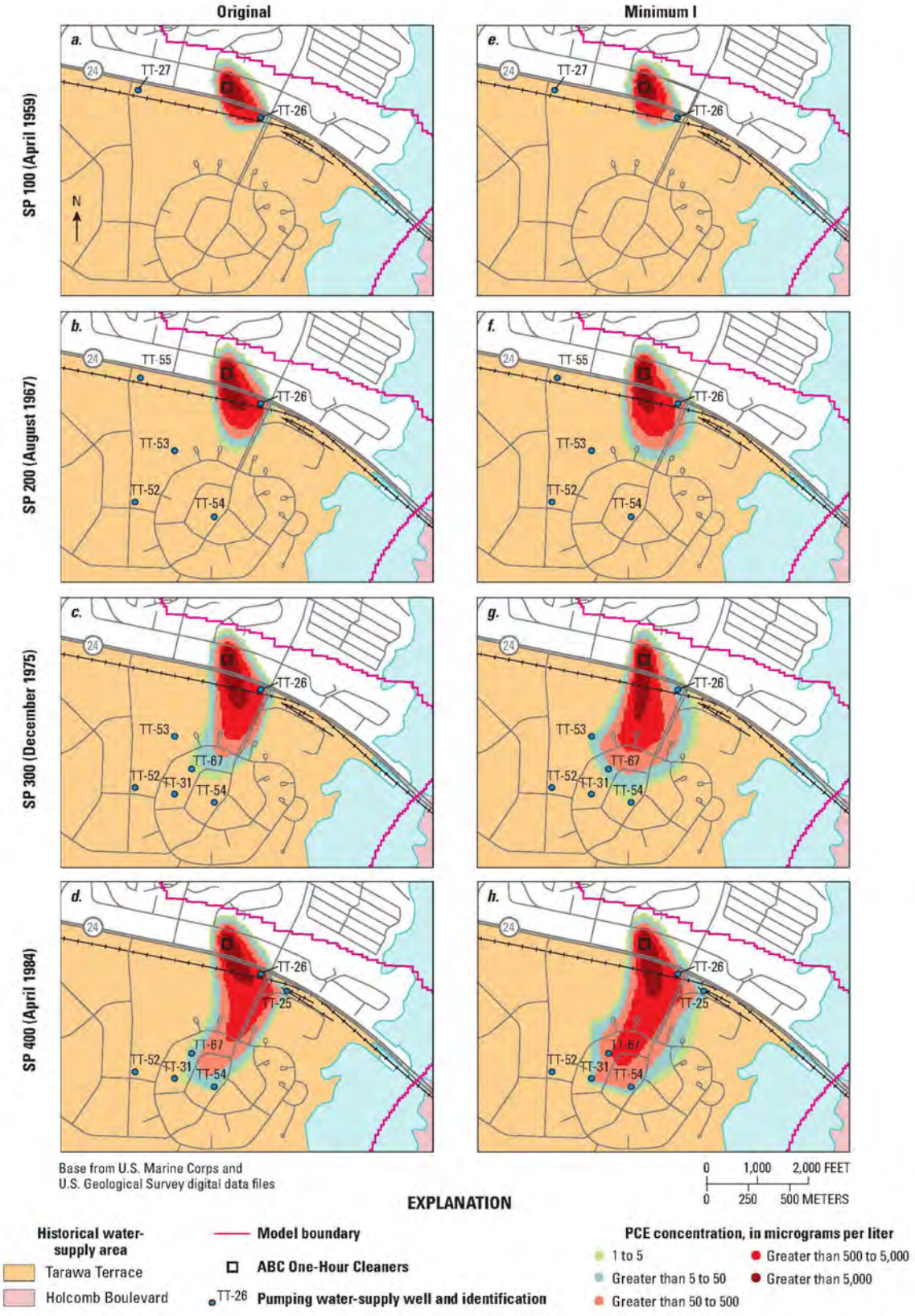

Figure H16. Comparison of tetrachloroethylene (PCE) distribution in model layer 1 under the Original Schedule for *(a)* SP 100, *(b)* SP 200, *(c)* SP 300, and *(d)* SP 400; and Minimum Schedule I for *(e)* SP 100, *(f)* SP 200, *(g)* SP 300, and *(h)* SP 400, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SP, stress period]

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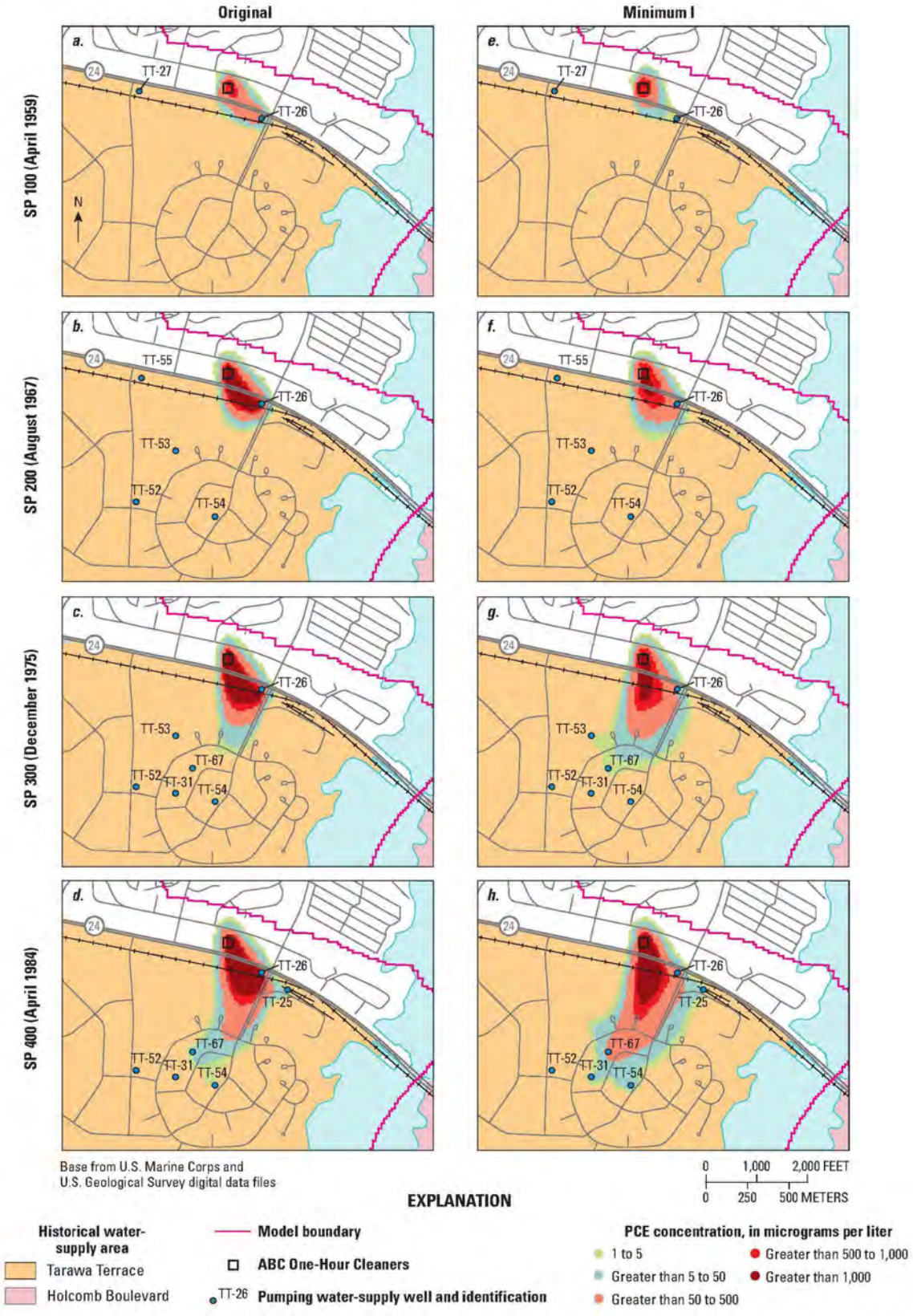

Figure H17. Comparison of tetrachloroethylene (PCE) distribution in model layer 3 under the Original Schedule for *(a)* SP 100, *(b)* SP 200, *(c)* SP 300, and *(d)* SP 400; and Minimum Schedule I for *(e)* SP 100, *(f)* SP 200, *(g)* SP 300, and *(h)* SP 400, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SP, stress period]

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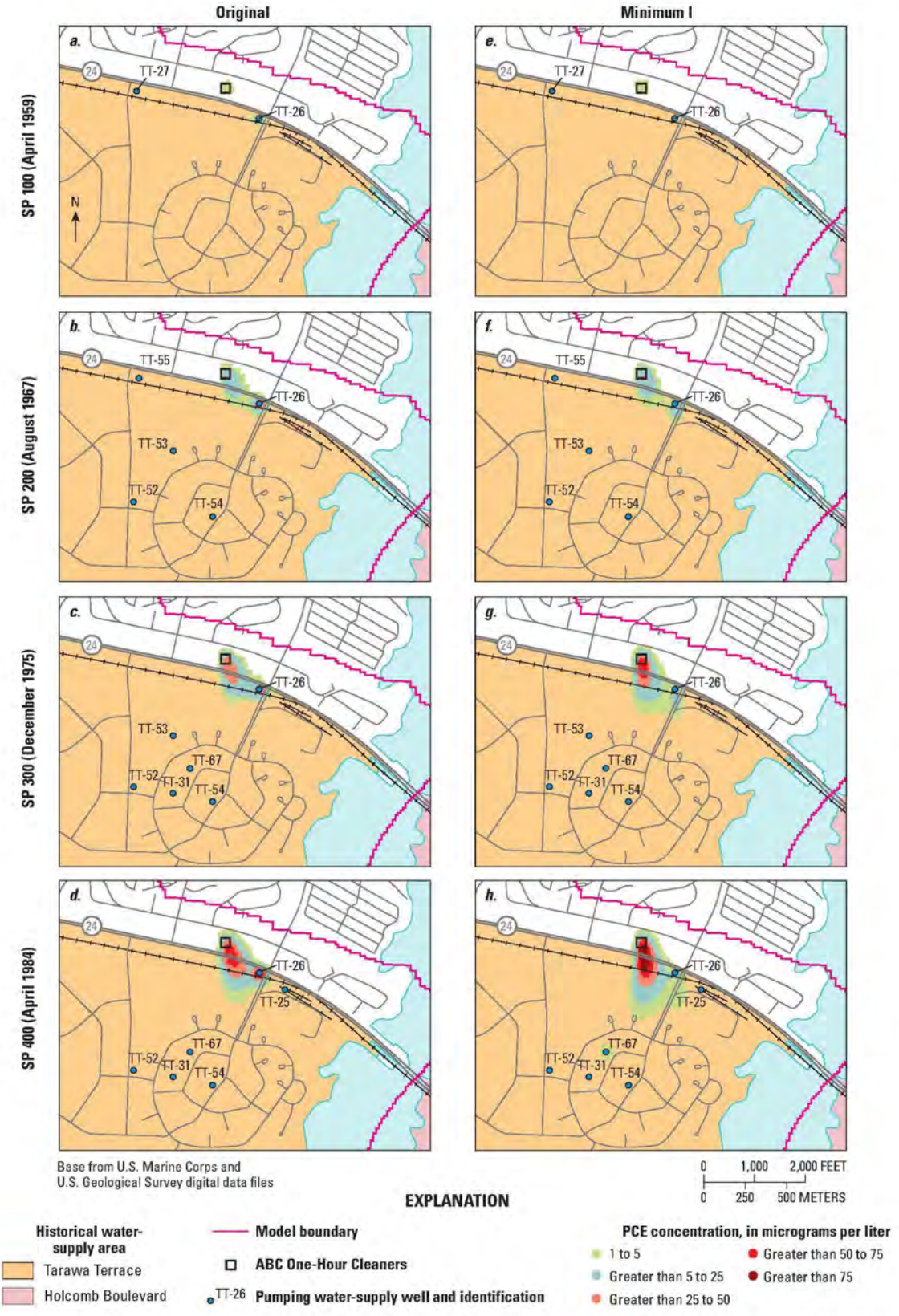

Figure H18. Comparison of tetrachloroethylene (PCE) distribution in model layer 5 under the Original Schedule for *(a)* SP 100, *(b)* SP 200, *(c)* SP 300, and *(d)* SP 400; and Minimum Schedule I for *(e)* SP 100, *(f)* SP 200, *(g)* SP 300, and *(h)* SP 400, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SP, stress period]

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PCE Concentration at Water-Supply Wells

The output of the MT3DMS simulation under Minimum Schedule I provides PCE concentrations at water-supply wells. These results show higher PCE concentrations in some pumping wells other than well TT-26 (Figure H19). Only wells with PCE concentrations exceeding 0.001 µg/L are shown in Figure H19. Another version of Figure H19, emphasizing the period of interest, is shown in Figure H20.

From the results shown in Figures H19 and H20, the following may be observed:

1. Instead of six water-supply wells (TT-23, TT-25, TT-26, TT-54A, TT-54B, and TT-67) having PCE concentrations exceeding 5 µg/L, as seen with the Original Schedule, nine pumping wells have PCE concentrations exceeding 5 µg/L under Minimum Schedule I. These wells are TT-23, TT-25, TT-26, TT-31A, TT-31B, TT-54A, TT-54B, TT-67A, and TT-67B. As discussed in the previous section, this is caused by the generation of a more dispersed contaminant plume under Minimum Schedule I.
2. PCE concentration at well TT-26 is always less under Minimum Schedule I than under the Original Schedule throughout the simulation period.
3. Well TT-26 is the first well to have a PCE concentration exceeding the PCE MCL. During the first half of the simulation period, well TT-26 is the only well with a PCE concentration greater than 5 µg/L. Therefore, well TT-26 is still critical to the PCE MCL arrival time at the WTP.
4. PCE concentration at well TT-26 exceeds 5 µg/L during August 1959 under Minimum Schedule I, which is 31 months later than the case for the Original Schedule (January 1957). This delay also would cause a "late" PCE MCL arrival time at the WTP.
5. Under Minimum Schedule I, PCE concentration in well TT-26 is no longer dominant during the second half of the simulation period. PCE concentrations at wells TT-23, TT-67A, and TT-67B are sometimes greater than the concentration at well TT-26. Higher PCE concentrations at these pumping wells also explain why well TT-26 is not always pumping at the lowest possible rates toward the end of the simulation period; with several pumping wells having high PCE concentration, Minimum Schedule I is managed in such a way that the plume front does not migrate to any particular water-supply well.

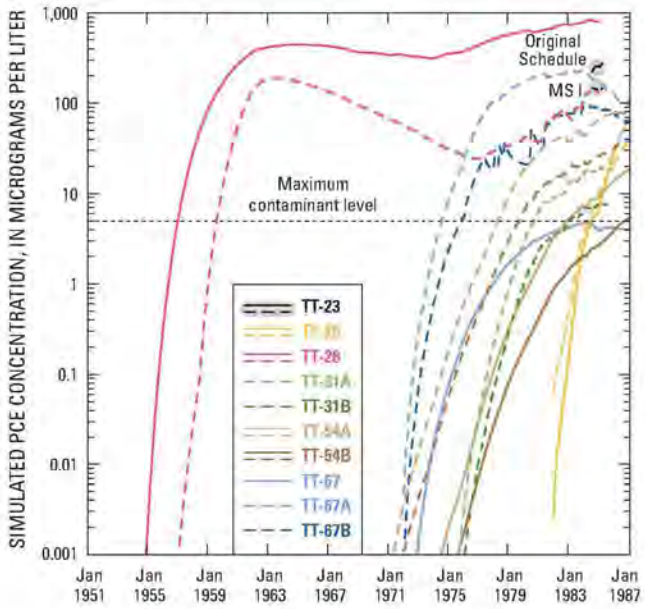

Figure H19. Simulated tetrachloroethylene (PCE) concentration at selected water-supply wells under the Original Schedule (solid line) and Minimum Schedule I (MS I, dashed line), Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [TT31A, TT-54A, and TT-67A, model layer 1; TT31B, TT-54B, and TT-67B, model layer 3]

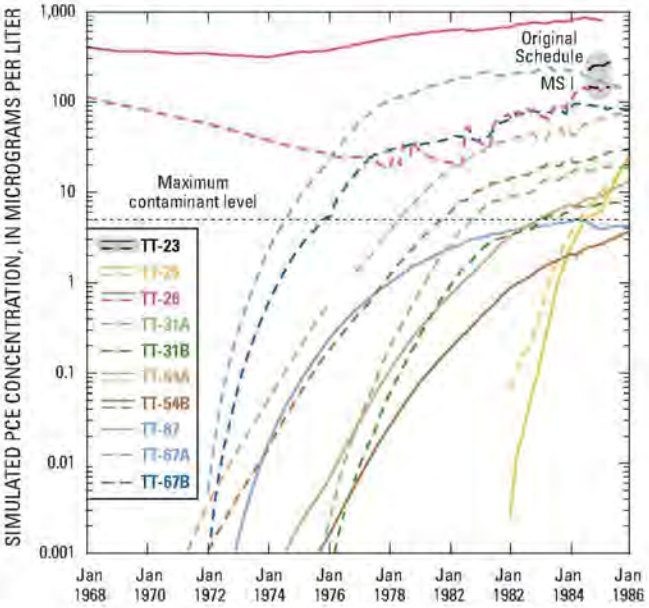

Figure H20. Simulated tetrachloroethylene (PCE) concentration at selected water-supply wells under the Original Schedule (solid line) and Minimum Schedule I (MS I, dashed line), period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [TT31A, TT-54A, and TT-67A, model layer 1; TT31B, TT-54B, and TT-67B, model layer 3]

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PCE Concentration at the Water Treatment Plant

PCE concentration at the WTP under Minimum Schedule I is calculated using Equation 3 and is shown in Figures H21 and H22.

The results shown in Figures H21 and H22 lead to the following observations:

1. PCE concentration at the WTP under Minimum Schedule I is lower than PCE concentration obtained under the Original Schedule except for the period after February 1985.

2. PCE concentration at the WTP reaches 5 µg/L during June 1960 under Minimum Schedule I, which is 31 months later than the arrival time of the Original Schedule. This is due to lower PCE concentration and lower pumping rate at well TT-26 under Minimum Schedule I. By the time the PCE concentration at the WTP reaches 5 µg/L, PCE concentrations at water-supply wells other than TT-26 are still negligible (Figure H19). Therefore, well TT-26 is the critical well affecting the PCE MCL arrival time at the WTP.

3. Under Minimum Schedule I, PCE concentration at the WTP increases steadily until December 1961, when PCE concentration declines below trace levels because of no pumping in well TT-26. PCE concentration again reaches 5 µg/L during November 1977. Between January 1962 and December 1971, PCE concentration at the WTP is less than 0.001 µg/L and, therefore, is not shown in these figures.

4. Sudden declines in PCE concentration that were observed during periods of July 1980–August 1980, January 1983–February 1983, and February 1985–December 1985 under the Original Schedule are not obvious under Minimum Schedule I for two reasons. First, overall PCE concentration level at the WTP is very low under Minimum Schedule I. Second, PCE concentration at well TT-26 is no longer dominant as shown in Figure H20.

Another observation that can be made from results presented in Figures H21 and H22 is that during the last 11 months of the period of interest, PCE concentrations at the WTP under Minimum Schedule I are slightly higher than those obtained under the Original Schedule, which is in contrast to the results obtained under the Maximum Schedule. The reason for this is the higher PCE concentrations in some water-supply wells other than well TT-26 (that is, wells TT-67A and TT-67B). The higher PCE concentrations in these two water-supply wells may be caused by the following factors:

1. By the end of the period of interest, less contaminant mass is extracted from the groundwater system under Minimum Schedule I, and more mass is left in the aquifer, which causes higher PCE concentrations in water-supply wells (Table H8).

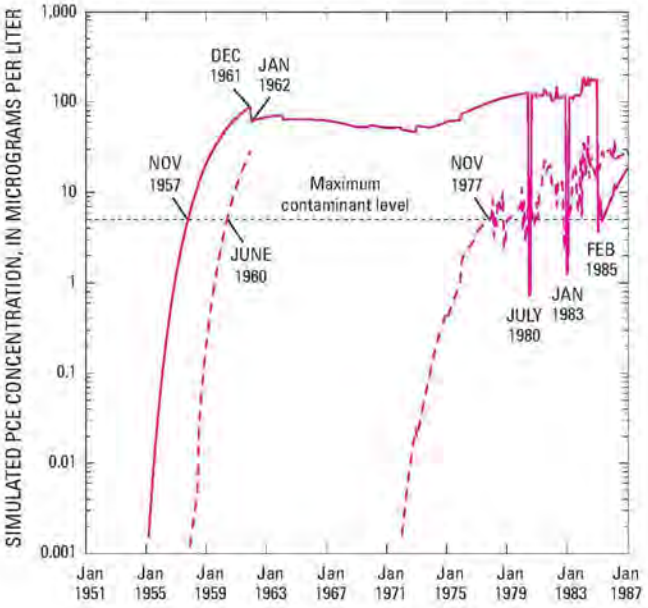

Figure H21. Simulated tetrachloroethylene (PCE) concentration at the water treatment plant under the Original Schedule (solid line) and Minimum Schedule I (dashed line), Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

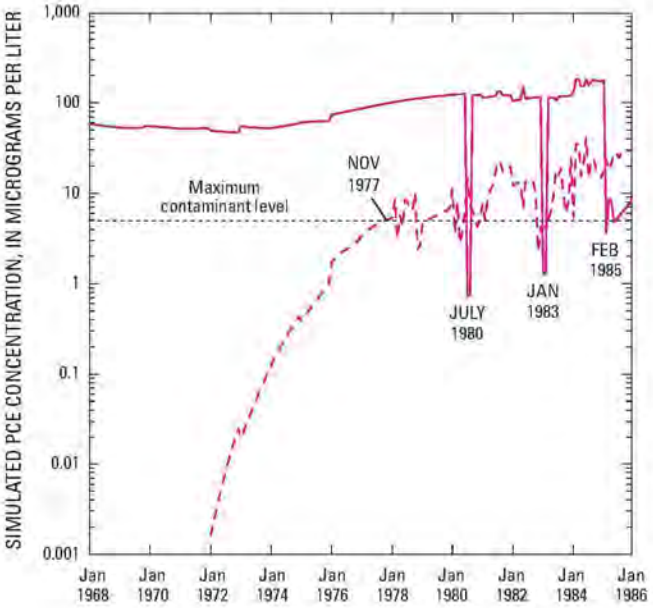

Figure H22. Simulated tetrachloroethylene (PCE) concentration at the water treatment plant under the Original Schedule (solid line) and Minimum Schedule I (dashed line), period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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2. Minimum Schedule I causes a more dispersed contaminant plume than the Original Schedule in the groundwater system (Figure H17). While PCE concentration at well TT-26 decreases, the PCE concentrations at some other wells increase.

Minimum Schedule I yields lower PCE concentrations at the WTP for the period of interest (Table H9). To keep this comparison consistent with the previous comparison made for the Maximum Schedule, the concentration distribution obtained from the 15 months when well TT-26 was out of service is not included in this analysis. The results shown in Table H9 indicate that the average PCE concentration at the WTP under Minimum Schedule I is 5.01 µg/L, which is close to the 5 µg/L MCL of PCE.

Table H8. Tetrachloroethylene mass withdrawn under the Original Schedule and Minimum Schedule I, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

	Total mass released (gram)	Mass withdrawn (gram)	Percentage[1]
Original Schedule	1.40×10^{7}	2.45×10^{6}	17.50
Minimum Schedule I	1.40×10^{7}	1.98×10^{5}	1.41

[1]Percentage of mass withdrawn relative to total mass released

Table H9. Tetrachloroethylene concentration at the water treatment plant under the Original Schedule and Minimum Schedule I for the period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter]

	Maximum[1] (µg/L)	Minimum[1] (µg/L)	Average (µg/L)
Original Schedule	183.04	46.69	86.39
Minimum Schedule I	41.36	7.84×10^{-8}	5.01
Difference	158.48	46.69	81.39

[1]Values for Original Schedule and Maximum Schedule occur during different stress periods

Optimization and Simulation Results for Minimum Schedule II

Results obtained under Minimum Schedule I indicate that water-supply well TT-26 was out of service for a long period of time, which is unrealistic based on historical records and considering that well TT-26 was one of the major water-supply wells for the Tarawa Terrace area. Therefore, a third PSOpS simulation was conducted to obtain a pumping schedule that could yield the "latest" arrival time but at the same time honor historical data on the schedule of well operations at the site. To achieve this, one more constraint was added to the optimization model—the pumping rate in well TT-26 is restricted to never being less than 25 percent of its pumping capacity at any time when in service. The pumping rate of well TT-26 obtained for this case is shown in Figure H23. Similar to Minimum Schedule I, the pumping rate for well TT-26 for Minimum Schedule II also is the minimum possible during the first half of the simulation period.

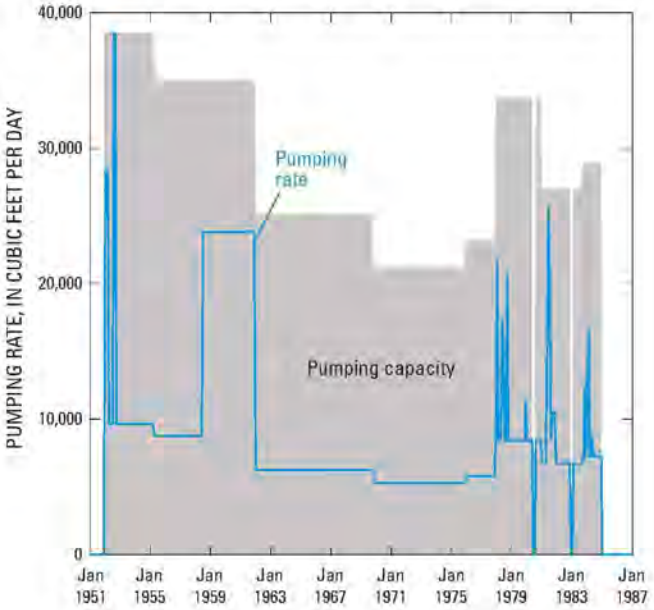

Figure H23. Pumping rate and capacity of water-supply well TT-26 under Minimum Schedule II, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

PCE Distribution in the Groundwater System

PCE distribution in the subsurface system at Tarawa Terrace and vicinity under the Original Schedule and Minimum Schedule II are shown in Figures H24–H26 for different stress periods for model layers 1, 3, and 5, respectively. A comparison of PCE distributions obtained under Minimum Schedule I and Minimum Schedule II are shown in Figures H27–H29 for different stress periods for model layers 1, 3, and 5, respectively.

A comparison of Figures H16–H18 and Figures H24–H29 indicates that Minimum Schedule II also causes the PCE plume to be more dispersed than the Original Schedule, but not as much as Minimum Schedule I. This is because the average pumping rate in well TT-26 under Minimum Schedule II is less than that obtained under the Original Schedule, but greater than the average pumping rate obtained under Minimum Schedule I. Therefore, PCE concentrations at well TT-26 and the WTP under Minimum Schedule II are expected to be between those obtained under the Original Schedule and Minimum Schedule I.

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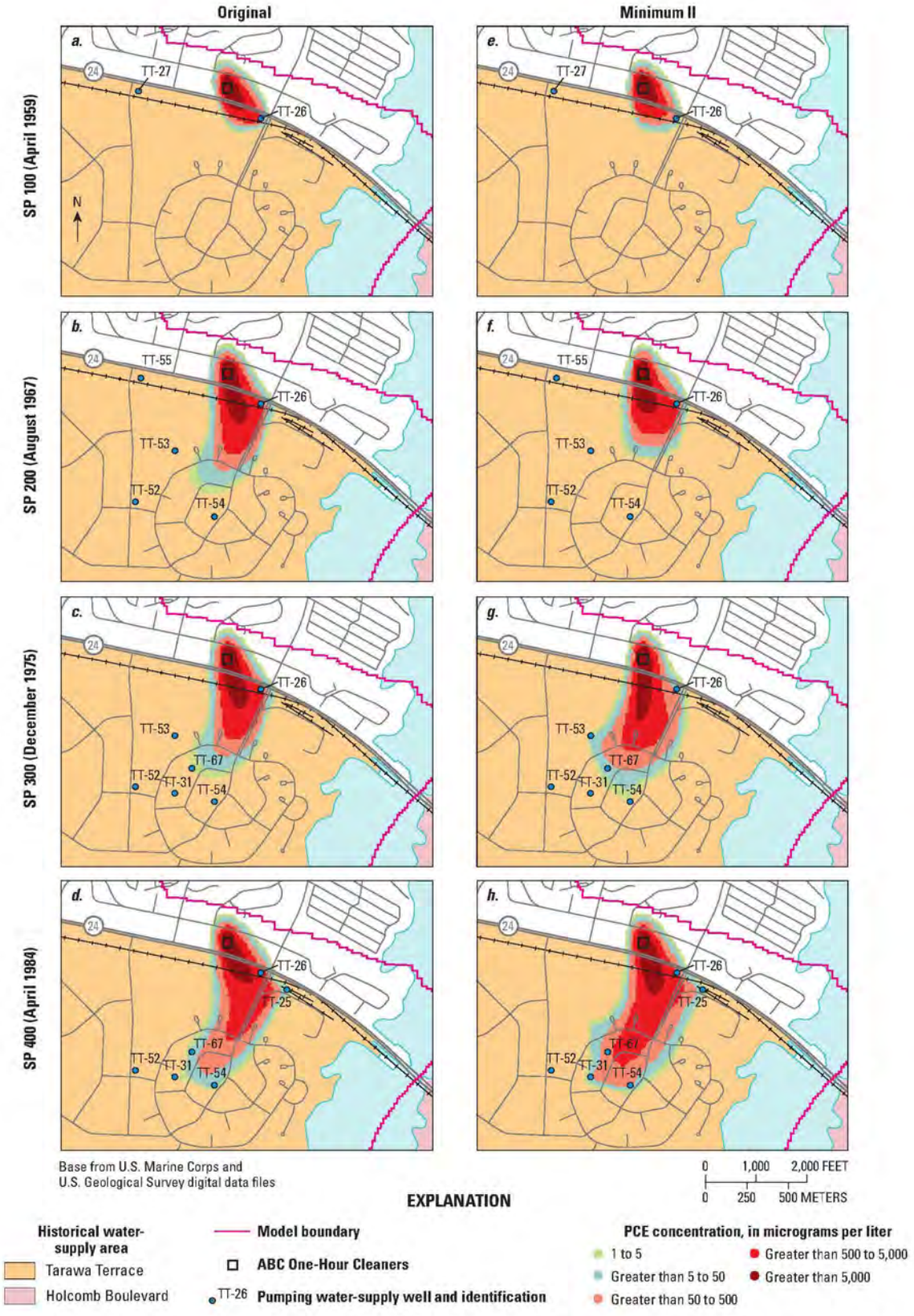

Figure H24. Comparison of tetrachloroethylene (PCE) distribution in model layer 1 under the Original Schedule for *(a)* SP 100, *(b)* SP 200, *(c)* SP 300, and *(d)* SP 400; and Minimum Schedule II for *(e)* SP 100, *(f)* SP 200, *(g)* SP 300, and *(h)* SP 400, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SP, stress period]

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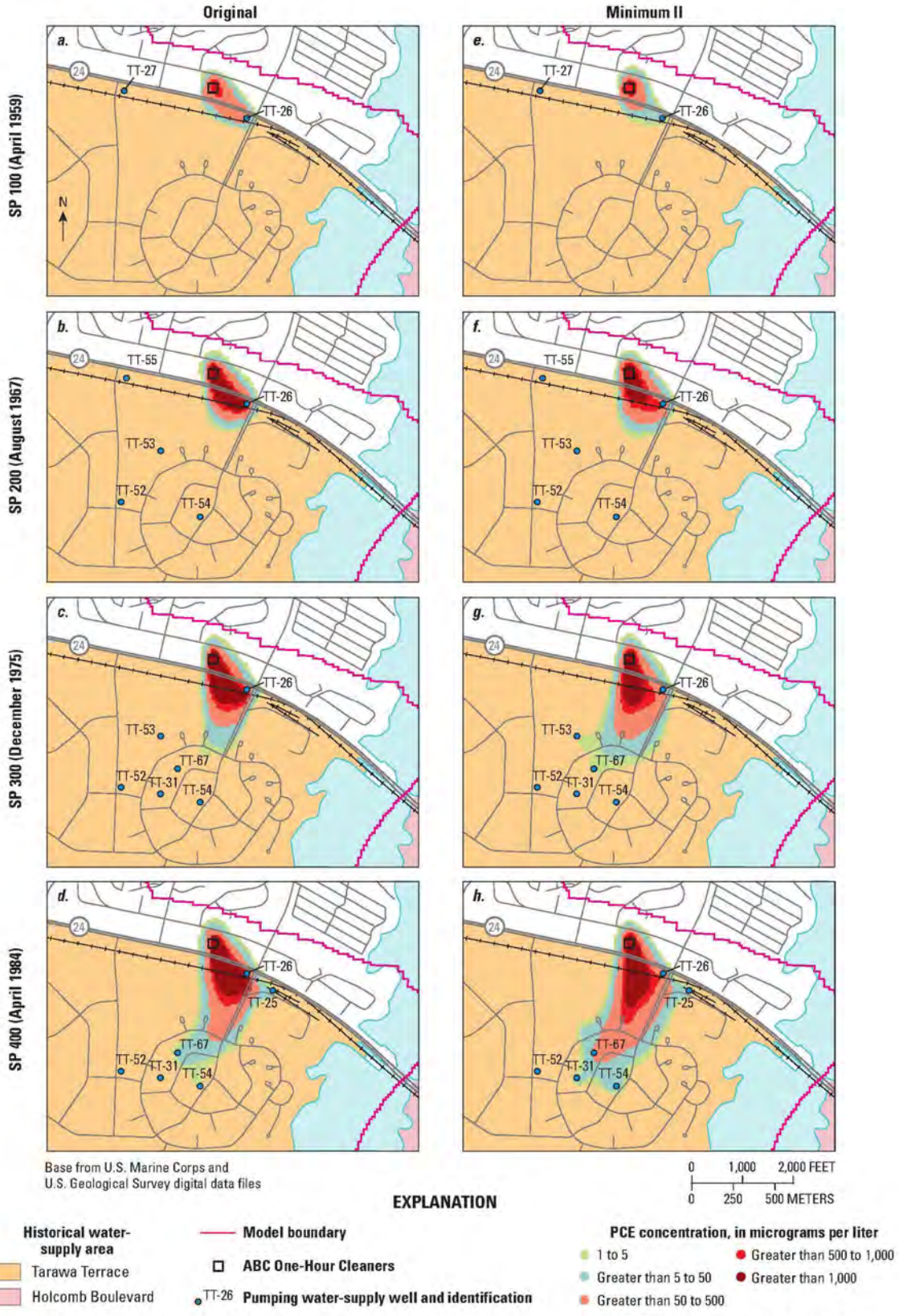

Figure H25. Comparison of tetrachloroethylene (PCE) distribution in model layer 3 under the Original Schedule for *(a)* SP 100, *(b)* SP 200, *(c)* SP 300, and *(d)* SP 400; and Minimum Schedule II for *(e)* SP 100, *(f)* SP 200, *(g)* SP 300, and *(h)* SP 400, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SP, stress period]

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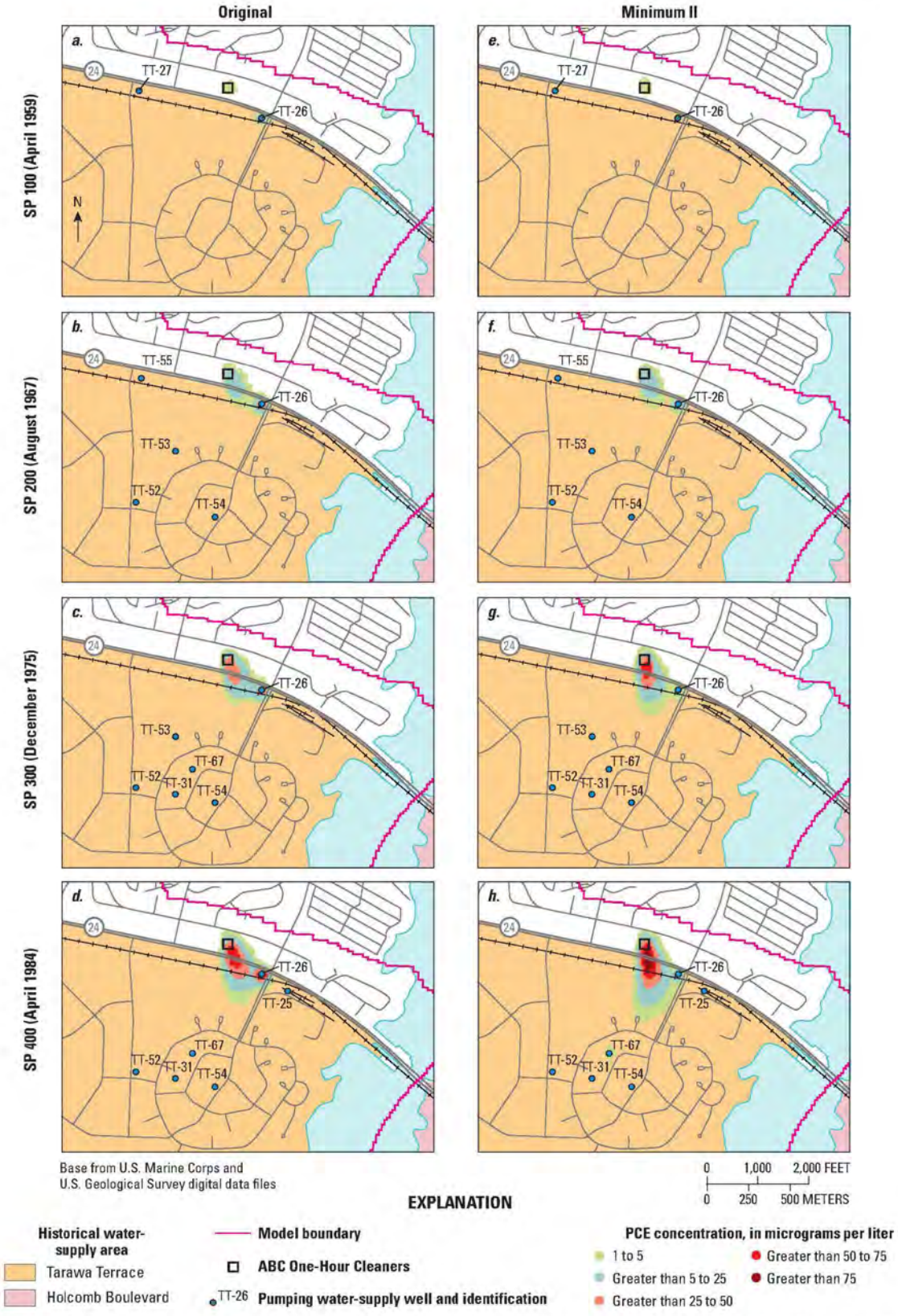

Figure H26. Comparison of tetrachloroethylene (PCE) distribution in model layer 5 under the Original Schedule for *(a)* SP 100, *(b)* SP 200, *(c)* SP 300, and *(d)* SP 400; and Minimum Schedule II for *(e)* SP 100, *(f)* SP 200, *(g)* SP 300, and *h)* SP 400, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SP, stress period]

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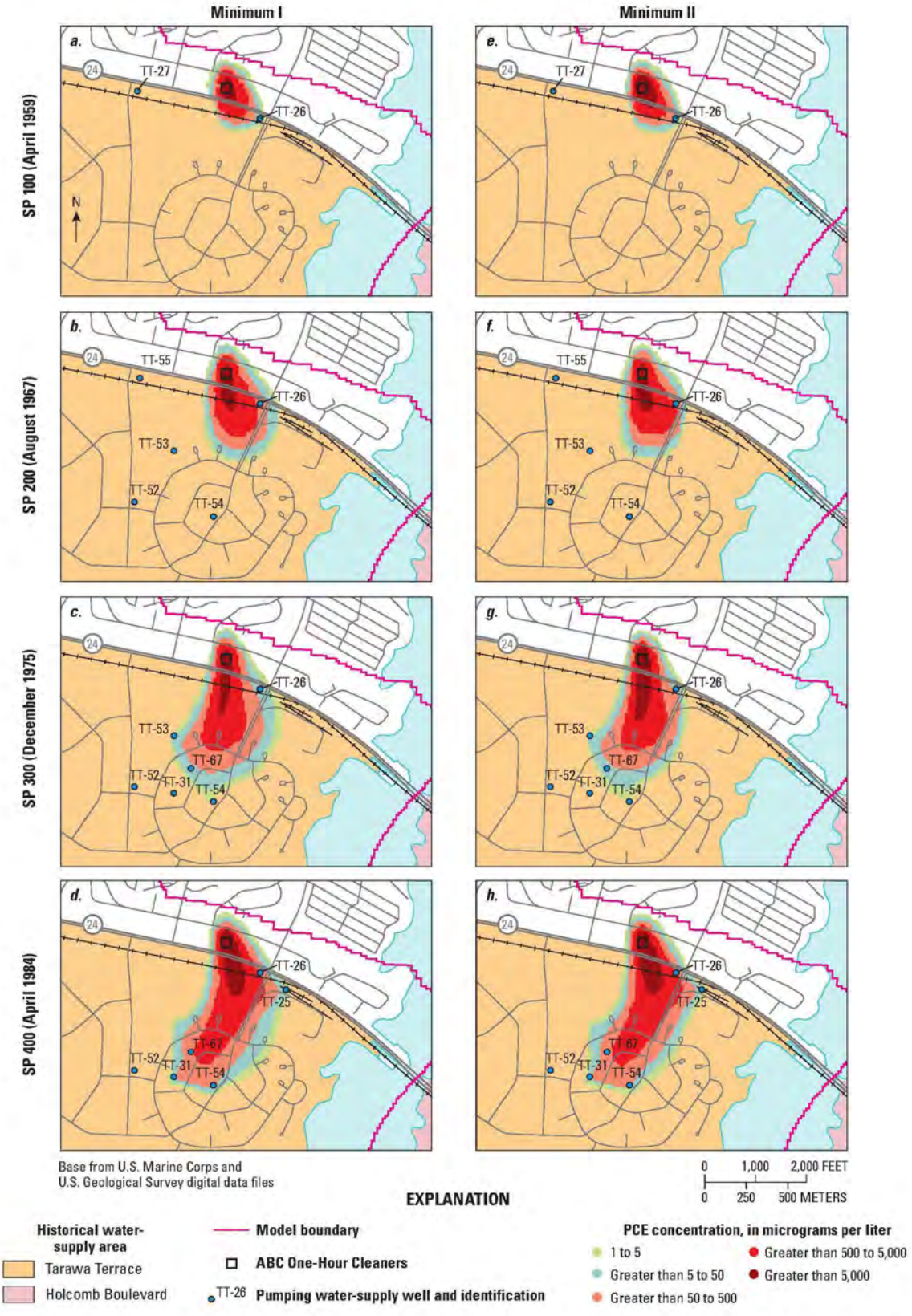

Figure H27. Comparison of tetrachloroethylene (PCE) distribution in model layer 1 under Minimum Schedule I for *(a)* SP 100, *(b)* SP 200, *(c)* SP 300, and *(d)* SP 400; and Minimum Schedule II for *(e)* SP 100, *(f)* SP 200, *(g)* SP 300, and *(h)* SP 400, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SP, stress period]

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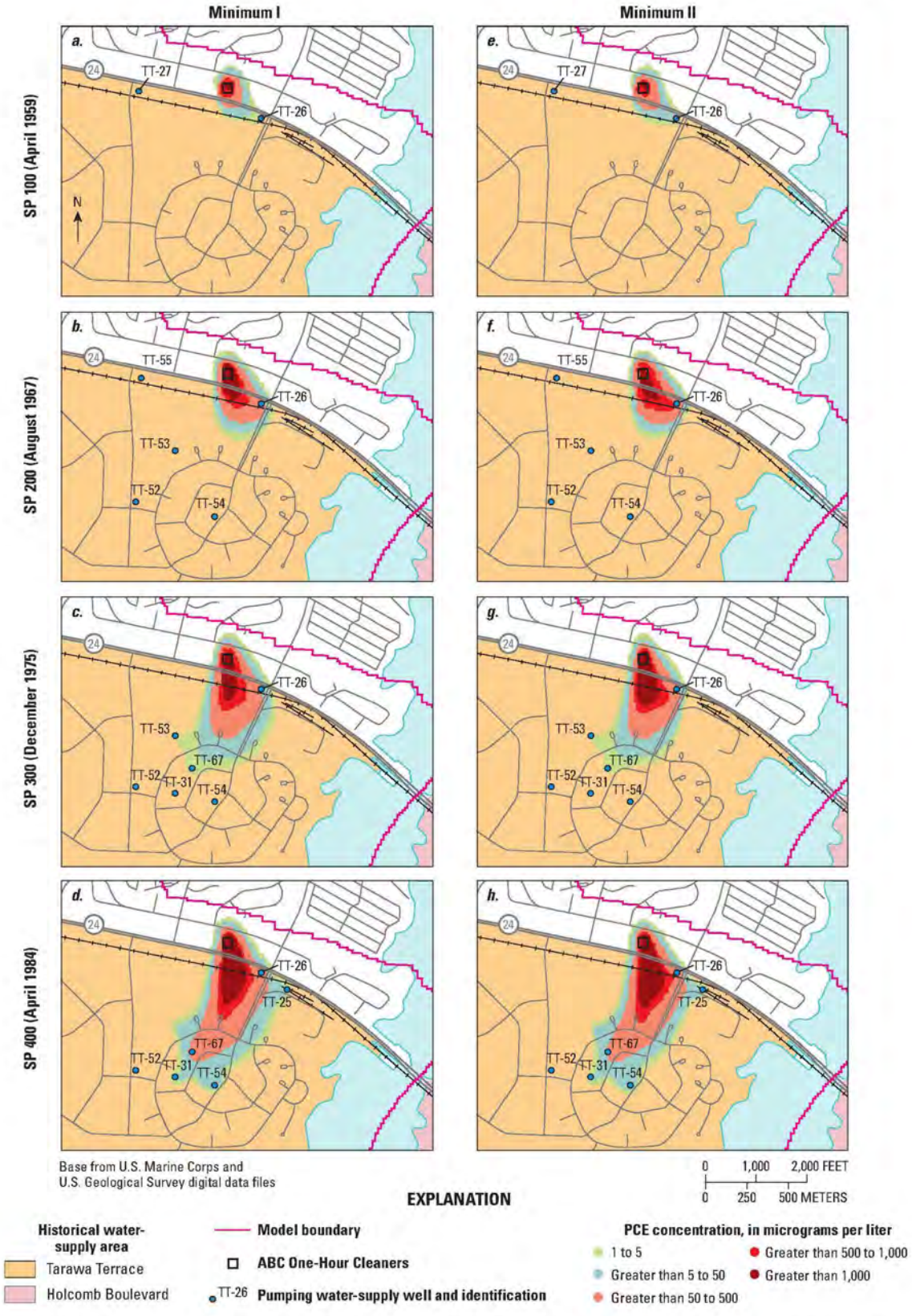

Figure H28. Comparison of tetrachloroethylene (PCE) distribution in model layer 3 under Minimum Schedule I for *(a)* SP 100, *(b)* SP 200, *(c)* SP 300, and *(d)* SP 400; and Minimum Schedule II for *(e)* SP 100, *(f)* SP 200, *(g)* SP 300, and *(h)* SP 400, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SP, stress period]

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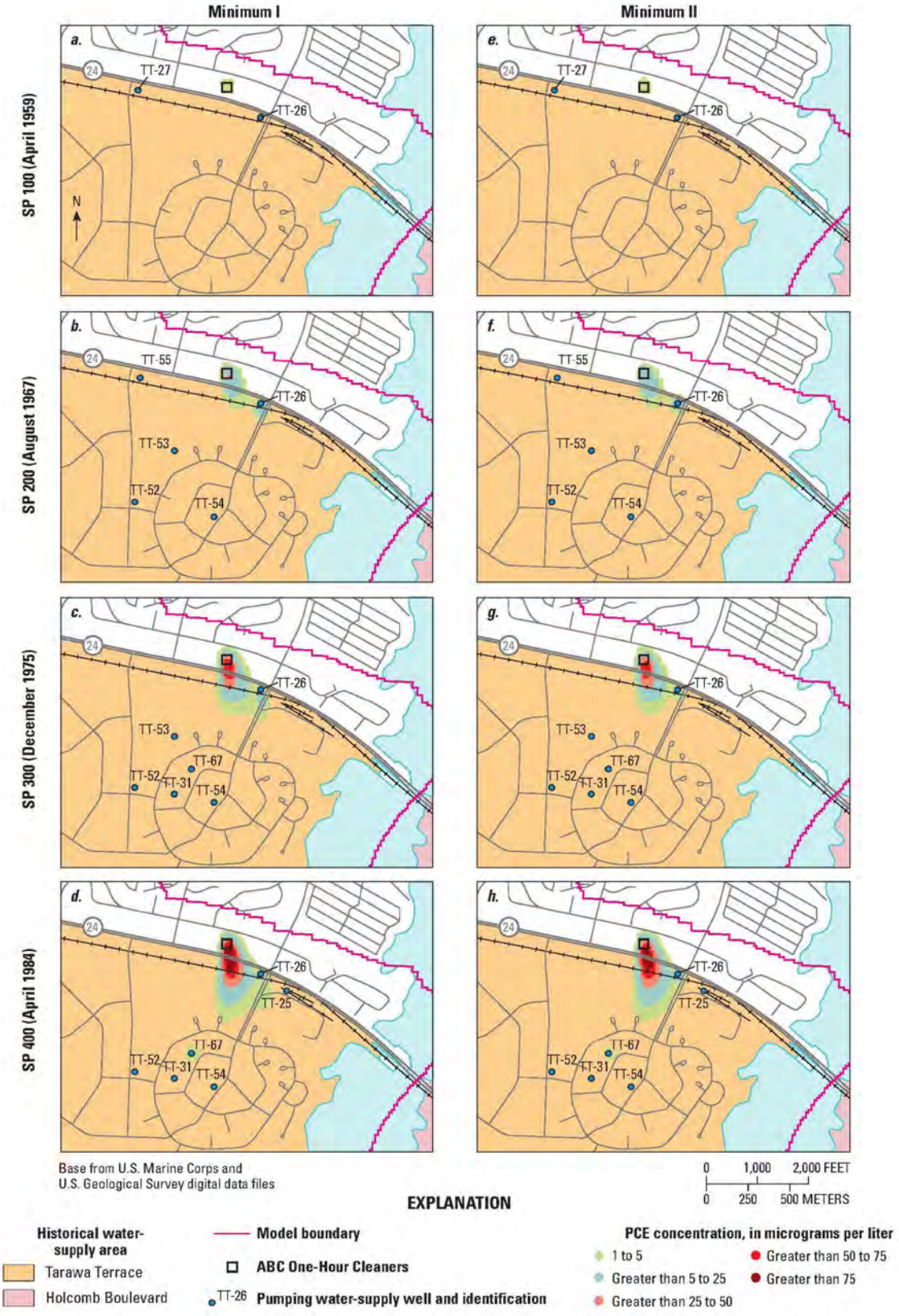

Figure H29. Comparison of tetrachloroethylene (PCE) distribution in model layer 5 under Minimum Schedule I for *(a)* SP 100, *(b)* SP 200, *(c)* SP 300, and *(d)* SP 400; and Minimum Schedule II for *(e)* SP 100, *(f)* SP 200, *(g)* SP 300, and *(h)* SP 400, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SP, stress period]

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PCE Concentration at Water-Supply Wells

Similar to results presented in Figures H19 and H20, PCE concentrations at water-supply wells which have PCE concentrations exceeding 5 µg/L are plotted in Figures H30 and H31 for Minimum Schedule II. A comparison of PCE concentrations at higher producing water-supply wells is shown in Figure H32.

Results summarized in Figures H30–H32 show that PCE concentration distribution at water-supply wells under Minimum Schedule II is similar to the distribution obtained under Minimum Schedule I. The differences for this case are: (1) PCE concentration at well TT-26 under Minimum Schedule II always exceeds PCE concentration obtained under Minimum Schedule I for most of the period of interest, and (2) PCE concentrations at wells TT-54A, TT-54B, TT-67A, and TT-67B are slightly lower than those obtained under Minimum Schedule I (Figure H32). This is because, as discussed in the previous section, continuous operation of well TT-26 yields a less dispersed PCE plume in the groundwater system and the contaminant plume is more directed toward well TT-26.

Higher PCE concentrations at well TT-26 cause a relatively early PCE MCL arrival time at this location. According to simulation results, PCE concentration at well TT-26 reached MCL during March 1959 under Minimum Schedule II, which is 5 months earlier than under Minimum Schedule I (August 1959). Thus, an earlier PCE MCL arrival time at the WTP is expected for Minimum Schedule II.

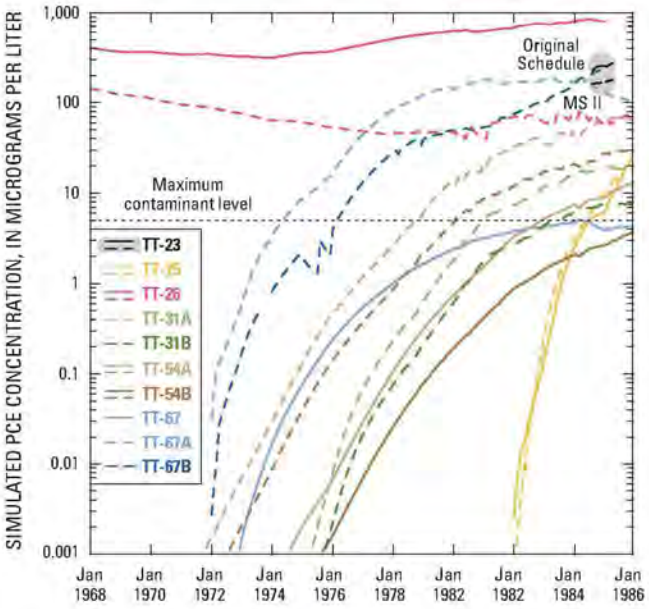

Figure H31. Simulated tetrachloroethylene (PCE) concentration at selected water-supply wells under the Original Schedule (solid line) and Minimum Schedule II (MS II, dashed line), period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [TT31A, TT-54A, and TT-67A, model layer 1; TT-31B, TT-54B, and TT-67B, model layer 3]

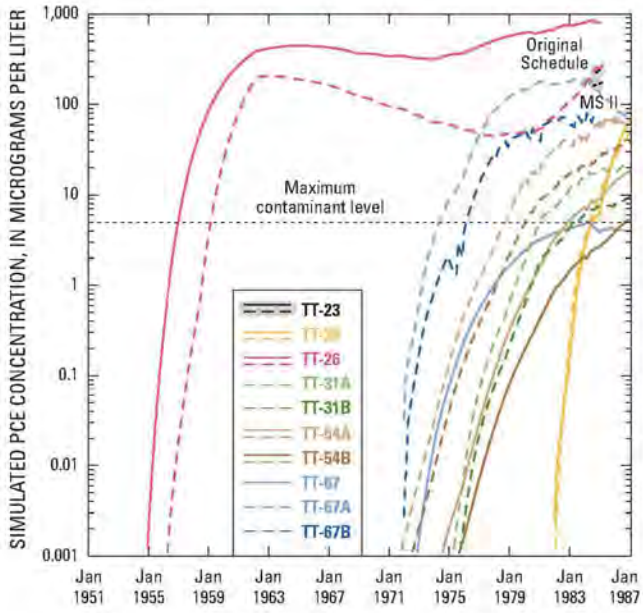

Figure H30. Simulated tetrachloroethylene (PCE) concentration at selected water-supply wells under the Original Schedule (solid line) and Minimum Schedule II (MS II, dashed line), Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [TT31A, TT-54A, and TT-67A, model layer 1; TT31B, TT-54B, and TT-67B, model layer 3]

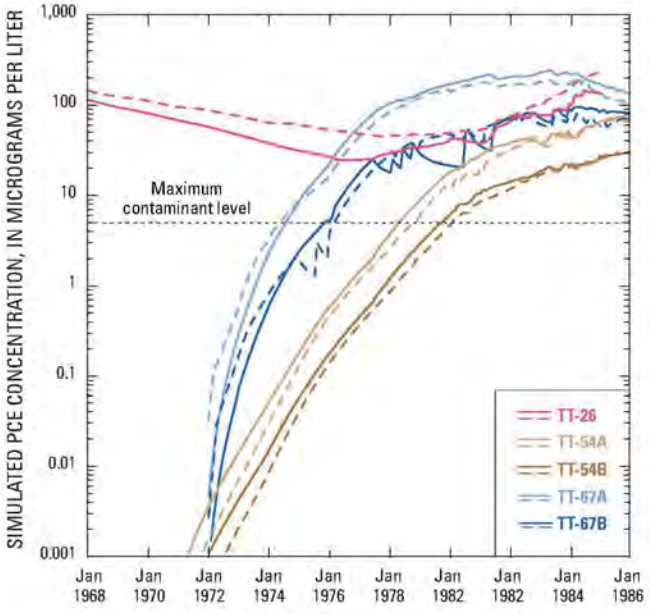

Figure H32. Simulated tetrachloroethylene (PCE) concentration at selected water-supply wells under Minimum Schedule I (solid line) and Minimum Schedule II (dashed line), period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [TT-54A and TT-67A, model layer 1; TT-54B and TT-67B, model layer 3]

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PCE Concentration at the Water Treatment Plant

PCE concentration at the WTP under Minimum Schedule II is shown in Figures H33 and H34. To illustrate the difference in PCE concentration between the two minimum schedules, PCE concentration obtained at the WTP under Minimum Schedule I also is shown in these figures.

Based on results presented in Figures H33 and H34, the following observations can be made:

1. PCE concentration at the WTP under Minimum Schedule II is lower than PCE concentration obtained under the Original Schedule except for the period after February 1985, which is similar to the Minimum Schedule I results.

2. PCE concentration at the WTP reaches 5 µg/L during February 1960 under Minimum Schedule II, which is 4 months earlier than obtained under Minimum Schedule I and a delay of 27 months when compared to the Original Schedule (November 1957).

3. Before January 1978, PCE concentration at the WTP under Minimum Schedule II is greater than PCE concentration obtained under Minimum Schedule I, but the difference is minimal after that time. This is because the pumping rate of well TT-26 under Minimum Schedule II after January 1978 is similar to that of Minimum Schedule I.

4. Due to the continuous pumping schedule of well TT-26 under Minimum Schedule II, PCE concentration at the WTP does not decrease below 1 µg/L; this also is observed under Minimum Schedule I. In fact, PCE concentrations at the WTP are greater than 5 µg/L most of the time after exceeding the MCL during February 1960, except for the period March 1970–September 1977.

The total mass of contaminant withdrawn from the groundwater system by water-supply wells under the three pumping schedules is listed in Table H10. PCE concentrations at the WTP for the three pumping schedules are listed in Table H11. Based on the results listed in Tables H10 and H11, it may be concluded that by forcing the pumping rate of well TT-26 to be at least 25 percent of its pumping capacity throughout the simulation period, when compared to Minimum Schedule I, about 72 percent more PCE mass is withdrawn by pumping wells under Minimum Schedule II. Furthermore, the average PCE concentration at the WTP for the period of interest is approximately 60 percent higher.

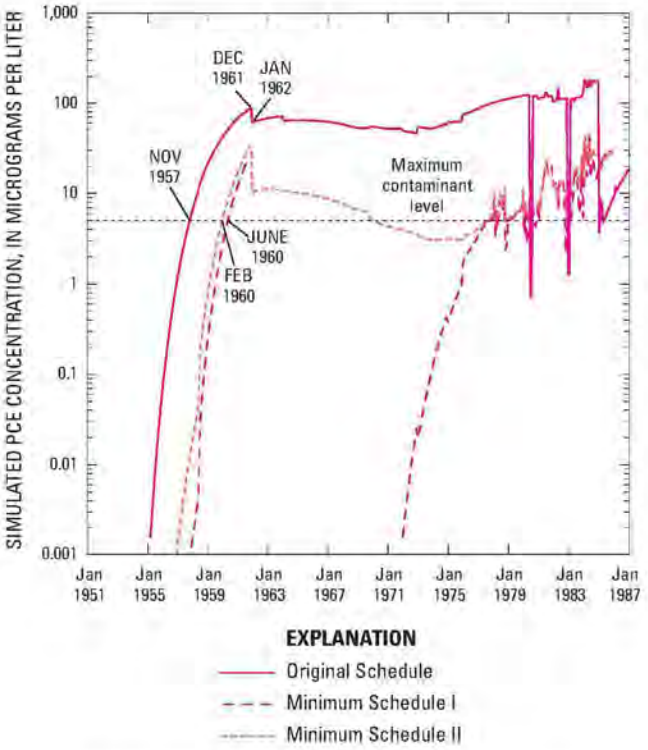

Figure H33. Simulated tetrachloroethylene (PCE) concentration at the water treatment plant under the Original Schedule (solid line), Minimum Schedule I, and Minimum Schedule II (dashed lines), Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

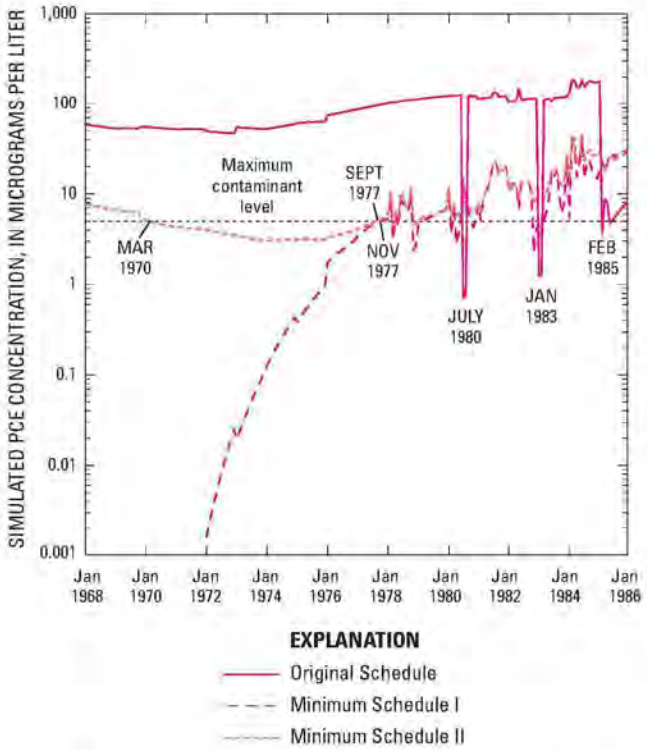

Figure H34. Simulated tetrachloroethylene (PCE) concentration at the water treatment plant under the Original Schedule (solid line), Minimum Schedule I, and Minimum Schedule II (dashed lines), period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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Table H10. Tetrachloroethylene mass withdrawn under the Original Schedule, Minimum Schedule I, and Minimum Schedule II, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

	Total mass released (gram)	Mass withdrawn (gram)	Percentage[1]
Original Schedule	1.40×10^{7}	2.45×10^{6}	17.50
Minimum Schedule I	1.40×10^{7}	1.98×10^{5}	1.41
Minimum Schedule II	1.40×10^{7}	3.41×10^{5}	2.44

[1]Percentage of mass withdrawn relative to total mass released

Table H11. Tetrachloroethylene concentration at the water treatment plant under the Original Schedule, Minimum Schedule I, and Minimum Schedule II for the period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter]

	Maximum[1] (µg/L)	Minimum[1] (µg/L)	Average
Original Schedule	183.04	46.69	86.39
Minimum Schedule I	41.36	7.84×10^{-8}	5.01
Minimum Schedule II	45.31	3.04	8.04

[1]Values for Original Schedule and Maximum Schedule occur during different stress periods

Summary of Simulation Results

Pumping Rate in Water-Supply Well TT-26

Based on results discussed in previous sections, it may be concluded that the pumping schedule variation causes significant changes in contaminant concentrations and MCL arrival times at water-supply wells and the WTP. In this case, the pumping rate in well TT-26 is critical to the PCE MCL arrival time because of its proximity to the contaminant source. The change of pumping rate in well TT-26 can cause PCE concentrations at the WTP to change from trace levels to amounts several orders higher than the MCL. The pumping rate percentage in well TT-26 relative to its pumping capacity under different pumping schedules is summarized in Figure H35. Figure H36 is plotted to give a clear view of the variation of the pumping rate in well TT-26 between 1976 and 1985.

Based on the results shown in Figures H35 and H36, the period January 1962–February 1976 is when the pumping rate in well TT-26 could have varied the most. This period also is consistent with the most variation of PCE concentrations that is observed at water-supply wells and the WTP under different pumping schedules. The periods when well TT-26 is out of service are consistent with the sudden declines of PCE concentration observed at the WTP under the Original Schedule and the Maximum Schedule.

From results presented in Figures H35 and H36, except for the first few months when pumping schedule has no significant effect on PCE concentration, well TT-26 is always being operated at its full capacity for early arrival simulations.

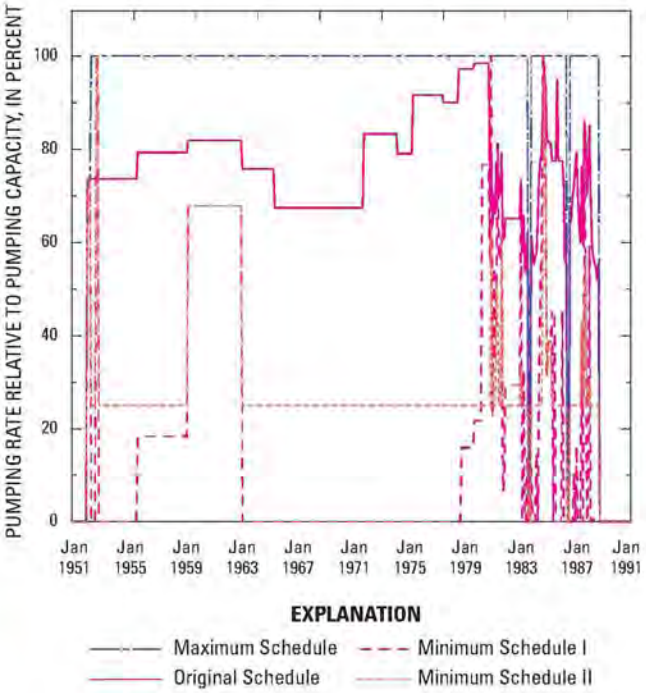

Figure H35. Percentage of pumping rate relative to its pumping capacity in water-supply well TT-26 under the Original Schedule (solid line) and updated pumping schedules (dashed lines), Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

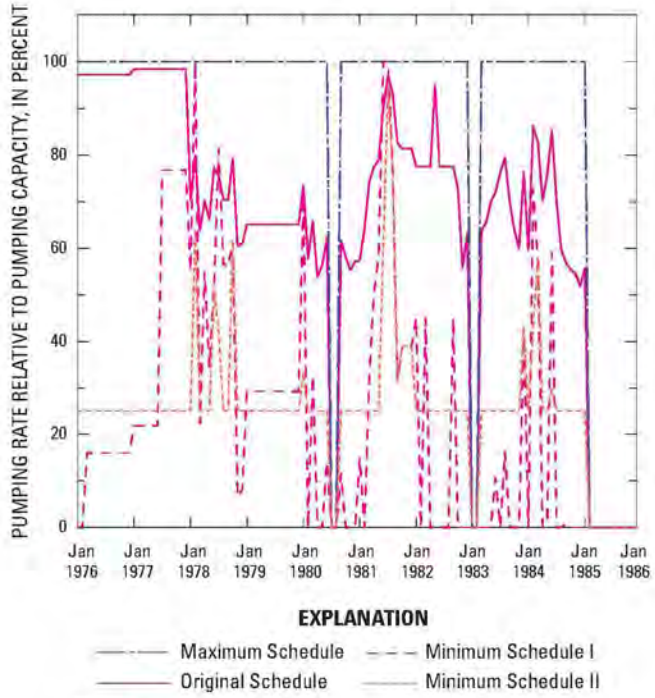

Figure H36. Percentage of pumping rate relative to its pumping capacity in water-supply well TT-26 under the Original Schedule (solid line) and updated pumping schedules (dashed lines), for the period 1976–1985, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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Under the Maximum Schedule, PCE concentration at well TT-26 is always much greater than other water-supply wells. Therefore, operation of well TT-26 at 100% capacity is required to obtain the maximum PCE concentration and the earliest arrival of PCE at the WTP. Under the two "late" arrival schedules, however, TT-26 is not pumping at the least possible rates for some stress periods near the end of the simulation. This occurs because in the second half of the simulation period for the "late arrival" cases, PCE concentration at well TT-26 is no longer the dominant source of contaminants.

All simulation results discussed here are based on pumping capacities used for this study, which limits maximum allowances for changes in pumping rates. If this limiting factor is not considered, pumping rates in water-supply wells may be changed without restriction, thus significantly affecting PCE concentrations and MCL arrival times. However, this would not be a realistic solution.

PCE Concentration at Water Supply Well TT-26

Simulation results for all three pumping schedules show that these schedules can cause changes in PCE distribution in the groundwater system, in PCE concentrations at water-supply wells and the WTP, and in PCE MCL arrival times. The comparison of PCE concentrations at water-supply well TT-26 under different pumping schedules is shown in Figure H37.

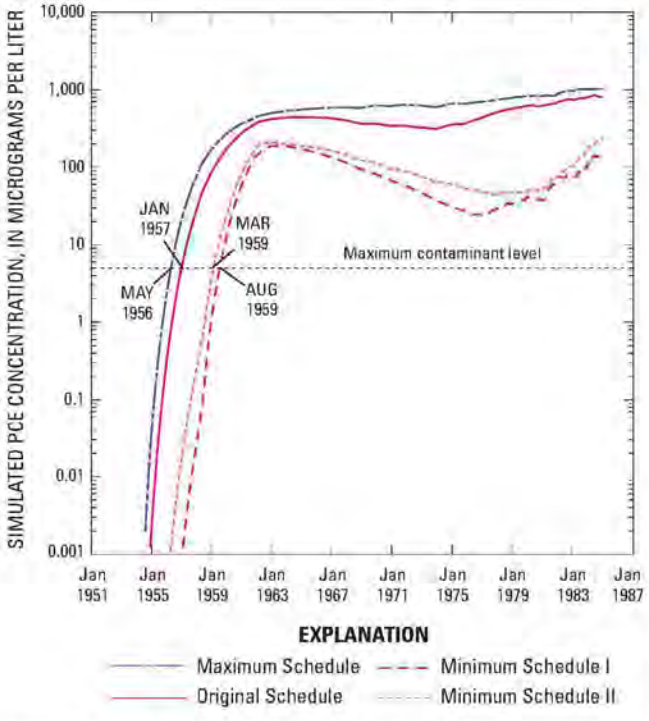

Figure H37. Simulated tetrachloroethylene (PCE) concentration at water-supply well TT-26 under the Original Schedule (solid line) and updated pumping schedules (dashed lines), Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

From results shown in Figure H37, it can be concluded that the earliest time for PCE concentration at well TT-26 to reach the 5 µg/L MCL is May 1956; the latest date is August 1959. This indicates that given hydrogeologic data—together with, and only with—a change of pumping schedules, the 5 µg/L arrival time of PCE at well TT-26 can vary from May 1956 to August 1959. This shows a 39-month variability between the "early" and "late" arrival dates. In this figure, the difference observed in the PCE MCL arrival time under Minimum Schedule I is greater than the one observed under the Maximum Schedule relative to the Original Schedule results. The reason for this is, as shown in Figure H35, the change of pumping rate in well TT-26 during the first half of the simulation period under Minimum Schedule I is greater than the change under the Maximum Schedule. Furthermore, the greater difference yields a more dispersed contaminant plume and a much lower PCE concentration at well TT-26. A summary of PCE concentrations and MCL arrival time at well TT-26 under different pumping schedules is listed in Table H12.

Table H12. Tetrachloroethylene concentration and maximum contaminant level arrival time at water-supply well TT-26 under the Original Schedule and updated pumping schedules for the period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter]

Pumping schedule	Maximum (µg/L)	Minimum (µg/L)	Average (µg/L)	Month and year
Original Schedule	851.19	312.62	490.62	January 1957
Maximum Schedule	1,023.32	585.98	738.40	May 1956
Minimum Schedule I	144.74	24.49	58.28	August 1959
Minimum Schedule II	243.00	44.32	85.49	March 1959

PCE Concentration at the Water Treatment Plant

PCE concentrations at the WTP calculated from different pumping schedules are shown in Figures H38 and H39. Figure H38 shows PCE concentrations at the WTP during the period January 1951–February 1987, while Figure H39 shows PCE concentrations at the WTP during the period of interest only.

Results shown in Figure H38 indicate that PCE concentration at the WTP could reach the 5 µg/L MCL as early as December 1956 or as late as June 1960. Compared to the PCE MCL arrival time at the WTP under the Original Schedule (November 1957), PCE concentration at the WTP could reach the MCL 11 months earlier or 31 months later.

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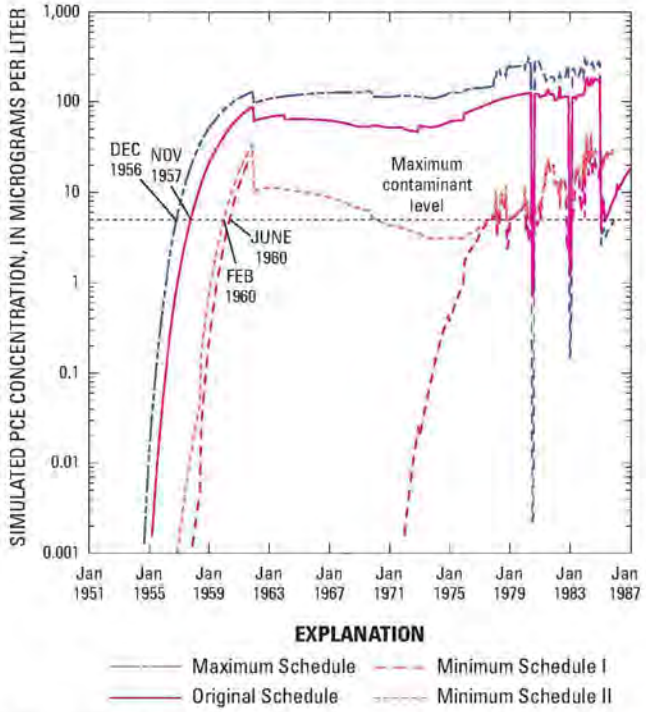

Figure H38. Simulated tetrachloroethylene (PCE) concentration at the water treatment plant under the Original Schedule (solid line) and updated pumping schedules (dashed lines), Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

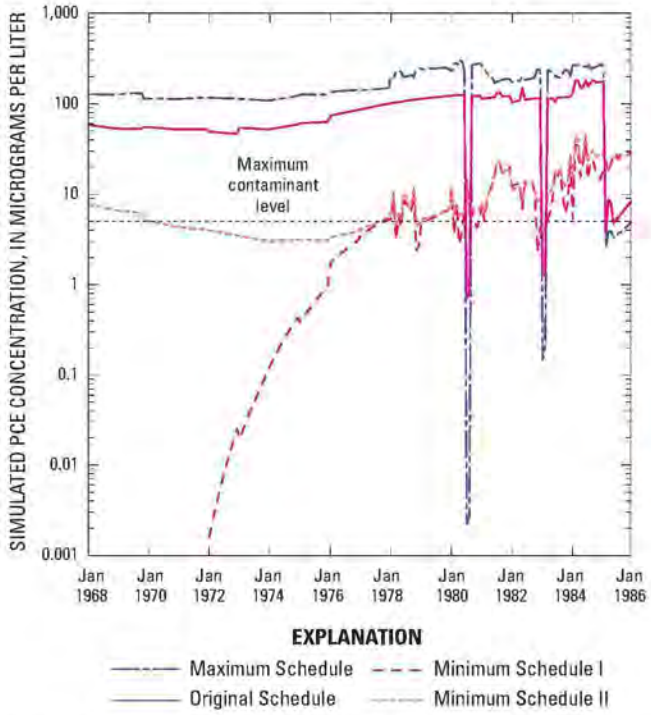

Figure H39. Simulated tetrachloroethylene (PCE) concentration in at water treatment plant under the Original Schedule (solid line) and updated pumping schedules (dashed lines), period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

These results are obtained without changing other calibrated model parameters that could affect the fate and transport of PCE in the subsurface and, thus, the 5-µg/L PCE MCL arrival time at the WTP. Therefore, the variation of pumping schedule has an important effect on PCE concentration at the WTP and on the MCL arrival time. A summary of maximum, minimum, and average PCE concentrations and MCL arrival times at the WTP under different pumping schedules is listed in Table H13.

Variation of pumping schedules also changes the amount of contaminant mass withdrawn from the groundwater system. A summary of PCE masses withdrawn under different schedules is listed in Table H14. In this table, the change of mass withdrawn from the groundwater system is quite significant.

Table H13. Tetrachloroethylene concentration and maximum contaminant level arrival time at the water treatment plant under the Original Schedule and the updated pumping schedules for the period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter]

Pumping schedule	Maximum (µg/L)	Minimum (µg/L)	Average (µg/L)	Arrival time
Original Schedule	183.04	46.69	86.39	November 1957
Maximum Schedule	304.66	108.76	166.07	December 1956
Minimum Schedule I	41.36	7.84×10^{-8}	5.01	June 1960
Minimum Schedule II	45.31	3.04	8.04	February 1960

Table H14. Tetrachloroethylene mass withdrawn under the Original Schedule and the updated pumping schedules, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Pumping schedule	Total mass released (gram)	Mass withdrawn (gram)	Percentage[1]
Original Schedule	1.40×10^{7}	2.45×10^{6}	17.50
Maximum Schedule	1.40×10^{7}	4.59×10^{6}	32.78
Minimum Schedule I	1.40×10^{7}	1.98×10^{5}	1.41
Minimum Schedule II	1.40×10^{7}	3.41×10^{5}	2.44

[1]Percentage of mass withdrawn relative to total mass released

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Summary and Conclusions

In this chapter of the Tarawa Terrace report series, the effect of pumping schedule variations on tetrachloroethylene (PCE) arrival times at water-supply wells and the Tarawa Terrace water treatment plant (WTP) is evaluated. Because of the large scale and complexity of the problem, a procedure was developed—identified as the Pumping Schedule Optimization System (PSOpS). This procedure is based on the simulation and optimization (S/O) approach. PSOpS was applied to optimize pumping schedules for evaluation of PCE maximum contaminant level (MCL) arrival time at the WTP. Final results indicate that PSOpS works well for this study and is computationally cost-efficient.

Simulation results presented in this study lead to the following conclusions:

1. Variation of pumping schedule has an effect on contaminant arrival time at water-supply wells. According to study results, a change in pumping schedules can cause changes in the contaminant plume distribution and the orientation of the plume front in the groundwater system. Changes in the contaminant transport characteristics lead to a variation of contaminant concentrations at water-supply wells. This is equivalent to the variation of contaminant arrival time at water-supply wells. For example, according to results presented herein, the arrival time of a 5-µg/L PCE concentration at well TT-26 varies from May 1956 to August 1959.

2. Variation of pumping schedule has an impact on the contaminant arrival time at the WTP, and this impact is twofold. The mixing-model equation indicates that PCE concentration at the WTP is calculated using PCE concentrations and pumping rates at water-supply wells. Therefore, a variation of pumping schedule changes the contaminant arrival time at the WTP by affecting both quantities of the mixing-model equation. Simulation results reported in this study indicate that the PCE MCL arrival time at the WTP varies from December 1956 to June 1960. This outcome is based on allowable changes to pumping schedules within the pumping capacity of each well.

3. Water-supply well TT-26 is critical for assessing the contaminant arrival time at the WTP. All simulation results show that by the time PCE concentrations at the WTP reach 5 µg/L, PCE concentrations at all water-supply wells, except well TT-26, are still negligible. This is due to some unique characteristics of well TT-26. First, well TT-26 is the closest water-supply well to the contaminant source, ABC One-Hour Cleaners. Second, well TT-26 is located in the downgradient groundwater-flow direction relative to the contaminant source. Third, well TT-26 has the longest pumping history among all water-supply wells. Therefore, increasing the pumping rate in well TT-26 can cause earlier contaminant arrival time at the WTP; conversely, reducing the pumping rate in well TT-26 can cause later contaminant arrival time at the WTP.

4. Variation of pumping schedule can cause a significant change in the amount of contaminant mass withdrawn from the groundwater system. Considering the total amount of water supplied to the WTP, a change in PCE concentration at the WTP caused by a variation in pumping schedule leads to a change in contaminant mass withdrawn. Given different pumping schedules derived in this study, the total PCE mass that was supplied to the WTP could vary from 1.41 to 32.78 percent of the total contaminant mass released from the contaminant source into the groundwater system at the site.

Based on optimal pumping schedules obtained from PSOpS, simulations have been conducted to demonstrate the effect of the pumping schedule variation on PCE arrival times at water-supply wells and the WTP. Analyses of simulation results indicate that a variation in pumping schedules can affect PCE arrival time. Considering this uncertainty factor, a change in pumping schedules yields the following outcomes according to simulation results: (1) PCE MCL arrival time at well TT-26 varies from May 1956 to August 1959, and (2) PCE MCL arrival time at the WTP varies from December 1956 to June 1960.

Acknowledgments

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The authors acknowledge the contributions of the USEPA, Region IV, Atlanta, Georgia, for providing reports and documents summarizing the results of investigations of groundwater contamination in the vicinity of ABC One-Hour Cleaners and in the northern part of Tarawa Terrace.

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Appendix H1. Simulation stress periods and corresponding month and year.

[Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Nov, November; Dec, December]

Stress period	Month and year	Stress period	Month and year	Stress period	Month and year	Stress period	Month and year	Stress period	Month and year	Stress period	Month and year
1	Jan 1951	49	Jan 1955	97	Jan 1959	145	Jan 1963	193	Jan 1967	241	Jan 1971
2	Feb 1951	50	Feb 1955	98	Feb 1959	146	Feb 1963	194	Feb 1967	242	Feb 1971
3	Mar 1951	51	Mar 1955	99	Mar 1959	147	Mar 1963	195	Mar 1967	243	Mar 1971
4	Apr 1951	52	Apr 1955	100	Apr 1959	148	Apr 1963	196	Apr 1967	244	Apr 1971
5	May 1951	53	May 1955	101	May 1959	149	May 1963	197	May 1967	245	May 1971
6	June 1951	54	June 1955	102	June 1959	150	June 1963	198	June 1967	246	June 1971
7	July 1951	55	July 1955	103	July 1959	151	July 1963	199	July 1967	247	July 1971
8	Aug 1951	56	Aug 1955	104	Aug 1959	152	Aug 1963	200	Aug 1967	248	Aug 1971
9	Sept 1951	57	Sept 1955	105	Sept 1959	153	Sept 1963	201	Sept 1967	249	Sept 1971
10	Oct 1951	58	Oct 1955	106	Oct 1959	154	Oct 1963	202	Oct 1967	250	Oct 1971
11	Nov 1951	59	Nov 1955	107	Nov 1959	155	Nov 1963	203	Nov 1967	251	Nov 1971
12	Dec 1951	60	Dec 1955	108	Dec 1959	156	Dec 1963	204	Dec 1967	252	Dec 1971
13	Jan 1952	61	Jan 1956	109	Jan 1960	157	Jan 1964	205	Jan 1968	253	Jan 1972
14	Feb 1952	62	Feb 1956	110	Feb 1960	158	Feb 1964	206	Feb 1968	254	Feb 1972
15	Mar 1952	63	Mar 1956	111	Mar 1960	159	Mar 1964	207	Mar 1968	255	Mar 1972
16	Apr 1952	64	Apr 1956	112	Apr 1960	160	Apr 1964	208	Apr 1968	256	Apr 1972
17	May 1952	65	May 1956	113	May 1960	161	May 1964	209	May 1968	257	May 1972
18	June 1952	66	June 1956	114	June 1960	162	June 1964	210	June 1968	258	June 1972
19	July 1952	67	July 1956	115	July 1960	163	July 1964	211	July 1968	259	July 1972
20	Aug 1952	68	Aug 1956	116	Aug 1960	164	Aug 1964	212	Aug 1968	260	Aug 1972
21	Sept 1952	69	Sept 1956	117	Sept 1960	165	Sept 1964	213	Sept 1968	261	Sept 1972
22	Oct 1952	70	Oct 1956	118	Oct 1960	166	Oct 1964	214	Oct 1968	262	Oct 1972
23	Nov 1952	71	Nov 1956	119	Nov 1960	167	Nov 1964	215	Nov 1968	263	Nov 1972
24	Dec 1952	72	Dec 1956	120	Dec 1960	168	Dec 1964	216	Dec 1968	264	Dec 1972
25	Jan 1953	73	Jan 1957	121	Jan 1961	169	Jan 1965	217	Jan 1969	265	Jan 1973
26	Feb 1953	74	Feb 1957	122	Feb 1961	170	Feb 1965	218	Feb 1969	266	Feb 1973
27	Mar 1953	75	Mar 1957	123	Mar 1961	171	Mar 1965	219	Mar 1969	267	Mar 1973
28	Apr 1953	76	Apr 1957	124	Apr 1961	172	Apr 1965	220	Apr 1969	268	Apr 1973
29	May 1953	77	May 1957	125	May 1961	173	May 1965	221	May 1969	269	May 1973
30	June 1953	78	June 1957	126	June 1961	174	June 1965	222	June 1969	270	June 1973
31	July 1953	79	July 1957	127	July 1961	175	July 1965	223	July 1969	271	July 1973
32	Aug 1953	80	Aug 1957	128	Aug 1961	176	Aug 1965	224	Aug 1969	272	Aug 1973
33	Sept 1953	81	Sept 1957	129	Sept 1961	177	Sept 1965	225	Sept 1969	273	Sept 1973
34	Oct 1953	82	Oct 1957	130	Oct 1961	178	Oct 1965	226	Oct 1969	274	Oct 1973
35	Nov 1953	83	Nov 1957	131	Nov 1961	179	Nov 1965	227	Nov 1969	275	Nov 1973
36	Dec 1953	84	Dec 1957	132	Dec 1961	180	Dec 1965	228	Dec 1969	276	Dec 1973
37	Jan 1954	85	Jan 1958	133	Jan 1962	181	Jan 1966	229	Jan 1970	277	Jan 1974
38	Feb 1954	86	Feb 1958	134	Feb 1962	182	Feb 1966	230	Feb 1970	278	Feb 1974
39	Mar 1954	87	Mar 1958	135	Mar 1962	183	Mar 1966	231	Mar 1970	279	Mar 1974
40	Apr 1954	88	Apr 1958	136	Apr 1962	184	Apr 1966	232	Apr 1970	280	Apr 1974
41	May 1954	89	May 1958	137	May 1962	185	May 1966	233	May 1970	281	May 1974
42	June 1954	90	June 1958	138	June 1962	186	June 1966	234	June 1970	282	June 1974
43	July 1954	91	July 1958	139	July 1962	187	July 1966	235	July 1970	283	July 1974
44	Aug 1954	92	Aug 1958	140	Aug 1962	188	Aug 1966	236	Aug 1970	284	Aug 1974
45	Sept 1954	93	Sept 1958	141	Sept 1962	189	Sept 1966	237	Sept 1970	285	Sept 1974
46	Oct 1954	94	Oct 1958	142	Oct 1962	190	Oct 1966	238	Oct 1970	286	Oct 1974
47	Nov 1954	95	Nov 1958	143	Nov 1962	191	Nov 1966	239	Nov 1970	287	Nov 1974
48	Dec 1954	96	Dec 1958	144	Dec 1962	192	Dec 1966	240	Dec 1970	288	Dec 1974

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Appendix H1. Simulation stress periods and corresponding month and year.—Continued

[Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Nov, November; Dec, December]

Stress period	Month and year	Stress period	Month and year	Stress period	Month and year	Stress period	Month and year	Stress period	Month and year
289	Jan 1975	337	Jan 1979	385	Jan 1983	433	Jan 1987	481	Jan 1991
290	Feb 1975	338	Feb 1979	386	Feb 1983	434	Feb 1987	482	Feb 1991
291	Mar 1975	339	Mar 1979	387	Mar 1983	435	Mar 1987	483	Mar 1991
292	Apr 1975	340	Apr 1979	388	Apr 1983	436	Apr 1987	484	Apr 1991
293	May 1975	341	May 1979	389	May 1983	437	May 1987	485	May 1991
294	June 1975	342	June 1979	390	June 1983	438	June 1987	486	June 1991
295	July 1975	343	July 1979	391	July 1983	439	July 1987	487	July 1991
296	Aug 1975	344	Aug 1979	392	Aug 1983	440	Aug 1987	488	Aug 1991
297	Sept 1975	345	Sept 1979	393	Sept 1983	441	Sept 1987	489	Sept 1991
298	Oct 1975	346	Oct 1979	394	Oct 1983	442	Oct 1987	490	Oct 1991
299	Nov 1975	347	Nov 1979	395	Nov 1983	443	Nov 1987	491	Nov 1991
300	Dec 1975	348	Dec 1979	396	Dec 1983	444	Dec 1987	492	Dec 1991
301	Jan 1976	349	Jan 1980	397	Jan 1984	445	Jan 1988	493	Jan 1992
302	Feb 1976	350	Feb 1980	398	Feb 1984	446	Feb 1988	494	Feb 1992
303	Mar 1976	351	Mar 1980	399	Mar 1984	447	Mar 1988	495	Mar 1992
304	Apr 1976	352	Apr 1980	400	Apr 1984	448	Apr 1988	496	Apr 1992
305	May 1976	353	May 1980	401	May 1984	449	May 1988	497	May 1992
306	June 1976	354	June 1980	402	June 1984	450	June 1988	498	June 1992
307	July 1976	355	July 1980	403	July 1984	451	July 1988	499	July 1992
308	Aug 1976	356	Aug 1980	404	Aug 1984	452	Aug 1988	500	Aug 1992
309	Sept 1976	357	Sept 1980	405	Sept 1984	453	Sept 1988	501	Sept 1992
310	Oct 1976	358	Oct 1980	406	Oct 1984	454	Oct 1988	502	Oct 1992
311	Nov 1976	359	Nov 1980	407	Nov 1984	455	Nov 1988	503	Nov 1992
312	Dec 1976	360	Dec 1980	408	Dec 1984	456	Dec 1988	504	Dec 1992
313	Jan 1977	361	Jan 1981	409	Jan 1985	457	Jan 1989	505	Jan 1993
314	Feb 1977	362	Feb 1981	410	Feb 1985	458	Feb 1989	506	Feb 1993
315	Mar 1977	363	Mar 1981	411	Mar 1985	459	Mar 1989	507	Mar 1993
316	Apr 1977	364	Apr 1981	412	Apr 1985	460	Apr 1989	508	Apr 1993
317	May 1977	365	May 1981	413	May 1985	461	May 1989	509	May 1993
318	June 1977	366	June 1981	414	June 1985	462	June 1989	510	June 1993
319	July 1977	367	July 1981	415	July 1985	463	July 1989	511	July 1993
320	Aug 1977	368	Aug 1981	416	Aug 1985	464	Aug 1989	512	Aug 1993
321	Sept 1977	369	Sept 1981	417	Sept 1985	465	Sept 1989	513	Sept 1993
322	Oct 1977	370	Oct 1981	418	Oct 1985	466	Oct 1989	514	Oct 1993
323	Nov 1977	371	Nov 1981	419	Nov 1985	467	Nov 1989	515	Nov 1993
324	Dec 1977	372	Dec 1981	420	Dec 1985	468	Dec 1989	516	Dec 1993
325	Jan 1978	373	Jan 1982	421	Jan 1986	469	Jan 1990	517	Jan 1994
326	Feb 1978	374	Feb 1982	422	Feb 1986	470	Feb 1990	518	Feb 1994
327	Mar 1978	375	Mar 1982	423	Mar 1986	471	Mar 1990	519	Mar 1994
328	Apr 1978	376	Apr 1982	424	Apr 1986	472	Apr 1990	520	Apr 1994
329	May 1978	377	May 1982	425	May 1986	473	May 1990	521	May 1994
330	June 1978	378	June 1982	426	June 1986	474	June 1990	522	June 1994
331	July 1978	379	July 1982	427	July 1986	475	July 1990	523	July 1994
332	Aug 1978	380	Aug 1982	428	Aug 1986	476	Aug 1990	524	Aug 1994
333	Sept 1978	381	Sept 1982	429	Sept 1986	477	Sept 1990	525	Sept 1994
334	Oct 1978	382	Oct 1982	430	Oct 1986	478	Oct 1990	526	Oct 1994
335	Nov 1978	383	Nov 1982	431	Nov 1986	479	Nov 1990	527	Nov 1994
336	Dec 1978	384	Dec 1982	432	Dec 1986	480	Dec 1990	528	Dec 1994

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ATSDR
AGENCY FOR TOXIC SUBSTANCES AND DISEASE REGISTRY

Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—Chapter H: Effect of Groundwater Pumping Schedule Variation on Arrival of Tetrachloroethylene (PCE) at Water-Supply Wells and the Water Treatment Plant

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EXHIBIT 35

IN THE UNITED STATES DISTRICT COURT
FOR THE EASTERN DISTRICT OF NORTH CAROLINA
SOUTHERN DIVISION
Civil Action No. 7:23-cv-00897

IN RE: CAMP LEJEUNE WATER LITIGATION

THIS DOCUMENT RELATES TO:
ALL CASES

VIDEOTAPED
DEPOSITION OF: MORRIS MASLIA
DATE: September 26, 2024
TIME: 9:22 a.m.
LOCATION: BELL LEGAL GROUP
219 North Ridge Street
Georgetown, SC

TAKEN BY: Counsel for the Defendants
REPORTED BY: Lauren A. Balogh, RPR

APPEARANCES OF COUNSEL:

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ALSO PRESENT:

Matthew Walters, Videographer

Justine Walters, Department of Health and Human Services
Deanna Havai, Motley Rice
(Via videoconference)

Alex Spiliotopoulos
(Via videoconference)
Mona Lisa Wallace
(Via videoconference)

(INDEX AT REAR OF TRANSCRIPT)

THE VIDEOGRAPHER: We're now on record. Today's date is September 26th, 2024 and the time is 9:22 a.m. This is the video deposition in regards to the Camp Lejeune water litigation Case No. 7:23-CV-00897 per the U.S. District Court for the Eastern District of North Carolina. Our deponent today is Morris Maslia.

THE WITNESS: Maslia.

THE VIDEOGRAPHER: Maslia. Thank you. Morris Maslia.

Will our court reporter please swear in our witness.

MORRIS MASLIA

being first duly sworn, testified as follows:

EXAMINATION

BY MR. ANWAR:

Q. Good morning, Mr. Maslia.

A. Good morning.

Q. I would like to -- and thank you for your patience while we worked out the technical issues. I would like to start by having you state and spell your full name for the record as well as provide your address.

A. Okay. My first name is Morris, M-O-R-R-I-S. Middle name Lavi, L-A-V-I. Last name

Maslia, M-A-S-L-I-A. My address is 3360 Norfolk, N-O-R-F-O-L-K, Chase, C-H-A-S-E, Drive, Peachtree Corners, Georgia 30092, USA.

Q. Thank you. My name is Haroon Anwar. I'm an attorney with the U.S. Department of Justice. I'm here to take your deposition today as it --

MR. ANWAR: It looks like it says the Zoom is muted. I'm sorry. Good?

MR. DEAN: Giovanni needs to turn off his mic.

MR. ANWAR: Okay. Good? All right.

BY MR. ANWAR:

Q. I'll start over. My name is Haroon Anwar. I'm here with the U.S. Department of Justice along with my colleague, Giovanni Antonucci. I'm here to take your deposition today related to the Camp Lejeune Justice Act Litigation. Do you understand that?

A. Yes, I do.

Q. Okay.

MR. DEAN: Before we go further, we really need to introduce ourselves on the record. This is Kevin Dean on behalf of the plaintiffs.

MR. ANWAR: Sure.

MS. BAUGHMAN: Laura Baughman on behalf of plaintiffs.

MR. ROBERTS: Jim Roberts appearing on behalf of the plaintiffs.

MR. DEAN: Can we also have identified on the record the DOJ attorneys present both on the record -- I mean, in the room and on the -- on the Zoom call, if any, and any representatives.

MR. ANWAR: I'm happy to do that. I think we had discussed just noting them on the stenographic record so we don't have to spend the time, but in the room is myself and my colleague, Giovanni Antonucci. Then on behalf of ATSDR here is Justine Walters. And then I don't have the list of everyone on the Zoom with me, but...

MR. DEAN: Is there any experts or other consultants with the DOJ appearing for this deposition?

MR. ANWAR: Yes, the same gentleman that appeared at the last deposition of Mr. Sautner.

MR. DEAN: Okay. And what was his name, remind me.

MR. ANWAR: It was Alex --

MR. DEAN: Yeah, Alex.

MR. ANWAR: Yeah.
MR. DEAN: I remember.
MS. BAUGHMAN: What's the last name?
MR. ANWAR: It's Spiliotopoulos.
MR. DEAN: Thank you.
MR. ANWAR: Okay. Good?
BY MR. ANWAR:
Q. Now, I understand that you've provided at least one deposition before, so you may -- you may know the rules already, so forgive me if I'm sort of repeating myself, but I just want to go over the basics of deposition taking or deposition -- for a deposition so that the deposition will be -- can be as smooth as possible today.
The first and foremost rule is that you are under the same oath to tell the truth as if you were in an actual court of law. Do you understand that?
A. Yes, I do.
Q. Okay. Is there any reason, as you sit here today, that you would be unable to testify truthfully?
A. No.
Q. Okay. If you don't hear me ask my question or if I ask a confusing question or an

unclear question, which is very likely given some of the topics we get into today, would you please let me know?

A. Yes.

Q. Okay. Otherwise, I'll assume you -- you understood my question, fair?

A. Fair.

Q. Okay. For the court reporter's sake, could you please respond verbally. The head nods and head shakes and those types of things just don't show up on the record.

A. Understood.

Q. Okay. And also for the court reporter's sake, can you please wait for me to finish my question before responding. That way our court reporter isn't trying to type people speaking over each other.

A. Yes, sir.

Q. Okay. Thank you. And finally, I think, you know, we'll be here at least for a couple of hours. If at any time you need a break, I'm happy to accommodate you. The only stipulation I would put on that, if there's a pending question, I would ask that you answer my pending question and then we can go ahead and take a break.

A. Understood.
Q. Thank you.
MR. ANWAR: Gio, can you go ahead and pull up the first exhibit.
(DFT. EXHIBIT 1, subpoena to testify at a deposition in a civil action, was marked for identification.)
BY MR. ANWAR:
Q. Okay. What is being shown on the screen now is --
MR. DEAN: Can we let it pause for just a second because it doesn't automatically show up in the folder.
MS. BAUGHMAN: Yeah, we don't --
MR. ANWAR: You don't have it?
MR. DEAN: We don't have it.
MR. ANWAR: Oh, okay.
MR. DEAN: You have to drop it to folder. Sometimes you have to refresh. Okay. I see the subpoena and the deposition.
MR. ANWAR: There should be two subpoenas and a deposition.
MR. DEAN: I see that now. Okay. We're good to go.
MR. ANWAR: Okay. Great.

MR. DEAN: So you just have to hit refresh on your screen and you should be good.

MS. BAUGHMAN: Right here.

MR. DEAN: Yep.

BY MR. ANWAR:

Q. So the first exhibit that I've put up for you or that we've put up for you, Exhibit No. 1, is the subpoena scheduling your deposition here today. Have you seen this before?

MR. DEAN: Hold on just a second. So show me which -- they're not marked as exhibit numbers, so which one are you referring to? Give me the file name. I'm going to pull it up on the screen for him.

MR. ANWAR: Oh, I've got you. It is the one described deposition subpoena.

MR. DEAN: There's two deposition subpoenas.

MR. ANWAR: There's a document subpoena and then a deposition subpoena.

MR. DEAN: Okay. So which -- you're using the depo?

MR. ANWAR: Correct.

MR. DEAN: Okay.

BY MR. ANWAR:

Q. You see it?

A. Yes, yes, sir.

Q. Okay. Have you -- have you seen the deposition subpoena before?

A. Could you just scroll to the bottom so I can them? Yes, yes, sir, I have.

Q. Okay. And you understand it's a subpoena that we're here today to -- it's the subpoena here that -- that brought you in today for today's deposition?

A. Yes.

Q. Okay. And you understand that we're here in connection with the Camp Lejeune Justice Act Water Litigation pending in the Eastern District of North Carolina?

A. Yes, sir.

Q. Do you understand that the United States has subpoenaed you for your testimony as a fact witness in your capacity as a former ATSDR employee?

A. Yes.

Q. Okay. In other words, I understand that you've been retained as a consultant for the plaintiffs, correct?

A. That is correct.
Q. Okay. So I'm here to ask you questions today related to your time as a government employee. Do you understand that?
A. I understand that.
Q. Okay.
MR. ANWAR: Gio, can you pull up Exhibit 2.
(DFT. EXHIBIT 2, subpoena to produce documents, information or objects or to permit inspection of premises in a civil action, was marked for identification.)
MR. DEAN: And if you want to, moving forward, either Giovanni can rename the file and add "EX1" in front of file name or -- which is what I did, or just read me the --
MR. ANWAR: Exhibit 2 is the deposition subpoena.
MR. DEAN: Okay. So just give me the -- the name of the file and I'll click on it and show it to him.
MR. ANWAR: Got it. Yeah.
MS. BAUGHMAN: You meant the document subpoena?
MR. ANWAR: I'm sorry. Yes, the

document subpoena. Kidding.

MR. DEAN: So I've got it up.

MR. ANWAR: Oh, you have it up. Okay.

BY MR. ANWAR:

Q. Do you see Exhibit 2, Mr. Maslia?

A. This looks like Exhibit 1 that you just showed me.

MR. DEAN: No, this is the deposition. One was a document subpoena.

THE WITNESS: Oh, okay.

MR. DEAN: This is a deposition subpoena.

THE WITNESS: Okay.

BY MR. ANWAR:

Q. And if you scroll down to the Attachment A, I'll represent to you, Mr. Maslia, that through the subpoena, the United States requested the production of a number of documents related to Camp Lejeune. And I will also note for the record that we received from your counsel a production -- an electronic production of roughly four thousand or so pages about a week and a half ago. And this morning we -- a hard copy -- a box, a banker's box full of hard copy documents was made available to us for inspection, so thank you for

producing that information.

Is that the information that you intended to produce in response to the government's document subpoena?

A. Yes.

Q. Okay. I just had a few questions about the documents in the bankers's box. It looked to me that the majority of the items in the banker's box were copies of the ATSDR water modeling reports related to Camp Lejeune. Is that your understanding as well?

A. Yes.

Q. Okay. There were a couple symposium papers in -- in the banker's box. Do you recall if those are publicly available or not?

A. They would be available, some of them, from the organization that made the presentation on their behalf --

Q. Okay.

A. -- that requested me to do that. I can't answer yes or no whether they're publicly available.

Q. Understood. And then there was -- on the back of the ATSDR water modeling reports there were some discs. The vast majority of the discs

appeared to be the original discs that would have been included with the reports; is that right?

A. That is correct.

Q. Okay. There was at least one disc in there that looked like it was a burned copy of a disc with some handwriting -- with handwriting on it. Do you know if that information would have been included with the original copy of the report?

A. I would have to see the report and the disc.

Q. Okay. I think maybe we can take a look at it at break, but we would formally request production of the symposium reports and the items on the handwritten discs.

MR. DEAN: At a break just point it out. I know what you're talking about, the presentations, but just point out to me the CD and maybe I can burn it while we're here today or something.

MR. ANWAR: Okay. Sounds good.

BY MR. ANWAR:

Q. I wanted to briefly ask you about your search process in terms of responding to the document subpoena. What did you do to gather documents to -- to produce in response to the

subpoena?

A. I had copies in my home basement office and so I pulled everything, all reports, with respect to Camp Lejeune, and then I was also instructed that you required the symposium presentation, so I actually printed those all off because I had them as, obviously, electronic versions.

Q. Understood. To the best of your knowledge, are there any documents that were requested by the subpoena that you haven't already produced or given to your counsel?

A. No.

Q. Okay. If you think of anything as we're talking today, would you let me know?

A. I will.

Q. Thank you.

How did you prepare for today's deposition?

A. I just reviewed my electronic versions of some of the Camp Lejeune reports that I was involved with as well as some of the more recent presentations that I made just to refresh my mind as to the concepts, the approaches, that we used.

Q. Understood. Are those -- those

presentations were produced in response to the subpoena, correct?

A. Yes.

Q. Thank you.

Did you review any other documents aside from the ones you just identified?

A. No.

Q. Did you meet with counsel?

A. Prior to the deposition?

Q. Correct.

A. No.

Q. In preparation for the deposition.

A. No.

Q. Did you meet with counsel this morning?

A. I saw him this morning.

Q. Okay. About how long did that meeting last?

A. About five minutes.

Q. And is that the only time that you've met with a lawyer to prepare for today's deposition?

A. I really did not meet with a lawyer to prepare for today's -- with an attorney to prepare for today's deposition.

Q. Okay. Okay. Did you bring any

documents with you asides from the documents in the banker's box?

A. No.

Q. I'm going to mark for the record Exhibit 3 as the signed Morris Maslia deposition.

(DFT. EXHIBIT 3, deposition of Morris Maslia dated June 30, 2010 Bates-stamped CLJA_HEALTHEFFECTS-0000049487 through 49712, was marked for identification.)

BY MR. ANWAR:

Q. Mr. Maslia, can you see Exhibit 3?

A. Yes.

Q. Okay. I will represent to you this is a copy of your deposition transcript -- or a copy of the transcript from your deposition on June 30th, 2010 in the Laura Jones versus United States matter.

Do you recall sitting for that deposition?

A. Yes, I do.

Q. Okay. And if you scroll to the very end of the document, close to the end, it's starting on --

MR. DEAN: Just give me the page number and I can --

MR. ANWAR: Yeah, it's starting on page 215 of the -- 226 of the PDF.

THE WITNESS: 187.

MR. DEAN: Huh?

THE WITNESS: It says 187 on there.

MR. DEAN: What's --

MR. ANWAR: Yeah, that's correct actually.

THE WITNESS: Oh, okay.

BY MR. ANWAR:

Q. 215 of the PDF, page 187, which you're looking at right now, did you have an opportunity to review your testimony from that deposition?

A. Yes.

Q. Okay. And you can feel free to look through the next few pages from 187 on. Is that your handwriting completing the errata or the correction sheet there for the deposition?

A. Yes, it is.

Q. And on the last page of the errata sheet, which is just 225 of the PDF, 197 of the document, at the bottom there, is that your signature at the bottom of the page?

A. Yes, that is my signature.

Q. Okay. And that prior deposition in

June 2010 in the Laura Jones matter, you gave that deposition under an oath to tell the truth as well, correct?

A. That is correct.

Q. Okay. And did you testify truthfully during that deposition?

A. Yes, I did.

Q. Okay. And do you stand by your prior deposition testimony today?

A. Yes, I do.

Q. And at that time in June 2010, when you sat for that deposition, were you employed by the ATSDR?

A. Yes, I was.

Q. And in June of 2010, ATSDR's water modeling efforts related to Tarawa Terrace would have been completed and the report published, correct?

A. That is correct.

Q. And as of June 2010, ATSDR's water modeling efforts related to Hadnot Point and Holcomb Boulevard would have been ongoing?

A. That is correct.

Q. Okay. Other than that prior -- and let me -- let me clarify. That was in the Laura Jones

matter, but that -- that case was also a Camp Lejeune case, correct?

A. It was never represented to me as to what case it was.

Q. Okay.

A. I was just requested to provide a deposition.

Q. Okay. And did you testify about your work at ATSDR related to Camp Lejeune?

A. Yes, I did.

Q. Okay. Other than that prior deposition, have you testified either in a deposition or a trial before?

A. No.

Q. So that was -- that's the only time that you've testified?

A. Yes.

Q. Okay. I am uploading --

MR. DEAN: Exhibit 4?

MR. ANWAR: Yes.

MR. DEAN: Okay.

MR. ANWAR: Actually upload both at the same time, but I'll identify Exhibit 4.

MR. DEAN: Maslia CV?

MR. ANWAR: Correct.

(DFT. EXHIBIT 4, resume for Morris L. Maslia Bates-stamped CLJA_ATSDR_BOVE_0000073110 and 73111, was marked for identification.)

BY MR. ANWAR:

Q. Mr. Maslia, you should have before you what is being marked as Exhibit 4. Is that a copy of your CV at least as of January 2018?

A. Could you scroll to the bottom of the page so I can see the date on it?

Q. Sure.

A. Yes, that is correct.

Q. And feel free to -- to look through the entire CV. There's two pages.

MR. DEAN: Yeah, so I'll just have to work --

THE WITNESS: That's fine.

MR. DEAN: Okay.

THE WITNESS: Okay. That's actually -- I need to correct that. That's actually a resume.

BY MR. ANWAR:

Q. It's a resume. Okay.

A. I distinguish between a CV and a resume.

Q. How -- in your mind, how do you distinguish between a resume and a CV?

A. A resume should be no longer than two pages, whereas, a CV can be 10, 20, 30 or multiple tens of pages and it provides more specificity on publications, on job activities, and stuff like that. It's more detailed.

Q. Understood. As of January 2018, would this have been a true and accurate copy of your resume?

A. Yes, it would have.

Q. Do you also maintain a CV separately?

A. Yes, I do.

Q. Do you have an updated version of your CV available?

A. Not with me on my person, but there is an updated CV.

Q. Okay. If we were to -- and I'll make the record on the record. We will request a copy of that CV. Would you be willing to produce it to us?

A. Yes.

Q. Okay.

MR. DEAN: No objection.

BY MR. ANWAR:

Q. And given that this is a resume and it's abbreviated from your CV, I assume there are

experiences and presentations and articles and things like that that are not reflected on this resume; is that right?

A. That is correct.

Q. Okay. Let's go ahead and mark -- show you Exhibit 5, which is a copy of your LinkedIn profile.

(DFT. EXHIBIT 5, LinkedIn profile page for Morris L. Maslia, was marked for identification.)

BY MR. ANWAR:

Q. Can you see Exhibit 5, Mr. Maslia?

A. I see it on the screen.

Q. Oh, it's also up there. Okay. Yeah scroll to the end.

I'll represent to you that I printed this a week or so ago on 9/20, it looks like, so less than a week ago. Is this a true and accurate copy of your current LinkedIn profile?

A. It appears to be.

Q. Okay. And are there experiences, articles, presentations, those types of things that are not necessarily reflected on your LinkedIn profile?

A. Yes.

Q. But those would be reflected in your CV?

A. That is correct.

Q. Okay. I would like to talk to you a little bit about your -- your educational background. As I understand it from your prior testimony and just the -- the resume and LinkedIn, you graduated with a bachelor's of civil engineering from Georgia Tech?

A. That's correct.

Q. And you graduated in 1976?

A. That is correct.

Q. Did you have a particular focus?

A. Not under the bachelor's degree other than general civil engineering.

Q. Did you do any modeling course work in your undergraduate study?

A. Yes.

Q. Could you tell me about that?

A. We did some basic fluid mechanics. We would call it modeling using numerical methods to represent mathematical equations. We also did some open channel flow.

Q. Understood. Anything else that comes to mind?

A. Not in the undergraduate.
Q. Did you complete any sort of, like, senior year thesis or capstone paper?
A. They did not have a senior year thesis for the undergraduate degree at Georgia Tech.
Q. Understood. Then I see you also graduated from Georgia Tech with a master of science in civil engineering; is that right?
A. That is correct, sir.
Q. And it looks like you graduated in 1980?
A. Yes.
Q. Did you have a particular focus in your master's program?
A. Yes, it was water resources, fluid mechanics, numerical analysis.
Q. Did you perform any sort of modeling course work in your master's program?
A. Yes, I did.
Q. Can you tell me about that?
A. I worked with and actually developed what's referred to as a very -- variably saturated or saturated/unsaturated flow model.
Q. Can you describe for me the unsaturated versus saturated flow model that you developed?

A. It's fully described in my thesis some 40 -- 50 years ago, however, very briefly --

Q. Sure.

A. -- going down from land surface before you hit the water table, which is referred to the saturated zone below that, there's an unsaturated zone that contains air, vapor and some water particles, and that's a more complex analysis than just looking at the water table and going below the water table.

Q. Understood. Thank you.

Is your -- you said your thesis related to that model?

A. Yes, yes, it related to a numerical model developed for that.

Q. Was your thesis published?

A. Yes, it was.

Q. Do you know if that publication is publicly available?

A. It should be publicly available from the Georgia Institute of Technology.

Q. Understood. Did you -- I understand that Mustafa Aral, was he one of your professors?

A. Yes.

Q. Did he publish that paper with you?

A. Not the thesis. That's under the graduate student's name.

Q. Okay. I saw a number of articles that you have published with Professor Aral or Dr. Aral.

A. Right.

Q. And so your thesis related to the model you just described, correct?

A. That is correct.

Q. Okay. And as I understand it, you do not have a doctorate or Ph.D. degree?

A. I do not. I took course work, but I did not complete the doctoral dissertation.

Q. Understood. How much course work did you complete towards the Ph.D.?

A. All of the required one, which I believe is at least 80. Back then it was quarter hours.

Q. And did you have a particular focus with respect to the -- the Ph.D. courses that you took?

A. Again, it was a greater emphasis on water resources, environmental fate and transport, and numerical modeling.

Q. And I think a moment ago you stated that you did not complete the Ph.D. thesis,

correct?

A. That is correct.

Q. Did you publish any other papers or articles coming out of your graduate level Ph.D. work?

A. I did as part of my job with the Federal Energy Regulatory Commission around 1980.

Q. Okay.

A. There were a couple of articles.

Q. Would all of those articles be reflected on your CV?

A. Yes.

Q. Okay. Are you familiar with the textbook Applied Groundwater Modeling: Simulation of Flow and Advective Transport by Mary Anderson?

A. Yes, I am.

Q. Okay. I believe the authors listed -- listed on it are Mary Anderson, William Woessner, and Randall Hunt; does that sound right?

A. That sounds right.

Q. Okay. Would you agree that textbook is established as a reliable authority in the field of groundwater modeling?

MR. DEAN: Object to the form of the question.

THE WITNESS: I could not say one way or the other.

BY MR. ANWAR:

Q. Okay. Have you -- have you reviewed or used that textbook before?

A. I've -- I've used it as a reference.

Q. And what have you used it as a reference for, in what context?

A. General modeling applications to -- if I'm searching for a particular technique or if someone else has used a technique and what their opinion of that technique is.

Q. Can you recall any specific examples where -- where you've referenced that textbook?

A. Not at this time, no.

Q. Are you familiar with any of the authors of that textbook?

A. I'm familiar with Dr. Mary Anderson.

Q. Do you know her?

A. I have met her professionally at a conference a number of years ago.

Q. Have you -- have you worked with her at all?

A. No, I have not.

Q. Do you respect her in the field of

groundwater modeling?

A. Yes, I do.

Q. Are you familiar with the textbook Modeling Groundwater Flow and Contaminant Transport by Jacob Bear and Alexander Cheng?

A. Yes.

MR. DEAN: Hold on. So I'm going to allow you, if you're going to continue to do this, if you'll give me a continuing objection. My problem is you're not designating a time frame with respect to your question. So to -- to the extent, as you know, he's been retained by the plaintiffs as our consulting expert since July the 15th of 2022. And to the extent you're asking him any questions that relate to that time period, from that time to the present, I make an objection. I'm not instructing him not to answer the question or anything like that, but I'm just saying, you know, this is not related to the facts of what went on with regard to his deposition.

MR. ANWAR: Sure. And I will give you that objection and I will -- a couple of things. One -- well, I'll rephrase the question, but if we could sort of limit the speaking objections, I would appreciate it as well.

MR. DEAN: Yeah.

BY MR. ANWAR:

Q. So understanding that you've been retained as a consultant for the plaintiffs in the litigation I believe as of June 2022, I'm not interested in what you've reviewed or what you've discussed with them from June 2022 forward, but prior to your retention as a consultant with the plaintiffs in the litigation, have you reviewed the textbook Modeling Groundwater Flow and Contaminant Flow by Jacob Bear and Alexander Cheng?

A. I've seen that -- that particular book. I've used other books by Jacob Bear.

Q. Okay. So you're familiar with it?

A. Yes.

Q. Would you consider that textbook as a reliable authority in the field of groundwater modeling?

MR. DEAN: Object to the form of the question and I am going to instruct him -- I'm going -- I'm not going to instruct him not to answer the question, but, again, you're not asking him questions about facts in this case. You're asking him about whether or not he has a current day opinion on whether some particular periodical

is reliable.

So I'm going to not instruct him to answer the question, but I thought we had an agreement that -- and I did it with Dr. Rennix. So you're asking him about something he -- a current opinion and that is not what we agreed to.

MR. ANWAR: And Kevin, your objection is noted and I'm going to ask you to limit your speaking objections. Mr. Maslia is here to testify, not you. And I will rephrase my question.

BY MR. ANWAR:

Q. Prior to your involvement in this litigation as a consultant, would you have considered that textbook as a reliable authority in the field of groundwater modeling?

A. Not that particular textbook.

Q. Okay. Why not?

A. There are other textbooks that not only I, but many, many other people rely on that are considered more classic textbooks in groundwater hydrology and modeling.

Q. And again, I'm asking about your personal knowledge --

A. Yes.

Q. -- prior to your involvement --

A. Yes.
Q. -- as a consultant in this litigation. So with that qualification, what are some of those other textbooks?
A. There's Dynamics of Fluids by Jacob Bear. And then there's Groundwater Hydraulics by Jacob Bear. And then there's, I think, also Groundwater Hydrology or Hydraulics, I don't remember exactly, by Freeze and Cherry.
Q. Okay. And prior to your -- your retention as a consultant for the plaintiffs, would you have considered those reliable authorities in the field of groundwater modeling or modeling generally?
MR. DEAN: Object to the form of the question.
THE WITNESS: Reliable textbooks that I would use to refer if I had groundwater or geohydrology questions, they do contain sections on modeling, but I would not necessarily call them a modeling book.
BY MR. ANWAR:
Q. Understood. Do you know Jacob Bear?
A. I don't know him personally.
Q. But you're familiar with him through

his work?

A. Yes.

Q. Do you respect him in the field of groundwater modeling?

A. Yes.

Q. Do you know Alexander Cheng?

A. No, I do not.

Q. Shifting gears a little bit, I want to talk about your -- your professional background. As I understand it, you -- you started out your career as a research hydrologist at the United States Geological Survey in 1980; is that right?

A. That is not correct.

Q. Okay. Well, please correct me.

A. I started as a hydraulic engineer with the Federal Power Commission in Washington D.C. in 1976.

Q. Okay.

A. Then I transferred to their office in at Atlanta and the agency name became Federal Energy Regulatory Commission. And then in 1980 I transferred as a hydrologist to the U.S. Geological Survey.

Q. Understood. Thank you for that clarification. For that position in 1976 to 1980,

remind me, what was the title of the position?

A. I was a hydraulic engineer, part of the civil engineering series in the government.

Q. What were your -- like, what was your role and what were your responsibilities as a hydraulic engineer?

A. The agency was a regulatory agency to inspect private hydroelectric dams that produced power, so we would inspect those dams and do analyses on the structural competency of those dams.

Q. Understood. Did you do any modeling in that role from '76 to '80?

A. I did one model with respect to using my master's dissertation on a dam in Georgia.

Q. Can you tell me about that model?

A. It was the saturated/unsaturated flow model, and one of the concerns of hydraulic engineers is when you build a dam, when you fill it or lower the reservoirs, that it becomes unstable based on pressures. So we did an analysis of Wallace Dam owned by the Georgia Power Company just for -- looking at the safety factors.

Q. How did you use that model to help you look at the question that you just described?

A. Well, you use measured water levels, field conditions, and then change some condition based on whether they're filling the reservoir or emptying the reservoir, you put in soil properties into the model and then the model produces results. And in the case of this model it produces pressures and hydraulic heads and then you can determine if those are exceeding or not exceeding certain factors that would make the dam safe or unsafe.

Q. And do you make that determination by comparing sort of data that you collect along the way to the predictions of the model?

A. That is correct, but we did not collect the data. That was obtained from the Georgia Power Company.

Q. Would that model be fairly described as a forecasting model?

A. It was applied to the present conditions of the day, okay, so it did not go out in time, which is what I would consider it a forecasting model.

Q. Understood. You said it was applied to the present conditions and time, so it would not have been a hindcasting or reconstruction either, correct?

A. That is correct.
Q. Did you do any other work related to models in that role from 1976 to '80?
A. No.
Q. Okay. And then in 1980, did you join the U.S. Geological Survey as a research hydrologist?
A. I joined in 1980 as a hydrologist. And then you had the opportunity based whether you wanted to take administrative track or a research track to be reclassified under the Office of Personnel Management's Research Grade Evaluation program. And so probably two or three years later I was promoted under the Research Grade Evaluation program based on publications and other criteria that that -- that RGE program requires.
Q. Understood. And were you promoted to research hydrologist?
A. Yes.
Q. How long did you work at the U.S. Geological Survey?
A. From 1980 to, I believe it was, 19 -- November of 1989.
Q. And could you describe for me sort of at a high level what you did in that role during

that time?

A. I did groundwater analyses using modeling techniques.

Q. Okay. Can you provide me with specific examples of the ways in which you used modeling techniques in relation to groundwater?

A. I was working on a congressionally funded project called the Regional Aquifer-Systems Analysis program or RASA that U.S. Geological Survey was doing all over the country. And being in the southeast we were looking at sections of the Florida aquifer system. And so we applied finite difference groundwater flow models to southwest Georgia and northwest Florida.

Q. And what was the purpose of using the model in that context with respect to the work you were doing in Florida and southwest Georgia?

A. To establish predevelopment conditions going back to the late 1800s of groundwater levels. And then also to establish, at that time, present day, which would have been about 1980 to '84 or '85, the current groundwater level conditions after the onset of pumping.

Q. Did you actually use that model to, I guess, reconstruct conditions all the way back to

1800?

A. We used data that was -- that was available back then because of artesian wells that's included as part of the model.

Q. Okay. Can you explain for me how you use that data to look back to 1800?

A. Well, you need to start a model at a starting point where you know what the water levels are. So if there was no pumping going on and you had reports through the literature, through historical documents, of people seeing water levels going ten feet above land surface or 20 feet above land surface, you can use that as an estimate to estimate predevelopment conditions along with the aquifer properties.

Q. Was there data available going back in time to the 1800s?

A. There's sparse data, but there are some data points, yes.

Q. Understood. And what did you ultimately use that model for again?

A. To assess the water resources conditions for the present time, which I'm referring to, you know, the 1980s. There was a question in some of the areas in northwest Florida

as to how much drinking water would be available for future use 20, 30, 50 years out. There was a question in southwest Georgia as to how much more available agricultural land that they could irrigate by installing additional water supply wells.

Q. Would it be fair to characterize -- or would it be fair to characterize the use of that model as a sort of planning tool or urban sort of planning development tool?

A. It would be a planning tool.

Q. Okay. Did you perform any other work related to modeling in your role with the USGS?

A. Yes, I did.

Q. Can you tell me about that?

A. I conducted, along with a colleague, studies at Hyde Park, New York, which is part of the Love Canal/Hyde Park superfund area. We were requested to assist the USEPA in determining the time it would take a water particle that had been contaminated to travel from the Hooker chemical landfill to the Niagara gorge.

Q. Understood. Can you describe for me a little bit how you were able to do that using the modeling techniques or a model?

A. Well, my -- my colleague had been a geohydrologist with USGS in the early 1960s when they were actually digging the power canals there, so he observed and witnessed water where water was coming out and the geology. And so we put that into the model. Obviously we were 20 years later. And then we had some current, at the time, water level measurements, and so we adjusted model parameters, hydraulic conductivities, soil saturation properties to come up with, you know, the current conditions.

Q. Would it be fair to characterize that model, the Hyde Park model, as a planning tool as well?

A. No, I would -- I would consider it a -- an analysis tool, okay? It's -- because we were not requested to do any planning.

Q. You were -- when you say you would describe it as an analysis tool, what were you analyzing?

A. We were requested by USEPA to determine how long it would take a water particle assuming, the water particle was contaminated, to travel along a flow path from -- from a landfill to the Niagara gorge.

Q. Would it be fair to characterize that model as a predictive model because you are planning --

A. Yes, that would have been a predictive model.

Q. Understood. Any other work related to models in your role at USGS?

A. Yes, I started to work on a model of Brunswick, Georgia. They had some chloride contamination, natural chloride coming up from the Floridan aquifer going to industrial pumping right along the coast and the barrier islands in Georgia.

Q. And what was the intended purpose of that model?

A. The intended purpose was to help the state of Georgia plan as to how much more water could be withdrawn from the Florida aquifer. How many more wells they could permit. How much more industry could withdraw.

Q. Would it be fair to characterize that model as a planning tool as well?

A. Yes.

Q. You're -- you're sort of looking into the future, right?

A. Yes.

Q. Any other work with modeling in -- during your time at USGS?

A. No.

Q. As I understand it from your prior deposition, you -- you went from USGS -- you left that role in 1989 and you joined Geosyntec Consultants; is that right?

A. That is correct.

Q. And the position I saw, I think, either in the deposition or in your -- your resume was manager of the water resources group; is that right?

A. That is correct.

Q. And you were at Geosyntec Consultants from 1989 to 1992?

A. Probably closer to -- from 1990 through 1992.

Q. Thank you.

What did you do in that role as water resource -- as a manager of water resources group at Geosyntec?

A. I established a library of model -- model codes publicly available and things like that, so the engineers at Geosyntec, if they had a reason to need modeling, they would be there

available to them.

Q. When you say you established a library of model codes, does that mean you collected existing codes or did you actually develop new codes?

A. No, I collected existing codes.

Q. Do you recall just some examples of the types of codes you collected for that library?

A. I really do not for that particular --

Q. Fair enough.

A. -- job that I had.

Q. Did you do any work related to modeling when you were at Geosyntec?

A. Yes, I did.

Q. Can you tell me about that?

A. We looked at a landfill, a proposed landfill area in Cinnaminson, New Jersey.

Q. How did you use modeling in that context?

A. Again, the client wanted to use the area as a landfill, and as most states, the jurisdictions have a regulation that the water table cannot come within a certain number of feet below a landfill liner. So the question was we had to determine what would the water -- what would the

altitude of the water table be below the liner given a high rainfall season, a low rainfall season, things like that.

Q. Was that model intended to be used as a planning tool as well?

A. Yes.

Q. Because it was looking into the future?

A. It was looking into current conditions and then predicting how many wells would be needed to -- to take the water out to keep the water table below the landfill liner.

Q. Understood. Did you do any other work related to modeling in your role at Geosyntec?

A. No.

Q. And as I understand it, you -- you left Geosyntec in 1992 and that's when you joined ATSDR, correct?

A. That is correct.

Q. And for the purposes of the record, what does ATSDR stand for?

A. It stands for the Agency for Toxic Substances and Disease Registry.

Q. Okay. And how would you describe ATSDR, its role?

A. Under CERCLA they are mandated to be a

scientific agency to look at potential health effects resulting from people living near landfills or ingesting contaminated media. They also are responsible for producing toxicological profiles.

Q. The work that ATSDR does in looking at particular health effects or chemicals, I think you mentioned toxic profiles, how does that work get used?

A. I can't speak to the toxic profiles because that was not the division I was in nor my expertise.

Q. Understood. As it relates -- so that's a good point. Let's -- what was your role when you joined ATSDR?

A. I was brought in as a civil engineer in the Division of Health Assessment and Consultations.

Q. Okay. And what is a civil -- what are the responsibilities of a civil engineer in, you said, health assessment consultations --

A. Right, right.

Q. -- do?

A. Let me -- let me correct the record.

Q. Sure.

A. My apologies. I was brought in as an

environmental engineer.

Q. Okay. Thank you for that clarification.

A. For the official classification for the --

Q. Understood. So we won't hold you to that. Thank you for the clarification.

So what does an environmental engineer do?

A. You look and assess at environmental data and then determine if there's going to be a completed or not completed exposure pathway that would impact humans.

Q. How -- how long roughly, give or take, I understand that this was a number of years ago -- did you hold the title of environmental engineer?

A. I'll say for maybe three years.

Q. So roughly '92 to '95?

A. Yes, sir.

Q. And what did you understand that the -- well, let me back up. What -- what did you do in that role as an environmental engineer? Can you remind me?

A. I looked at different sites under CERCLA. ATSDR is responsible for assessing any

site that EPA classifies as a national priorities list site, NPL site. And ATSDR, by congressional mandate, has about two years to render an opinion to assess that and produce a public health assessment on that site, the scientific document, okay? And so that's what I worked on on a number of different sites.

Q. Was -- was your work relied upon for purposes of others that produce the public health assessment?

A. Yes.

Q. Do you know, from your time at ATSDR, how the public health assessments would be used?

A. Could you qualify that? Are you talking about from a scientific, regulatory, public? I'm not sure I understand the question.

Q. Sure. Were the -- so let me make sure I understand your testimony correctly. The work you did as an environmental engineer, that -- that helped the folks that worked on the public health studies do what they do; is that right?

A. No, the work that I did as an environmental engineer collecting data, analyzing contaminant data, would be used by ATSDR staff working on the public health assessments, not

health studies.

Q. I see. Okay. Did you do any modeling in that role as an environmental engineer?

A. Yes.

Q. Can you tell me about that?

A. One site in particular was Groton, Massachusetts and there was some -- and I would have to look back at the document. I don't recall whether it was PCE or TCE, but a volatile organic compound contamination.

Q. Okay.

A. And so we wanted to look because it was in a residential area.

Q. What was the purpose of that particular model?

A. To look at the time of travel of the contaminant and when it may have reached or made a completed exposure pathway so that humans would -- would have been impacted by that.

Q. Were you looking at the time of travel into the future?

A. I would have to look at the -- go back to my, you know, my CV or whatever and look at that.

Q. Okay. Was -- to the best of your

recollection, was that what you would describe as a historical reconstruction modeling project?

A. No.

Q. In your -- in that role as an environmental engineer from '92 to '95, did you do any other work related to modeling?

A. I was asked for my technical advice and opinion on a number of different sites. I don't recall offhand specific site -- site names we did because we did a full model, but on the other ones it may have been a short analysis. It may have been a probabilistic analysis, things like that.

Q. Would -- would all of those -- understanding that you don't recall the specific sites, would those models have been used to either analyze sort of present day conditions or sort of look into the future and make predictions?

A. They most likely would look at past conditions and current day at the time conditions.

Q. Okay. Do you recall any of the models that you worked on that looked at past conditions?

A. I know the Groton, Massachusetts one looked at past conditions.

Q. Do you recall how far back you looked for --

A. No, I do not.
Q. Is there -- was there information published about that site and your work on that site?
A. I believe we did -- coauthored, I published a peer reviewed journal article on -- on the Groton site and I believe there's also a public health assessment by ATSDR on the Groton site. I do not specifically recall if they used the model result in the public health assessment or not.
Q. Understood. Would you characterize the Groton site or the modeling work that you did on the Groton site as historical reconstruction?
A. It's got a component of historical reconstruction.
Q. What do you mean by that?
A. Historical reconstruction, as I developed it for the agency along with a coauthor, is a process. So it involves many aspects. Modeling, data analysis, uncertainty analysis. So it spans the gamut, so it's not just one application or one model.
Q. Would you have performed the types of things you -- you do for historical reconstruction such as uncertainty analysis with respect to that

-- that Groton site?

A. Not at that time.

Q. Still just focusing on '92 to '95 in that role as an environmental engineer, is there any other work you did related to modeling that you can recall?

A. I probably looked at a number of different sites and, again, may have done some probabilistic analysis looking at whether some contamination exceeded a certain threshold or not a certain health threshold.

Q. Understood. What position did you take on after 1995 or in 1995?

A. I was promoted again. The CDC and ATSDR being part of the CDC also had the Research Grade Evaluation program under Office of Personnel Management. So again, you could either go administrative or scientific. So I was promoted under the RGE program and then assigned as the project officer for the agency's exposure-dose reconstruction program.

Q. When were you assigned as a project officer to the exposure-dose reconstruction program?

A. I don't recall the exact date. The

program was -- document was published around 1993 by the agency where I coauthored it and the director of the agency at the time signed off on it.

Q. Who was the director at the time?

A. Actually he -- at that time he was -- they called them assistant administrators. It was Dr. Barry L. Johnson.

Q. And this would have been in 1993?

A. That's when the agency program -- yes, yes, he was the first assistant administrator for ATSDR.

Q. Okay. You became project officer for the exposure-to-dose reconstruction program in '95?

A. Yes.

Q. And did you hold that title all the way until you retired?

A. Yes.

Q. Did you hold any other titles from '95 until you retired in 2017?

A. Not within ATSDR.

Q. What -- starting at a high level, how would you describe your -- your roles and responsibilities as project officer for the exposure-to-dose program at ATSDR?

A. I would be the scientific and technical advisor for sites or for people who -- who needed some historical reconstruction. And so they would come to our group or our program, and then we would determine, you know, what approaches to use, what methodologies needed to be used to answer questions that they would pose to us.

Q. Any other roles or responsibilities that you can think of related to that role?

A. Well, under the RGE program they reevaluate you every so often, so you have to have a number of publications and things like that. So we would work on sites and publish documents. We would also -- I was responsible for overseeing the corporative agreement with the university partner that spanned five-year increments. So I would author that RFP and then the CDC grants office would put it out for bid. And we had a university partner as a corporative agreement partner.

Q. When did you take on that role with the university partner?

A. I'm thinking it's around 1995.

Q. And did you partner with multiple different universities?

A. No, we partnered with Georgia Tech.

Q. Okay. Was -- and Georgia Tech was the only university that you partnered with?

A. Yes, yes.

Q. Now, I understand that you led the water modeling efforts related to Camp Lejeune, and we'll talk about that. Putting that aside for a moment, can you tell me about any other work you did related to modeling in that role as project officer for the exposure-to-dose reconstruction program?

A. We did work on some selected sites that we were asked to look at. It could be groundwater modeling, fate and transport modeling, water distribution system modeling. So we -- you know. And again, if there was a special analysis code that we needed or that we did not have or it was not in the public domain, then, of course, we would ask our university partner to assist us.

Q. Okay. Understood. Do you recall any of the -- again, putting Camp Lejeune model aside, any -- do you recall any of the types of models you used?

A. We used water distribution system modeling at Southington, Connecticut and Toms River, Dover Township, New Jersey.

Q. What -- what was the project in Connecticut?

A. They had a water distribution system, and the Connecticut -- I'm going to call it public health agency. I don't recall the exact name. It was VOC contamination and they were concerned about, I believe, kidney cancer and miscarriages, and so they wanted to see how the contamination traveled through the pipelines of their water distribution system.

Q. Was that looking at travel into the future?

A. Not necessarily. Water distribution systems operate on time scales of hours. Okay. So it could be the present day condition or it can be a past condition based on the past condition of the water distribution system.

Q. Okay. Would you consider that -- that work you did in Connecticut as historical reconstruction?

A. No, I would consider it more present day. Present day for that time.

Q. Okay.

A. Not present day now.

Q. And I understand Dover and Toms River.

That was a historical reconstruction, correct?

A. Yes, it was.

Q. Was that the first historical reconstruction project you had performed at ATSDR?

A. That was probably the first and most publicly-acknowledged project.

Q. Okay. Is it -- is it the first historical reconstruction you had performed at ATSDR or the first one you had performed period at any place of employment?

A. It would be the first complete historical reconstruction. Again, historical reconstruction is a process, so we may have taken a certain aspect of historical reconstruction model or data analysis and done some for some other sites, but Toms River, New Jersey was the first complete application of a historical reconstruction process.

Q. Who did you work with on the Toms River project?

A. We worked -- we had a corporative agreement. When I say "we", I mean ATSDR, just to clarify. ATSDR had a corporative agreement with the New Jersey Department of Health and Senior Services, and they requested ATSDR's assistance

because of the increasing number of childhood cancer cases that they had observed.

Q. Okay. Who from ATSDR worked with you on that project?

A. Myself and probably Mr. Jason Sautner.

Q. Okay. Did you work with any university partners on that project?

A. Yes.

Q. Who -- who was that?

A. The -- it was referred to as the multiple environmental simulations -- multimedia environmental simulations laboratory at Georgia Tech.

Q. Is that the laboratory run by Mustafa Aral?

A. Yes.

Q. Okay. And as I understand it, he was -- he was a professor that you had while you studied at --

A. That is correct.

Q. -- Georgia Tech, correct?

A. That is correct.

Q. Okay. As it relates to Toms River, can you walk me through a little bit, sort of your thinking as a scientist or your -- kind of the

scientific process of determining whether you can do a historical reconstruction, particularly since it sounds like you had never done one before?

MR. DEAN: Object to the form of the question.

BY MR. ANWAR:

Q. You can answer.

A. Okay. It's not that -- again, historical reconstruction is a process, okay? So we had applied previously parts of that, but for Toms River, New Jersey we were asked to look at the development of their water distribution system from its infancy, 1960s, all the way to the current day, which was, I believe at the time, 1998. And on a monthly and annual basis, the people, the health scientists at New Jersey Department of Health and Senior Services wanted to know which well field was contributing which volume of water to the total water supply so they could do an epidemiologic study.

Q. How big was the Toms River site, do you recall?

A. Big in area or big in population?

Q. Why don't we start with physical area.

A. Oh, it's maybe 40 square miles.

Q. Okay. How does -- just out of curiosity, just for my own kind of conceptualizing, it how does that relate to Camp Lejeune?

A. Camp Lejeune in its entirety is probably around 150 or more square miles.

Q. Okay. Do you recall how many water distribution systems you were looking at at the Toms River site?

A. There was one because it was a privately owned water utility, United Water, but there were multiple well fields.

Q. Do you remember the number of well fields?

A. I believe it was eight, but I would -- I just want to couch that and say I would have to go back and look at our publications.

Q. And how many chemicals were you looking at with respect to Toms River?

A. That is where discussions between the New Jersey Department of Health and Senior Services, epidemiologists in our group decided we could use a novel approach and we did not have to look at chemical-specific compounds.

Q. Can you -- can you explain a bit more for me what you mean by that? You said a novel

approach where you don't have to look at chemical-specific compounds.

A. Uh-huh.

Q. What did you mean?

A. What they were interested in from the epidemiology standpoint is, again, the volume of water that, you know, Jane and John Smith would be receiving from well field A, well field B, C, D, E and F, okay? And the epidemiologist decided that that was of primary importance. If they could determine the volume of water, then based on additional epidemiologic study information, like consumption activities at the home, they could establish the epidemiologic statistics that they needed. So they did not need -- so it was decided that they did not need a specific compound to trace through the water distribution system. They assumed whatever compound was there would be conservative, would not degrade, so you really did not need a specific compound.

Q. I see. So it was just sort of hypothetical compound -- or not hypothetical, but undefined compound?

A. It was -- no, it was a compound defined as a conservative compound.

Q. Okay.
A. And then we assumed a certain concentration, and then we could tell what percentage of that concentration originating from well field A, B, C, D or E where it traveled to in -- in their distribution system.
Q. Did you have -- I think a moment ago you said for Dover -- the Dover reconstruction project you looked at the time period from 1960 to 1998?
A. 1962.
Q. 1962. Excuse me. To 1998.
Did you have historical data during that period related to the water?
A. We had some, yes.
Q. How much -- what data did you have? How much data did you have?
A. We had information from the water utility as to when they installed certain pipelines in certain locations. Certain water appurtenances; pumps, valves, stuff like that. So as the system changed, we had information on that.
Q. Since you were dealing with a compound that you defined as conservative, but not necessarily any specific chemical, I assume you

didn't have, like, historical sampling data related to any particular chemical?

A. No, that's not correct.

Q. Okay. Could you -- could you explain it for me?

A. Yes, it turns out that the groundwater in New Jersey that they used is -- in the water region system has naturally occurring high barium. And so we had some -- and so New Jersey took some barium readings in the 1990s, and so we were able to match the model. When I say "match", we were able to compare modeling for a specific date and time with barium readings, and that's all described in our -- in a journal article that I published in 2000.

Q. Okay. Prior -- did you have pumpage data related to the Dover site?

A. Are you talking about groundwater well pumpage or water distribution system pumps?

Q. Either one.

A. We had water distribution system pump curves which is required by the model that we used and that, again, came from the water utility. We knew how much water they were pumping out of their round water wells.

Q. At the time that you worked on the Dover reconstruction effort, were you aware of any other reconstruction efforts taken to look at, I guess, water chemical concentrations over, you know, the period of time that you were looking, 30-some years?

A. Like other parties or by ATSDR?

Q. By anyone.

A. Well, yes, there was the ongoing -- I think it's the Department of Energy dose reconstruction programs at, like, Hanford, Savannah River plant.

Q. Okay.

A. And some of those big facilities assessing, for example, the fallout at Hanford and the Downwinders and things like that.

Q. I had a thought and I lost my train of thought for a second. Give me one second.

And if you want, we've been going for about an hour. We're welcome to take -- you're welcome to take a break.

A. I would like a fresh cup of tea.

MR. ANWAR: You want to grab -- let's take five.

MR. DEAN: Take five, if you don't

mind.

MR. ANWAR: Sure.

THE VIDEOGRAPHER: Going off the record. The time is 10:38 a.m.

(A recess transpired.)

THE VIDEOGRAPHER: Going back on the record. The time is 10:50 a.m.

BY MR. ANWAR:

Q. We are back on the record from a short break. Mr. Maslia, are you okay to continue?

A. Yes, I am.

Q. Great. Did you speak with your lawyers during the break at all?

A. No, I did not.

Q. Okay. Before the break we were discussing your work as it relates to the Dover, New Jersey -- or the Dover Toms River site, correct?

A. That's correct.

Q. And I think earlier in your testimony you mentioned that the modeling work you did related to that site was to help perform health studies; is that right?

A. It was for New Jersey Department of Health and Senior Services to conduct their

epidemiologic study of the area.

Q. Do you know if the New Jersey Department of Health did, in fact, perform the health study?

A. Yes, they did.

Q. Do you know what that health study was used for?

A. To determine -- they were conducting a case control study, so to determine if people received water from a certain well field had a higher risk of incurring certain health diseases than people who did not receive water from that particular well field.

Q. Okay. Do you recall any of the conclusions in that health study?

A. It's really an epidemiologic question.

Q. Sure.

A. So I can answer the contribution of the model, but not the epidemiological results.

Q. Understood. Do you recall whether the New Jersey Department of Health took any sort of action as a result of that health study?

A. I'm not aware if they're a regulatory agency or what -- what their involvement from that standpoint is.

Q. Okay. So, you know, you did the reconstruction?
A. Right.
Q. They did the study?
A. Yes.
Q. And that's it?
A. That's correct.
Q. Okay. I wanted to go back to -- you mentioned some work you did related to Savannah River; is that correct?
A. No, no.
Q. What was --
A. We did some work -- Savannah River I mentioned in terms of just doing dose reconstruction --
Q. Oh, correct.
A. -- because they were part of the Department of Energy plants producing...
Q. Thank you for that clarification. I was misremembering. So you mentioned Savannah River in the context of a question I asked about whether anyone else had done sort of a reconstruction project, correct?
A. Yes.
Q. And that Savannah River project, my

understanding about it is that it involved an air model related to nuclear fallout; is that right?

A. I really don't know the specifics. I just remember seeing in the scientific literature reports from Savannah River plant, Hanford, and things of that nature where they would have had DOE facilities that produced, you know, weapons-grade materials, so...

Q. Aside from Savannah River, at the time that you did the Toms River Dover reconstruction, are you aware of any others -- reconstructions, sort of historical reconstruction modeling projects that had been performed anywhere?

A. Not at the time, however, there's a literature review in 2010 by Jennifer Somheil and others and they do a complete review of environmental reconstruction analyses.

Q. Off the top of your head, there's -- there's your work as it relates to Dover and Toms River and then we will talk about your work related to Camp Lejeune. Are you aware -- and then you mentioned the Savannah River project as well. Are there any other historical reconstruction modeling projects that you can think of?

A. There's one, for example, in Tucson,

Arizona from the Hughes Aircraft TCE plume. That was sealed under the courts.

Q. Okay.

A. So it was private consultants. So while ATSDR is aware of that, ATSDR, it's not publicly available.

Q. Okay. Fair to say you haven't seen that work?

A. I've seen parts of that work.

Q. Okay. Do you know what specifically that work entailed?

A. No, no, no.

Q. Okay. At the time that you were working at the Toms -- on the Toms River project, did you consult any modeling textbooks?

A. Consulted modeling manuals.

Q. What modeling manuals did you consult?

A. EPANET.

Q. Okay. Anything else that you recall?

A. No.

Q. And then you mentioned that -- as I think you mentioned, and you should correct me if I'm misremembering, that as project officer for the ATSDR's exposure-to-dose reconstruction program, that you started that; is that right?

A. That is correct.

Q. Okay. I'm trying to understand if in starting that program you started from scratch or did you look to some sort of existing scientific methodology for that program?

A. The program evolved and was proposed by me and a coauthor because at the time, ATSDR came under scrutiny by the Government Accountability Office. They were handed 1200 NPL sites. In the congressional mandate they were supposed to review all of them within two years. So the agency essentially were taking remedial investigation reports and rubber stamping them and saying, yeah, let's go to the next one.

And so the assistant administrator, Dr. Barry Johnson, the conversations initially just started out as, you know, you know, nothing technical or anything. We agreed that ATSDR needed some quantitative computational ability to independently check results in either the remedial -- remedial investigation reports or proposed remediations by EPA. And so that's how -- that was the origin of the exposure-dose reconstruction program, was to provide a technical and -- and scientific section within ATSDR that people could

tag into and...

Q. And in providing the technical support in that role, did you -- were there existing methodologies that you looked to and relied upon or did you -- did you start from scratch?

A. Well, there are existing published models that would be part of their existing probabilistic analysis, but we also had our corporative agreement partner and they developed their own models and approaches, so we would incorporate everything as determined by what particular site or what particular question we were asked to answer.

Q. Understood. At the time that you did the Dover historical reconstruction, did you -- did you start from scratch on that or was there existing sort of scientific methodology on how to do a historical reconstruction?

A. We started from scratch, from the corporative agreement partner, New Jersey department asked us to look at the water distribution system. And for a few pipes you can do that by hand. It's taught in engineering school.

Q. Okay.

A. And once they showed us the expanse of the distribution system, we told them you needed some automated method, and that's when we were -- we looked through the literature and we found out about the EPANET program out of EPA.

Q. And I think earlier you described only some of the work you did related to Toms River as novel; is that right?

A. Yes.

Q. Can you -- and I apologize if you already explained this, but can you remind me how it was novel?

A. It was the first time that multiple or several dozen pressure launders --

MR. ANWAR: I apologize. I don't know what that is. Sorry.

MR. DEAN: It almost caused me a heart attack.

BY MR. ANWAR:

Q. Okay. Could you -- could you remind me why -- the aspects of Toms River, New Jersey that were novel?

A. It was -- first of all, to my knowledge, a water distribution system had not been reconstructed from its beginning stages, for

example, 1962, year by year, all the way up through 1998. And it was the first time that a large number of automated pressure recorders had been used to obtain data and monitor the system. And that's all, again, in that published article that we published in the Journal of Water Resources Planning and Management in 2000 under the auspices of the American Society of Civil Engineers. And they considered it novel enough that they awarded us the best practice-oriented paper for 2000.

Q. Okay. And I think I saw online that there was an ATSDR report published related to Toms River as well?

A. Yes, there was a number of ATSDR reports published. One for the current conditions at the time, which I believe were 1998, and then the historical reconstruction going back from 1962 forward.

Q. Okay. I think maybe the report I saw was the reconstruction.

A. Okay.

Q. So putting Toms River aside, Dover and Toms River, putting Camp Lejeune aside, during your time as project officer for the exposure-to-dose reconstruction program at ATSDR, are there any

other historical reconstruction efforts you worked on while you were at ATSDR?

A. We did an uncertainty probabilistic analysis in Morriston -- Marston, Missouri. Again, it was quick. Somebody needed an analysis to see if -- I think it was PCBs, if they were exceeding a certain health criteria. So again, that was a statistical analysis, but, again, it's, you know, part and parcel of the work that we did under the auspices of the dose reconstruction program at ATSDR.

Q. Okay. And the work you just mentioned, were you -- you mentioned you were looking at PCBs and whether they exceeded --

A. The health assessors were.

Q. The health assessors were.

A. Right.

Q. What time period were you focused on?

A. I don't recall that. I would have to go back to a presentation or --

Q. Sure.

A. -- some documents to look at that.

Q. Do you recall whether you were looking back in time or you -- it was forward looking or present day?

A. I really don't -- don't recall.
Q. Okay. Fair enough. Any -- anything else you can remember related to historical reconstruction with the -- putting everything that we've already discussed aside?
A. Not...
Q. Did you have any other roles or responsibilities aside from modeling work and the technical support as project officer for the exposure-to-dose reconstruction program at ATSDR?
A. One, I would oversee and maintain the corporative agreement with our university partner.
Q. Sure.
A. If they needed something or they needed equipment or whatever. And it was a five-year corporative agreement, so every year they would have to submit a report and I would have to, you know, sign off and say that they -- what they said in the report was true and they accomplished what they wanted to do. I also was responsible, and it was not an official duty, but I mentored people coming from graduate school.
Q. Who are some of the people that you mentored?
A. Mr. Jason Sautner. Mr. Rene

Suarez-Soto. Dr. Amy Funk, who is now with the Centers for Disease Control.

Q. Okay. If I remember correctly, Mr. Sautner was also a Georgia Tech grad; is that right?

A. That's -- that's where I became aware of him.

Q. Okay.

A. Through our corporative agreement partner. I mentioned the undergraduate student that could assist us.

Q. And did he -- if I remember correctly, do you know, did he study under Mustafa Aral as well?

A. I don't specifically recall.

Q. Okay. Fair enough.

A. Although because he was -- Dr. Aral did recommend him to us, but I don't know if he studied underneath him.

Q. Okay. Would you consider Dr. Aral, Mustafa Aral, a mentor to you?

A. Yes, absolutely.

Q. What -- what is Mustafa Aral's sort of focus at Georgia Tech?

A. It varied from developing what he

referred to as innovative techniques for modeling analyses, health risk analyses.

Q. Okay. You retired from ATSDR in December of 2017; is that right?

A. December 31st, 2017.

Q. And upon retirement or after you retired, you started your own consulting firm or you started consulting?

A. I -- I established my name as an independent consultant.

Q. Okay.

A. But did not do any consulting for several years.

Q. And the name I saw on your resume is M.L. Maslia, Consulting Engineer?

A. That is correct.

Q. What types of consulting work or projects do you handle? And let me caveat, I'm not asking -- again, aware that you're observing as a consultant for the plaintiffs --

A. Right, right.

Q. -- in this litigation, so not asking about that.

A. Yeah.

Q. But aside from that.

A. Aside from that I've done some work for a private consulting firm in Woodstock, Georgia overseeing some of their staff that were conducting groundwater modeling at a proprietary site that they were asked to be consultants on.

Q. And where was this at?

A. Where was the site?

Q. Yeah.

A. I'm not allowed to say that.

Q. Okay. I thought you said -- was it Woodstock?

A. Well, the consulting company is located in Woodstock --

Q. Okay.

A. -- Georgia, which is about 15 miles from where I live.

Q. Can you share how you supported the groundwater modeling on that project?

A. Yes, I reviewed the assumptions that their geohydrologist put into the model. They also collected field samples. I can say it was around a landfill, okay? I would provide them professional engineering advice as to how many samples they should be collecting, how spaced out, and then review the model simulations that their staff

would -- would make to see if the assumptions, boundary conditions, et cetera, were consistent and with best engineering practices.

Q. Understood. Was -- was that a historical reconstruction model?

A. No, no.

Q. What type of model was it?

A. It was a current day.

Q. Current day.

A. Current day.

Q. Any other projects or work that you can think of as a consultant?

A. I occasionally review, actually for the same company, a semiannual report that they have to submit to the Georgia Power Company, and I review it as a professional engineer. Okay.

Q. And you are a professional engineer, correct?

A. Yes, I'm registered in Georgia as a professional engineer with an active license.

Q. Anything else you can think of that you've worked on since becoming a consultant?

A. Not as a consultant.

Q. Besides Camp Lejeune.

A. Yeah, not as a consultant.

Q. Okay. Again, not asking about Camp Lejeune specifically, but generally speaking, what do you charge as your -- your consulting rate?

A. Around $300 an hour.

Q. Okay. I would like to switch gear and -- switch gears a little bit and talk more specifically about Camp Lejeune. We're going to pull up what we're marking Exhibit 6. It should be titled ATSDR website -- or no, it should be -- it's actually a different one.

MR. DEAN: I don't know why mine is not pulling up.

MS. BAUGHMAN: Did you refresh it?

MR. DEAN: Yeah.

MR. ANWAR: The one I want is actually -- you can leave that one in there, though. It's the CDC 24/7.

MR. DEAN: That is weird. Can I see that, my iPad?

MS. BAUGHMAN: This one?

MR. ANWAR: Okay. It's in there. It's -- Exhibit 6 is CDC 24/7 Camp Lejeune summary. And just let me know when you see it.

MR. DEAN: I'm just having a little...

MR. ANWAR: Let's go off the record for

a second.

THE VIDEOGRAPHER: Going off the record. The time is 11:12 a.m.

(Off the record.)

(DFT. EXHIBIT 7, CDC 24/7, Camp Lejeune, Summary 2014 PowerPoint Bates-stamped CLJA_WATERMODELING_01-0000003764 through 3792, was marked for identification.)

THE VIDEOGRAPHER: Going back -- going on the record. The time is 11:15 a.m.

BY MR. ANWAR:

Q. We are back on the record from a short break to deal with a technical issue. I have pulled up what I have, before the break, described as Exhibit 6, but it's actually Exhibit 7. It should be showing on your screen now and it's -- it's pulled up on the larger screen up there as well.

I'll represent to you that it's a PowerPoint presentation entitled CDC 24/7, Camp Lejeune, Summary 2014. Do you recall -- and feel free to skim through it. I don't know if you have that ability.

A. Yeah, yeah, yeah. No, I can't.

Q. Gio is skimming through the slides.

A. Oh, I'm sorry. Okay. Yeah. Go ahead and just -- okay. Okay.

Q. Okay. My question was, do you recall ever seeing this presentation before?

A. No, I've never seen that presentation.

Q. Okay. Do you recall if you were involved -- or do you know if you were involved in preparing the presentation or populating any of the information contained in it?

A. Only if it contained modeling results or analyses that we had published in the ATSDR historical reconstruction -- under the historical reconstruction for Camp Lejeune and they would want a particular figure or not with this, so -- but I don't recall this actual -- being involved with this particular presentation.

Q. Okay. I'll just represent to you that the presentation, we pulled it from ATSDR's water modeling project files.

A. Oh, okay.

Q. Which I think are referred to as the EDRP files.

A. Yes, yes.

Q. Are you familiar with the EDRP files?

A. Yes.

Q. What are those?
A. Under ATSDR they had a LAN, large area network, but did their work and each person at ATSDR was assigned, you know, user ID and then they could keep files underneath there. Their work files, project files, and so on. So EDRP obviously stood for exposure-dose reconstruction program and so we would have files in there.
Q. And that's the program you were the project officer for?
A. Yes.
Q. Would you have had access to the EDPR files or the folders?
A. Yes, they would have under my user ID.
Q. And you would have -- that would have been true until you left in -- on December 31 --
A. That is correct, that is correct.
Q. And just for the record, so it's clear, that would have been true until you left in December of 2017, correct?
A. That is correct.
Q. Thank you.
And so this presentation is dated 2014. I wanted to start by asking you about a few slides.
MR. ANWAR: Can we go to slide two.

BY MR. ANWAR:

Q. So slide two says "Camp Lejeune is a Marine Corps Base in North Carolina. Camp Lejeune opened in 1942." Is that your understanding?

A. Construction started in 1941.

Q. Okay.

A. And then they started getting Marines in and being operational in 1942.

Q. Okay. Thank you.

Go to slide four, please. Well, actually slide three. So slide three says "what happened?" And then slide four contains the slide that is titled "water contamination." The slide discusses water distribution --

A. May I go on the record for a second?

Q. Sure.

A. Just to clarify, this is not anything I put together. I can tell by the language, okay?

Q. Okay. Fair enough.

A. Okay. Just so this is the first time I'm -- I'm seeing it.

Q. Understood.

A. Okay.

Q. So this particular slide discusses water distributions affected at Camp Lejeune and

sources of contamination, right?

A. Yes.

Q. Okay. And so we'll discuss the water distribution systems and the sources in more detail a bit later, but I wanted to focus your attention to the bottom of the slide. It states "1989 EPA listed both the dry cleaner and Camp Lejeune, CL, Camp Lejeune, on the national priorities list, which triggers ATSDR's involvement." And I think you mentioned this earlier, but is that your understanding?

A. That's my understanding. It was the -- just to clarify, it would have been the off-base dry cleaner.

Q. Okay.

A. Okay. There's an on-base dry cleaner.

Q. Understood. And thank you for that clarification. And the first bullet point says "offsite dry cleaner", correct?

A. Right.

Q. And would that have -- the offsite dry cleaner is ABC Cleaners?

A. That is correct.

Q. So this -- where it says the NPL triggers ATSDR's involvement --

A. Can you pull the slide back on to this screen? Thank you. Okay.

Q. Where it says national priorities list triggers ATSDR's involvement, is that your understanding as well in terms of how ATSDR became involved with looking at Camp Lejeune?

A. Yes.

Q. Okay. And I think you -- you said this earlier in your testimony. Let's go to slide five. And I believe you already said this, but this says "CERCLA" -- The Comprehensive Environmental Response, Compensation and Liability Act of 1980 -- "requires ATSDR to conduct public health assessments at all NPL sites. ATSDR is required to revisit sites until they are removed from the NPL."

Is that your understanding?

A. That is my understanding.

Q. Okay. Let's go to slide six. So according to this slide, there was a Camp Lejeune public health assessment performed in 1997; is that correct?

A. That is correct.

Q. Are you familiar with the 1997 public health assessment?

A. Yes, I am.

Q. Can you tell me about it?
A. It was a standard health assessment, again, as we discussed, that ATSDR was required under law to conduct. And out of the health assessment there were questions about exposure to contaminated drinking water, specifically to children, but the health -- and at that time there were very, very few studies that could be used or relied upon to determine if this was a potential health problem or not.
Q. Okay.
A. So the recommendation is to conduct health -- health studies on children.
Q. Okay. And so one of the recommendations that came out of the 1997 public health assessment was to study whether there was an association between Camp Lejeune drinking water and specific birth defects and childhood cancers?
A. Yes.
Q. Okay. I saw in some of the documents produced in the case that there was mention of criticism around the 1997 public health assessment. Do you know what that's referring to?
A. Yes.
Q. Can you tell me about that?

A. The 1997 health assessment, I believe, did not have any emphasis or data on benzene contamination. And also it had -- I think they were provided with an incorrect startup date for one of the water treatment plants.

Q. Okay. Where was the -- or where or who was the criticism coming from?

A. Well, I became aware of the criticism in one of the Camp Lejeune advisory panel meetings, the CAP meetings, that was brought up.

Q. Who -- who brought that up to you?

A. I don't recall a specific person, but it was brought up.

Q. Okay.

A. Excuse me.

Q. Was it a member of the CAP?

A. Yes.

Q. And do you recall the conversation?

A. Well, they were requesting ATSDR to withdraw the health assessment because of those omissions or errors and there were a number of other issues that they brought up. I don't recall them specifically. And they based that because we were at the time -- not 1997, but when that request from the CAP came through at a CAP meeting, we were

in the process of conducting this historical reconstruction of Tarawa Terrace and they said, well, you're going to have new information, you need to do a new health assessment.

Q. Aside from the member of the CAP that -- from whom you became aware about the criticism of the '97 public health assessment, are you aware of any public criticism of the '97 -- 1997 public health assessment?

A. Well, I mean, by public, my colleagues on the health study side would -- would also state what the issue -- that there were issues with the public health assessment.

Q. To the best of your recollection, did -- did any Congress members criticize the study?

A. I don't recall that.

Q. Okay. So coming out of the -- the 1997 public health assessment was the recommendation to perform another health study related to Camp Lejeune water and birth defects in childhood cancers, right?

A. It was to perform a health study. There wasn't any past health study.

Q. To perform a future health study --

A. Yes.

Q. -- correct?

How did the decision come about to perform water modeling related to Camp Lejeune?

A. One of the epidemiologists in the Division of Health Studies at ATSDR was aware of the work that we did in New Jersey, in Dover Township, and so he came to me and said, do you think you could apply those same techniques to Camp Lejeune because we are writing a health study and we want to be able to quantify past exposures, and that seems like the only technique that -- that's viable and that has been proven to be useful that we could use in our health study.

Q. Was -- was that epidemiologist, was that Dr. Frank Bove?

A. Yes.

Q. Was anyone else involved in the decision-making process to move forward with the Camp Lejeune water modeling?

A. Well, my immediate supervisor, excuse me, division management and obviously agency leadership would have had to be involved because of the budgetary issues associated with that, but I was only involved from the technical scientific standpoint.

Q. Understood. And so the purpose of the water modeling was to support that epidemiological study related to childhood cancers and birth defects, correct?

A. Yes.

Q. Would you agree that, generally speaking, a person's exact exposure to contaminated water at Camp Lejeune is unknown?

MR. DEAN: Object to the form of the question. If you're asking him about some -- some opinion he had before July of '22, then you're free to discuss it with him, but...

BY MR. ANWAR:

Q. Yeah. And you can assume for purposes of our --

MR. ANWAR: So -- and you can have an standing objection to that.

BY MR. ANWAR:

Q. And for purposes of all of my questions, you can assume that I'm not asking about the period --

A. Okay.

Q. -- from which you were retained as a consulting expert, so --

A. Okay. Could you repeat the question?

Q. Sure. Would you agree that, generally speaking, a person's exact exposure to contaminated water at Camp Lejeune is unknown?

MR. DEAN: Object to the form of the question. You're asking him for an expert opinion, correct?

MR. ANWAR: I'm asking him for his --

MR. DEAN: No, I need to understand -- you're asking for an expert opinion and expert opinions in this case are not yet due.

MR. ANWAR: You can make your objection. Unless you're instructing him not to answer, Mr. Maslia, you can answer.

MR. DEAN: Just give us -- give me just two seconds.

MR. ANWAR: And let me -- let me rephrase the question.

MR. DEAN: Let me solve this problem and say that I'm not going to instruct this witness not to answer this question, but you do know that expert opinions to which we anticipate Mr. Maslia providing expert opinion in this case at some point in time are not yet due. They are not refined. They are not complete, and his work continues today. So I'm not going to instruct him not to

answer the question, but understand it's subject to later modification or changes. And I understood we were here to talk about the facts, but, again, you can continue with my caveats.

MR. ANWAR: Yeah. And I'm not asking for his retained expert opinion. I'm asking for his opinion as the ATSDR employee who oversaw the dose reconstruction program at ATSDR. And I'm not ask about any discussions that have taken place since you all have retained him as a consulting expert.

BY MR. ANWAR:

Q. So with that in mind as the -- the employee, the project officer of the dose reconstruction program at ATSDR, would you agree that, generally speaking, a person's exact exposure to contaminated water at Camp Lejeune is unknown?

MR. DEAN: Same objection.

THE WITNESS: I think we need to understand the relationship of the water modelers and the exposure-dose reconstruction program to the health study side. We always kept ourselves blinded to any characterization of exposure or not exposure. We just focused on providing concentrations of -- of water delivered from the

water treatment plants. So we were never involved in populations or studies or specific individuals. I really -- that's -- I could not answer that question.

BY MR. ANWAR:

Q. Okay. And my understanding of the -- the purpose of the Camp Lejeune water modeling was to simulate estimates of monthly contaminant levels in Camp Lejeune drinking water; is that right?

MR. DEAN: Object to the form of the question.

THE WITNESS: It was to reconstruct historical concentrations.

BY MR. ANWAR:

Q. Using a computer model, correct?

MR. DEAN: Object to the form of the question.

THE WITNESS: Using -- using a variety of techniques.

BY MR. ANWAR:

Q. And you were reconstructing estimates of the monthly concentration levels of contaminants in the water at Camp Lejeune, correct?

A. So we reconstructed mean monthly concentrations.

Q. Okay. Now with respect to the Tarawa -- I always butcher this, the TT, Tarawa Terrace modeling, if I recall correctly, there were estimated mean monthly concentrations, but it also included estimated median concentrations on the distribution curve as well as the 2.5 percentile and the 97.5 percentile; is that right?

A. Yeah, a number of different analyses, okay? The numbers you're referring to come out of a number of different analyses.

Q. With respect to the Hadnot Point/Holcomb Boulevard modeling, if my memory is correct, it looks like you -- you reconstructed estimates of -- or attempted to reconstruct estimates of mean monthly concentrations only; is that right?

A. We could take the same estimates that we did for Tarawa Terrace.

Q. Okay. So does the Holcomb Boulevard -- excuse me, the Hadnot Point/Holcomb Boulevard also include median estimates and the 2.5 percentile?

A. I would have to look in my summary of findings reports or whatever to...

Q. Okay.

A. We would have probably mentioned some

means in there.

Q. Okay. We can get back to that question. We can take a look a little later. You didn't work on the childhood cancers and birth defects studies, correct?

A. No, no.

Q. No as in correct you didn't work on it, correct?

A. I did not work on anything related to epidemiology, which that would have been under.

Q. And that's because you're not a toxicologist or epidemiologist, right?

A. That is part of it, but, again, in order to retain scientific objectivity, we had to be blinded. The water modelers had to be blinded to the epidemiology. The results we presented had to be robust and applicable to anywhere the epidemiologists wanted to use them. So that -- we maintained, you know, distinction and purposefully did not ask for nor did we ever receive anything related to the epidemiology.

Q. Okay. So you weren't involved in ATSDR's epidemiology, correct?

A. Not in the Division of Health Studies, no.

Q. And what capacity -- you were involved to the extent the water modeling was used to support the health studies?

A. That is correct.

Q. And just based on our discussion about your background and your resume, would you agree that you're not that person or your expertise is not to determine what levels of any chemical will cause an illness or put a person at risk for that?

A. That is correct.

Q. Was -- was Frank Bove the lead ATSDR epidemiologist that worked on both the childhood cancer study and the other Camp Lejeune health studies?

A. He was classified as a senior epidemiologist and there was another person who is now Dr. Perri Ruckart, and I -- I always dealt -- I dealt with both of them. I really couldn't say or do I remember who was designated as, in quotations, the lead, okay?

Q. Do you know when Perri Ruckart, Dr. Perri Ruckart, left ATSDR?

A. I was not aware that she had left.

Q. Oh, okay. And has she left ATSDR, or do you know?

A. I don't know that either.
Q. Okay. During the entirety of the period that you were at ATSDR until December 31st, 2017, was Perri Ruckart at ATSDR?
A. I don't know about the early years. Actually I don't know until we started with Camp Lejeune in about 2003 that I became aware that she was involved with the Camp Lejeune project.
Q. As of the time that you left in ATSDR in 2017, do you know, was Perri Ruckart still involved in the health studies related to Camp Lejeune?
A. Yes.
Q. Do you know what she -- where she's at today or what she's doing today?
A. I do not.
Q. When did ATSDR's water modeling efforts related to Camp Lejeune start?
A. We wrote an initial proposed work plan. I'm thinking it was around January of 2003, maybe January of 2002. It's an early work plan that proposed some steps and some timelines and some budgets like that. So that's when I would think that it began.
Q. Early 2003 you developed the timelines,

the budgets and sort of the planning phase, correct?

A. That is correct.

Q. Sort of at a general level, could you -- could you describe for me what the work related to the Camp Lejeune water modeling entailed?

A. Yes. I would like to start by saying those work plans were developed without any knowledge of data or databases or anything like that.

Q. Sure.

A. But -- so it was a conceptual work plan from that standpoint, but it gave steps and, again, literature review, obtaining databases or data, formulating model input data files. Conducting groundwater flow, groundwater fate and transport modeling, water distribution system modeling, and then publishing the results.

Q. Understood. If we go to slide eight. According to slide eight, it states here that "2007-2009 Tarawa Terrace water modeling chapter released"; is that right?

A. Well, there's more than one chapter.

Q. The entirety of the -- so my reading of

that, like, statement is that the first report was released in 2007 and the last of the reports related to Tarawa Terrace were released by 2009.

A. That is correct.

Q. Okay. And when would have the water modeling efforts related to Tarawa Terrace been performed, the actual work related to it?

A. We started -- we made our first site visit to Camp Lejeune in July 2003.

Q. Okay.

A. So a little bit before that. That's what we considered the -- and that's when we were told we had the budget to proceed.

Q. Understood. And Tarawa Terrace was one of the three water distribution systems at Camp Lejeune impacted by VOC contamination, correct?

A. That is correct.

Q. And when I -- just as kind of like a general matter, when I refer to Camp Lejeune water modeling -- or excuse me, when I refer to Camp Lejeune water contamination, can we agree that I'm referring to VOC contamination?

A. Well, it also involved BTEX contamination.

Q. My understanding -- and we can talk

about this more, but when I'm referring to it, I'm referring to it specifically as to the -- the chemicals that were modeled in your reports. Can we agree to that?

A. No, we modeled BTEX also.

Q. Okay. And is BTEX a VOC or --

A. BTEX stands for benzene, toluene, ethylbenzene and xylenes, and they're products of fuel -- fuel spills.

Q. When you say BTEX are you primary referring to benzene?

A. That's the -- that's primary component, yes.

Q. Okay. So can we -- so let me clarify. When I -- when I say, hey, water contamination at Camp Lejeune, can we agree that I am referring to the VOCs and benzene?

A. Yes.

Q. Okay. I just want it -- for purposes of the record, I'm not --

A. Right.

Q. If there are other chemicals that you're referring to, please let me know.

And so the slide currently on the screen mentions two challenges. The first

challenge is "United States Marine Corps, Department of Navy delayed data acquisition and funding decisions." Did I read that correctly?

A. You read that correctly.

Q. And so I understand from your prior deposition testimony that there was perhaps some frustration about the speed with which documents were provided to the water modeling team at ATSDR by the Navy and the Marine Corps; is that right?

A. That is correct.

Q. Okay. But I think in that deposition you -- you ultimately agreed that the Navy and the Marine Corps never refused to provide documents requested by ATSDR?

A. I would say we eventually obtained all the documents, but there was never a sense of urgency on the part of the Department of Navy or the U.S. Marine Corps.

Q. Okay. But they never refused to provide documents and you did eventually obtain them all, correct?

A. No, I would not say obtained them all. Again, we obtained information and documents that were required for model calibration. And for model calibration we need specific amounts of information

of data, but no more, okay? So we were not in the process nor did we put into the program a universal search for all the documents at the Navy or the Marine Corps.

Q. Sure. And I guess my question, I just wanted to be clear, and this is what you testified to in your last deposition, but I think you agreed that the Marine Corps and the Navy never refused to provide documents to ATSDR?

A. That is correct.

Q. During the course of ATSDR's water modeling efforts related to Camp Lejeune, you received and reviewed historical and other documents from the Navy and the Marine Corps, right?

A. That is correct.

Q. What kind of documents did you review and receive?

A. Anything from CERCLA administrative record files, which were actually public documents, to laboratory reports on analyses to underground storage tank files to water supply well operations to operations of their water distribution systems.

Q. Okay. And my understanding from your prior deposition testimony is that the cost of

ATSDR's water modeling on Camp Lejeune was about 1.5 to 1.8 million per year?

A. That would be the budget people. I could not really answer that, okay? I was never involved -- I was only involved in submitting the staff that we needed each year to accomplish what we needed to accomplish, but that total would have been out of the -- I forget the specific name of the office, but it would be up in the office of the director who handled the budgets and the communications back and forth with -- with the Department of Navy.

Q. If those are the numbers that you -- you testified to in your 2010 deposition, do you have any reason to disagree with that?

A. Well, those were the numbers probably at the time because we had to finish Tarawa Terrace, but I could not say that was necessarily correct for the entirety of the project.

Q. I understand. I appreciate that clarification. So would you agree that at the time that you finished the Tarawa Terrace water modeling, the cost had been averaging 1.5 to 1.8 million per year?

A. For Tarawa Terrace, yes.

Q. Okay. And with respect to funding, the Marine Corps and the Navy paid for ATSDR's water modeling efforts related to Tarawa Terrace, right?

A. They funded it under the annual plan of work that was submitted to them each year.

Q. Which means they paid for it, right?

A. Yeah.

Q. And ultimately ATSDR did receive the funding it needed to complete water modeling efforts and epi studies related to Camp Lejeune, correct?

A. I can't speak about the epi studies. I'll speak about the water modeling as yes.

Q. The second challenge on the slide states "missed milestones. Modeling took longer than predicted." What missed -- what were the missed milestones, if you know?

A. Well, originally we had proposed a four-year project. The Navy only wanted to fund a three-year project. We started and, you know, someone decided we'll agree down the road how long the project should go on. You know, in getting the information that we needed to develop the models, that took longer because it was more spread out in desperate locations and, in fact, the Department --

Department of Navy hired a consulting firm to do a search through all of Camp Lejeune to find additional documents.

We also were made aware later in the game, around 2009, of an undisclosed portal containing underground storage tanks around 2010 or 2011. We were made aware of another consultant's report that we were never provided with. So -- and there were instances of where we were told certain water supply wells were located in terms of coordinates and we found maps in their files that showed it was located someplace else, so we had to go back and, you know, recalibrate models and stuff like that.

And then I think there was a time when there was not an agreement on the annual plan of work and it had to go to arbitration and all the way up to the Office of the Secretary of Navy to be settled, so I had to send contractors home.

Q. Let's go to the -- the next slide, nine. It states there -- it states on this slide "2009 to 2013, Hadnot Point/Holcomb Boulevard water modeling released." And I interpret that meaning the first report related to the Hadnot Point/Holcomb Boulevard water modeling was released

in 2009 and the last report related to the Hadnot Point/Holcomb Boulevard water modeling report -- or the last report was released in 2013.

A. I don't recall 2009 having released. I would have to look at my reports here.

Q. Okay.

A. I know 2010 we released a report.

Q. Okay.

A. And then 2013 the remaining reports were released, but I would have to look at the publication date on the specific reports.

Q. Understood. So either 2009 or 2010 to 2013?

A. Yes, that is correct.

Q. And by 2013, the -- the Hadnot Point/Holcomb Boulevard water modeling had been completed?

A. Yes.

Q. And this slide lists the same challenges that we just discussed. Is -- is this -- is this referring to the same discussion we had about Tarawa Terrace?

A. Yes.

Q. Okay.

A. I believe the delay -- or the delay in

funding, end date acquisition were probably impacted more at Hadnot Point/Holcomb Boulevard area because it was a far more complex area than Tarawa Terrace.

Q. Okay. And I understand there were sort of disagreements and negotiations and misunderstandings or however you want to describe it related to the data gathering.

A. I would like to still characterize it as a lack of urgency.

Q. Okay. But the Navy and the Marine Corps, like we agreed earlier, never refused to -- never refused to provide you information, right?

A. Eventually, that is correct.

Q. Okay. And the Navy and the Marine Corps paid for -- or at least you're aware -- well, they funded and paid for the cost of the water modeling, correct?

A. Yes, that is correct.

Q. Now, I understand that you were the lead on ATSDR's Camp Lejeune water modeling team, correct?

A. That is correct.

Q. Who else was on the team?

A. Let's see. We had Jason Sautner. Rene

Suarez-Soto. Barbara Anderson. We may have had temporary grad students, but I don't recall their name without looking through my files. Well, I mean, files at ATSDR. And there was also our university partner and they had a number of people working on it, so -- and then there was Mr. Robert E. Faye who was a private consultant subcontracted to ATSDR.

Q. Understood. Thank you.

A. Oh, and I think two more. Dr. Walter Grayman, at various points in time, we hired as a consultant. And then for a short period of time, a few days or a week, we hired Dr. John Doherty, D-O-H-E-R-T-Y, who is the developer of the PEST, parameter estimation modeling technique.

Q. Okay. That is helpful. I would like to go through and ask you about each of the team members one by one.

A. Okay.

Q. Jason Sautner, he was an ATSDR employee, right?

A. Yes, yes.

Q. Was he an environmental health scientist, was that his role or title when --

A. That is my recollection of what his

official GS, general service, classification was.

Q. Do you recall sort of his educational and experience background?

A. He had -- I know he's got a degree in civil engineering from Lehigh University. Obviously Georgia Tech. And he started basically when we did Toms River, so his expertise was around water distribution system modeling.

Q. Understood. Did you supervise Mr. Sautner?

A. Yes, I did. Now let me clarify that. I supervised him from a scientific or technical standpoint. Because I was under the research grade classification system, I could supervise people at lower grades or higher grades than me, okay? So -- but I -- I would hand in evaluations annually for his critique, but it would be my supervisor who actually did his supervision, administrating supervision.

Q. Understood. And you said Mr. Sautner worked on water distribution modeling?

A. Water distribution system modeling, yes.

Q. System modeling.

And was that his role with respect to

the Camp Lejeune water modeling?

A. Yes, it was.

Q. And then Rene Suarez-Soto, he was also an ATSDR employee?

A. He started out as a -- finishing up his master's under a Pan American Hispanic Universities, PAHO, procedure or funding -- funding. And then -- and that was run through ORISE, which is the Oak Ridge Institute for Science and Education. So he was actually at -- for a few years -- for probably two or three years, he was a contractor to ORISE that they assigned to ATSDR. And then of course when a position became -- full-time position came open at ATSDR, he applied and was selected to be a full-time ATSDR employee.

Q. Got it. Do you recall his sort of educational and professional background?

A. General groundwater modeling, statistical and probabilistic analysis.

Q. And did you -- was that his role on the Camp Lejeune water modeling team?

A. Yes.

Q. And did you supervise Mr. Suarez-Soto in the same way that you just mentioned that you supervised Mr. Sautner?

A. Yes.
Q. Was Mr. Suarez-Soto, he was also, at least at the time that you worked with him, an environmental health scientist?
A. I really don't recall his classification.
Q. Okay. Then I think you mentioned Barbara Anderson?
A. Right.
Q. She was also an ATSDR employee?
A. Yes.
Q. Was she also an environmental health scientist?
A. Again, I don't know what she was classified as.
Q. Do you recall her educational and professional background?
A. Not specifically, but I know she -- her focus on the Camp Lejeune project was data analysis. Excuse me.
Q. And I know we're getting close to noon and we agreed to take a noon break, so I could do a couple more minutes of questioning or --
MR. DEAN: That's fine.
BY MR. ANWAR:

Q. Okay. Were there any other, I guess, formal ATSDR employees involved in the Camp Lejeune water modeling efforts?

A. Not that I recall.

Q. And then I think there were some consultants that also worked on the team, right?

A. Yes, yes.

Q. And you mentioned the university partners. Was -- are you referring to Mustafa Aral and some of the grad students from Georgia Tech?

A. Yes, yes.

Q. And Mustafa Aral is the professor from Georgia Tech that we've talked about, correct?

A. Yes.

Q. And I think you described him as the director of multimedia environmental simulations laboratory --

A. That is correct.

Q. -- at Georgia Tech?

A. That is correct.

Q. What was his role on the Camp Lejeune water modeling team?

A. When we had a technical or scientific issue or we needed an analysis that went beyond what's just publicly available in terms of pulling

something off the shelf, for example, Holcomb Boulevard, the intermittent release of water from Hadnot Point to Holcomb -- Holcomb Boulevard required a special analysis. And so we would -- I would call under the corporative agreement he can speak with the principal investigator.

Q. Okay.

A. So I would call him and we would discuss what our objectives, what we needed, and then he would assign graduate students to conduct those analyses.

Q. Understood.

A. And their names are listed on -- as coauthors on some of these reports, so...

Q. You also mentioned Robert Faye?

A. That is correct.

Q. Who is Robert Faye?

A. I first professionally met -- and I refer to him as Bob Faye -- when we were both at the U.S. Geological Survey.

Q. Okay.

A. And he retired and I retired. And when we were doing Toms River we needed -- again, ATSDR was not allowed to hire full-time employees. They had a hiring freeze almost continuously on, but we

were able to go through, like, Eastern Research Group or ORISE and things like that, so we hired him through Eastern Research Group to assist us on the modeling at Toms River, New Jersey. And then when the Camp Lejeune activities came up -- and he's a very senior experienced geohydrologist, so we hired him again through -- I say we hired him, Eastern Research Group hired him. He's subcontracted to ATSDR.

Q. Understood. And I think I also saw some references to probably his consulting company, R.E. Faye and Associates?

A. That's correct, yes.

Q. And did Mr. Faye, he worked on groundwater modeling?

A. Yes.

Q. And then you also mentioned Walter Grayman.

A. Yes.

Q. Who is Walter Grayman?

A. Walter Grayman is an internationally renowned consulting engineer and one of the early developers of water distribution system modeling in the mid-1980s. And again, we became aware of him when we were working on the Toms River, New Jersey

site. We asked for his advice or input. And then when we got to Camp Lejeune, at times we needed also his advice and assistance in conducting field studies and characterizing the water distribution system.

Q. And he worked on water distribution modeling?

A. Yes.

Q. Okay. And I asked that generally, but he worked on water distribution modeling as it relates to the Camp Lejeune modeling, correct?

A. He did not do the day-to-day number crunching, but, again, in modeling you have to set up first your conceptual model and then decide what techniques would best be used for that, what field data you night need, and so he provided us with consulting services and input into that as well as when we went out in the field to collect water distribution system data, he, Bob Faye, and others came out during the field test to assist us to collect the data.

Q. Understood. And I just have a couple more questions and then we can take a break.

I saw in one of the slides, I think one of your presentations, a reference to the U.S.

Geological Survey and then like maybe like a Georgia Water Institute or something like that. Does that ring any bells? Did you have any consultants with the USGA -- or USGS?

A. Not consulting. They would ask me every now and then to come present work, because the work at Camp Lejeune was not the standard run-of-the-mill groundwater flow modeling, water distribution system modeling or site analysis. So every now and then, both locally in Georgia and at USGS headquarters in Reston they would put on workshops or whatever, and so they knew of me from my days at USGS. They would ask me to present, and it was a good opportunity to teach their hydrologists and also a good opportunity for ATSDR to receive critical feedback on what we were doing.

Q. Understood. Did you put the water modeling team related to Camp Lejeune together?

A. Yes.

Q. And I guess you've explained it to some degree already, but why did you select the individuals that you selected?

A. Jason Sautner was already assigned to the exposure-dose reconstruction program. When I wrote up the work -- initial work plan, I obviously

indicated in there we would need some more staff, so that's when Rene Suarez-Soto came in, and being right out of college and all of that, that's, you know, a young engineer that we can mentor and bring along like that. Obviously Georgia Tech had their expertise nationally and internationally and all of that.

And then, again, Mr. Robert Faye, my knowledge of his specific expertise in geohydrology, which I knew we would need to look at geohydrologic information at Camp Lejeune. And then of course Walter Grayman is from the water distribution side and, again, as I said, he's internationally recognized, so...

Q. Were you happy with the performance of your team?

A. Absolutely.

Q. Okay.

A. And I might add Barbara Anderson, she did not work for the project full time.

Q. Okay. And you were satisfied with the performance of your team?

A. Yes, absolutely.

MR. ANWAR: Why don't we take break there.

THE VIDEOGRAPHER: Going off the record. The time is 12:05 p.m.

(A luncheon recess transpired.)

THE VIDEOGRAPHER: Going back on the record. The time is 12:51 p.m.

BY MR. ANWAR:

Q. We are back on the record from a short break, a lunch break. Mr. Maslia, are you okay to continue?

A. Yes, I am.

Q. Okay. And during the lunch break, did you discuss the substance of your testimony with your lawyers at all?

A. Not at all.

Q. When we concluded before the lunch break, we had just finished up a conversation about the water modeling team. Do you recall that?

A. Yes.

Q. There was one person I forgot to ask you about, so I wanted to revisit. You had mentioned a John Doherty and I think you said test parameter estimation, something like that.

A. Yes.

Q. Could you -- could you tell me who John Doherty is?

A. Yeah, one of the more advanced techniques that are sometimes applied, depending on the situation, is an automated way of estimating model parameters. It would be called parameter estimation techniques. They are based on objective stochastic and statistical methods. He is internationally renowned as being in the forefront of developing those. And he's out of Australia, but he occasionally makes trips to the U.S. --

Q. Okay.

A. -- to teach or lecture or do whatever. And he is the developer of the PEST -- all uppercase P-E-S-T code that is used either independently of models or incorporated in some models. And so when we got to the Hadnot Point and Holcomb Boulevard, we were -- it was far more complex than Tarawa Terrace would be, and found out he was going to be in the U.S., so we figured we could benefit from his expertise at ATSDR for a few days or a week at most. And so he came down and gave us some guidance in using the PEST model which we used and is described in the Tarawa -- the Hadnot Point and Holcomb Boulevard reports.

Q. Understood. Thank you.

Did he only work on your team with

respect to Hadnot Point/Holcomb Boulevard modeling?

A. Yes.

Q. Okay. And could you describe for me a little bit more about what he specifically did as it relates to the Hadnot Point/Holcomb Boulevard modeling?

A. Well, the application of parameter estimation is a complex endeavor. And you don't just throw numbers at it. You have to understand about parametrization and the statistics and what you want to get out of it and stuff like that. So he sort of helped us get the program going and apply it to the Hadnot Point groundwater flow and transport models as well as the water distribution system models, and that's described in the -- the Hadnot Point/Holcomb Boulevard Chapter A, which is the summary of findings and the supplements.

Q. Okay. I've got it. Thank you.

So let's turn to slide eight.

MR. DEAN: Slide -- so we're back on the same Exhibit 7?

MR. ANWAR: Yes, we're, I think, back a slide.

BY MR. ANWAR:

Q. And on slide eight, do you see it says

"2006 Community Assistance Panel convened?"

A. Uh-huh.

Q. Is that your understanding of when the Community Assistance Panel was convened?

A. Yes. I was not directly involved in convening it or putting it together, but that seems to be around the time that I remember.

Q. Okay. What is the Community Assistance Panel or the CAP as it relates to Camp Lejeune?

A. That was -- that was a recommendation from Congress. They had had a health studies expert panel in 2005, so one of the recommendations that -- a congressionally mandated expert panel for the health studies part. And they saw that the affected community at Camp Lejeune, being widespread and disbursed out, really did not have any representation in assessing their health -- health conditions. And so it was put together and they, you know, provided input to ATSDR, not in decision-making, but just about historical issues related to Camp Lejeune.

Q. And is that where it says "involvement" on the slide, "recommendations of 2005 CL Scientific Advisory Panel", is that the panel you're referring to that Congress mandated?

A. Yes, yes, yes.
Q. Did you attend that expert panel?
A. Yes.
Q. Could you describe for me generally what the discussion was at that panel?
A. I was limited, really, to just talking about, you know, groundwater modeling there. It was primarily focused on health affects, health studies. What additional health studies may be undertaken by ATSDR or what health studies should be undertaken. So it was primarily a health studies panel.
Q. Do you recall who else attended that panel?
A. I know a couple of ATSDR people did and the chair. I remember their names.
Q. Okay. What are their names?
A. The chair was Dr. Cantor. I believe that's K-A-N-T-O-R [sic]. And they had some other panel members, but because they were in the epi/tox health, I really did not know of them professionally. And then it was Dr. Bove and Perri Ruckart. There may have been other ATSDR management people there.
Q. Understood. Do you know Dr. Cantor's

first name?

A. Not off the top of my head.

Q. Okay. Were there any CAP members at the panel? The CAP hadn't been formed yet, right?

A. Right. There may have been some community members, but I don't recall specifically.

Q. Okay. Then on the slide it lists challenges. One is perception of lack of transparency. Untimely provision of information. And then two is -- well, so wait. Let's focus on one. Do you know what that's referring to?

A. I believe the CAP felt that they should be provided information on a regular basis as to what the ATSDR was doing, what the Department of Navy/USMC was providing to ATSDR and the progress of the health studies. And so they wanted a more open -- open process.

Q. It was the CAP that wanted that process?

A. Yes.

Q. Okay. And then --

A. They wanted it more formalized.

Q. Understood. Do you know what steps were taken to, I guess, formalize it?

A. There are documents at ATSDR that you

could, I assume, pull down from the Camp Lejeune website at ATSDR that describes the CAP, and that would probably be a better approach than asking me.

Q. Okay. Fair enough. And then number two under challenges is frustration with missed milestones?

A. Right.

Q. Do you know what that's referring to?

A. Probably the health study because the health study was waiting for results from the water modeling.

Q. When you set out to do the initial Tarawa Terrace water modeling, I think before the break you told me you-all started setting, like, timelines and budgets in 2003, right?

A. Somewhere around there, yes.

Q. What was your original goal to complete the Tarawa Terrace modeling?

A. We thought we could complete it in four years with a caveat depending on the information that we needed, okay? Again, we did not know what information we needed operari other than general types with models required, but not specific to Camp -- Camp Lejeune, okay? So that's -- that's what we -- we said that...

Q. Would you say it's fair to characterize the sort of data gathering process at Camp Lejeune as a large undertaking?

A. Yes.

Q. And I think you mentioned this already, but could you remind me what the purpose of the CAP is?

A. The actual full description of what the CAP is is described in the documents on the ATSDR website. We would provide them with regular updates, quarterly updates, as the progress of water modeling results or problems we were encountering. Health studies would provide them with what they were working on, and the CAP would provide feedback as to what some of the issues the community felt needed to be addressed.

Q. Was the CAP compromised only of community members?

A. At some point there were some representatives of the U.S. Marine Corps, Department of the Navy, and Veterans Administration, but I don't know if they were just brought in as technical-type people or representatives of those agencies. I don't know if they were officially on the CAP or not. You would

have to look that up.

Q. Okay. Do you recall how much input the CAP had on the water modeling project related to Camp Lejeune and/or the epi studies?

A. They might bring us a document that they found saying, you know, there's this contamination here or there and all of that. And then, you know, we would have to look at the document and see if it's scientifically acceptable or that we need to do further research or investigation on to obtaining other documents to corroborate that. There were members of the CAP that actually served time at Camp Lejeune, so if we had a question about a housing area or, you know, a water treatment plant type thing they -- they -- they could provide us sometimes some very useful information.

Q. Who are the members of the CAP that served at Camp Lejeune?

A. It -- it varied. I remember -- I mean, two of them I know of, but there were others and I don't recall their names. Again, ATSDR has on its website the quarterly CAP meetings and you can pull them and find out who the CAP members were.

Q. Who are the two that you recall?

A. Mike Partain and Jerry Ensminger.
Q. Okay.
MR. ANWAR: Can -- can you go to slide 22. Yeah, 23.
THE WITNESS: Okay.
BY MR. ANWAR:
Q. So slide 23 --
A. Yeah, that's not pulled up on my screen.
MR. DEAN: I'm sorry. What?
THE WITNESS: 23.
MR. DEAN: 23. What's -- it's not numbered on here. Bates stamp, can you tell me the last three, four -- 37.
MR. ANTONUCCI: 86.
MR. DEAN: 86.
THE WITNESS: There you go. One more slide. Okay. That's -- okay. Now I see it.
BY MR. ANWAR:
Q. And so this -- this slide is focused on the CAP and it says "the purpose of these panels is to, one, enhance effective communication of environmental health concerns to ATSDR by the public and to establish an avenue for ATSDR to inform the community of site specific scientific

finds as they become available." And then two, it says "provide a means for community participation in ATSDR activities." Did I read that correctly?

A. Yes.

Q. Okay. And is that your understanding -- or is that consistent with your understanding of the purpose of the CAP?

A. My understanding with respect to provide means of community participation would be -- I would add in an advisory role, okay? They didn't influence the ATSDR policy, but they could provide advice.

Q. And then underneath there it lists the members of the CAP --

A. Right.

Q. -- as of 2014.

A. Uh-huh.

Q. And you mentioned Jerry Ensminger and Mike Partain. Who is -- well, and then there's also listed Dr. Richard Clapp and he is denoted, I think, as one of the original members of the CAP. Is that consistent with your understanding?

A. I don't know if he was original or not, but he was a technical expert to the CAP. The CAP could have technical experts as part of their

committee.

Q. Do you know what he was a technical expert in?

A. Public health and epidemiology.

Q. For as long as you were at ATSDR, were Jerry Ensminger, Mike Partain, and Dr. Richard Clapp part of -- or, yeah, Dr. Richard Clapp part of the CAP?

A. Jerry Ensminger and Mike Partain were. I don't know when exactly Dr. Clapp got assigned to the -- to the CAP.

Q. Okay. Did -- prior to 2014, were there other members of the CAP that aren't listed here?

A. Yes, but I wouldn't -- I don't recall their -- their names.

Q. Okay. And I don't think I asked you this before. Who is Jerry Ensminger?

A. He's a retired Marine that's a community activist.

Q. Okay. And what about Mike Partain?

A. He is the son of a Marine, or his parents resided at Camp Lejeune, and developed male breast cancer at the age of 35.

Q. Is Mr. Partain also -- would you view him as a community activist?

MR. DEAN: Object to the form of the question.

THE WITNESS: I really couldn't say about Mr. Partain.

BY MR. ANWAR:

Q. Okay. Do you know who Lori Freshwater is?

A. I know of her, yes.

Q. Who is she?

A. She was a member of the CAP. I believe she's -- has something to do with -- with the news reporting type -- type industry. Well, I mean, that's her occupation.

Q. Okay. Do you know her personally?

A. No.

Q. Who is Christopher Orris, if you know?

A. Yeah, I don't know.

Q. Okay. Who is Tim Templeton, if you know?

A. A member of the CAP. Again, I don't recall when he was appointed to the CAP, but he was a member of the CAP.

Q. Then we -- we discussed Dr. Ken Cantor.

A. Right.

Q. Who is Gavin Smith?

A. I -- I do not know.
Q. Okay. Are there any members of the CAP that are not listed of -- like past members of the CAP that aren't listed here but you recall?
A. Not -- not really. I would have to go through the ATSDR CAP meeting transcripts to...
Q. Okay. Understood. Could we fast-forward to -- it's slide 26. Oh, there it is. Slide 26 ending in Bates range 3789.
THE WITNESS: Kevin, can you pull up there --
MR. DEAN: I'm sorry. What page?
MR. ANWAR: It's slide 26 ending in Bates range 3789.
BY MR. ANWAR:
Q. And it says "why important?" And then if we scroll to the very next slide there's a slide. It's called H.R. 1742, the Janey Ensminger Act. And I'll read the text. It says "to amend Title 38 United States Code to direct the Secretary of Veterans Affairs to establish a presumption of service connection for illnesses associated with contaminants in the water supply at Marine Corps base Camp Lejeune, North Carolina and to provide health care to family members of veterans who lived

at Camp Lejeune while the water was contaminated."
Did I read that correctly?
A. Yes.
Q. With you familiar with the Janey Ensminger Act?
A. Yes.
Q. What was your understanding of it?
A. It was signed by President Barack Obama. The exact year I don't know. Maybe 2012 or so.
Q. And is it this act that established presumptions of service connection for illnesses related to exposure to water at Camp Lejeune as --
MR. DEAN: Object -- object to the form of the question.
BY MR. ANWAR:
Q. Okay. Let me -- let me rephrase it. Based on your -- what is your understanding of what the Janey Ensminger Act did?
A. I don't have a specific understanding. I never actually read the act. In general it provided health care for family members.
Q. Okay.
A. But that's all that -- I don't know any other specifics.

Q. Okay. And when you say health care, do you mean through the VA or...

A. I'd really have to read -- read the act.

Q. Okay. Who is Janey Ensminger?

A. It's the deceased daughter of Jerry Ensminger.

Q. Okay. If you go to the next slide, that slide says "President Obama signed the bill into law on August 6, 2012." Did I read that correctly?

A. Yes.

Q. And that's consistent with your understanding that it was passed in 2012, correct?

A. That's correct.

Q. Okay. And then it says "the bill applies to 15 specific ailments believed to be linked to contamination." And then it lists those. Do you have any understanding of that?

A. Just what it says on the slide.

Q. Okay. Aside from what it says on the slide, you don't have any understanding of the Janey Ensminger Act aside from that it provides health care?

A. Not the legal or political

ramifications of the act.

Q. Okay. Would you agree that ATSDR's water modeling efforts and health studies related to Camp Lejeune were used to help make policy decisions in passing this bill?

MR. DEAN: Help. Object to the form of the question. You used the word "help", so it's an opinion. So object to the form of the question. I mean, you can rephrase your question if you want to, but...

MR. ANWAR: I mean, I'll ask it again, and you can object to form, but I'm asking for your understanding.

BY MR. ANWAR:

Q. Would you agree that ATSDR's water modeling efforts and health studies related to Camp Lejeune were used in some manner to make policy decisions that ultimately led to the passage of the Janey Ensminger Act?

MR. DEAN: Object to the form of the question.

BY MR. ANWAR:

Q. You can answer.

A. Okay. The policy issue is well, well, well above my pay grade when I was in ATSDR. The

water distribution system modeling, again, provided mean monthly concentrations and if someone saw that they were above a certain health criteria, they may have considered that in the act, but I don't know of a direct linkage between what we did -- I was never asked to provide input to the legislation.

Q. Okay. Let's pull up what we'll mark as Exhibit 7 -- no, exhibit --

MS. BAUGHMAN: Eight.

MR. ANWAR: Eight.

(DFT. EXHIBIT 8, letter from Department of Health and Human Services dated January 16, 2013, was marked for identification.)

MR. DEAN: Is it in Dropbox? I mean, in -- what's it called? I don't see it in the --

MR. ANTONUCCI: I can add it right now. Sorry about that.

MR. DEAN: Okay.

MR. ANTONUCCI: It's in the shared folder marked as Exhibit 8.

MR. DEAN: Okay. Got it.

THE WITNESS: Okay.

MR. ANWAR: And would you mind zooming into it a little bit.

BY MR. ANWAR:

Q. I'll just represent to you that -- that I just pulled this letter from ATSDR's website and it looks to be -- to me to be a letter dated January 16, 2013 addressed to General Allison Hickey of the Under Secretary for Benefits at the VA from a Christopher Portier the, at the time, director for the National Center of Environmental Health and Agency for Toxic Substances and Disease Registry. Do you see that?

A. Yes. Well, I mean, you zoomed -- I saw it when you scrolled real quickly.

Q. Okay.

MR. DEAN: So -- so let me object to the use of this document because it's not Bates stamped. I presume it's been produced somewhere and I recognize you said you got it from the public website, but I don't have that personal knowledge. Do you know -- it's not in -- it's not in the government's productions in this case, but with that said, I'm just making a point that I -- it's not a Bates-stamped document and it's not in the government's protections in this case.

MR. ANWAR: Okay. I'm not sure that it's not in the government's production. I suspect it likely is, but I pulled it from the website,

so --

MR. DEAN: No objection. Just making a note here if we do have it somewhere, I would like to substitute the Bates-stamped version at a later date. That's all I'm going at.

MR. ANWAR: Fair enough.

BY MR. ANWAR:

Q. And my first question to you about this document is have you seen it before?

A. No, I've never seen that.

Q. Okay. I would just -- do you know who, excuse me, General Allison Hickey is for the Under Secretary for Benefits Department of VA?

A. I've never heard the name.

Q. Do you know who Christopher Portier is?

A. Yeah, Dr. Portier was the ATSDR director maybe from 2010 through 2013.

Q. Okay. And I'm just going to quickly direct your attention to the first -- the first paragraph of the letter says, "the purpose of this letter is to provide the Department of Veterans Affairs preliminary information regarding our assessment of volatile organic compound exposures in drinking water distributed by Hadnot Point and Holcomb Boulevard water treatment plants at the

United -- at United States Marine Corps base Camp Lejeune."

Did I read that correctly?

A. Yes.

Q. Okay. And then the second paragraph states "the Agency for Toxic Substances and Disease Registry has conducted a series of environmental and epidemiological assessments of contaminated drinking water at USC -- USMC base Camp Lejeune. The foundation of our effort is based on modeling of contamination of the drinking water supply before 1987. The modeling was necessary because there was relatively few drinking water samples tested for VOCs during the period of contamination, none prior to 1982 when VOC contamination was first detected."

Did I read that correctly?

A. Yes.

Q. And is that consistent with your understanding?

A. Yes.

Q. Okay. We can read the next paragraph quickly. It says "ATSDR has focused on three different drinking water distribution systems; Tarawa Terrace, Hadnot Point, Holcomb Boulevard."

Did I read that correctly?

A. Yes, yes.

Q. And are those the three -- three systems that you modeled to estimate contaminant concentrations?

A. Yes, it is. Yes, they are.

Q. And then it goes on to say "we released the final Tarawa Terrace drinking water system report June 2007. That report concluded that former Marines and their families who lived in Tarawa Terrace family housing units during the period November 1957 through February 1987 received drinking water with the dry cleaning solvent PCE at levels above current EPA maximum contaminant level of five parts per billion. The executive summary of the report is located on our website." And then it sites to the modeling -- the executive summary for TTE. Did I read that correctly?

A. You read that correctly.

Q. Okay. And is that your understanding of the -- the water modeling related to Camp Lejeune -- or is it consistent with your understanding related to your water modeling efforts for Camp Lejeune?

A. With one caveat.

Q. Sure.

A. The executive summary was prepared for senate subcommittee members and their staffers and it is not written or presented in the highly technical matter that the summary of findings Chapter A and all the chapters of the Tarawa Terrace reports are. Those were released initially in July 2007.

Q. Okay. Did you write the executive summary?

A. Yes, I did.

Q. Okay. And did you write it knowing that it was going to be provided to senate committee members?

A. Yes.

Q. And I guess other Congress members?

A. I'm sorry. I didn't mean to interrupt.

Q. No, it's okay. It's very natural.

A. Yes, I specifically tailored it. And I don't mean this as a criticism, but it was using larger font type and...

Q. Yeah.

A. Okay.

Q. Making it easier to read and understand --

A. Yes.
Q. -- for people that are not modelers, right?
A. That is correct.
Q. Okay. Do you remember what senators or Congress members that the letter was sent to?
A. I would have to look up because I was subpoenaed to appear at that senate subcommittee hearing.
Q. Okay.
A. And there's obviously some record of who -- who -- who was there, but I don't recall offhand their specific names.
Q. The senate subcommittee hearing you're referring to, is that the one that took place in June of 2007?
A. Yes.
Q. Okay. And so this would've gone to the senators and Congress members that attended that hearing?
A. Yes, it was released whatever the date of the subcommittee hearing. I seem to think June 12th, but whatever. So it was typical that we did -- they would embargo a report and release it first to the parties that needed it, in this case,

the senators and their staffers, and then publicly release -- release it after that.

Q. Okay. And then it goes on to talk about the findings of the model, but I wanted to direct you to the last paragraph.

A. Okay.

Q. It says "I hope this information is useful as the Department of Veteran Affairs evaluates" --

A. Please scroll. Okay. Thank you.

Q. It says "I hope this information is useful as the Department of Veterans Affairs evaluates claims from veterans who served at USMC Camp Lejeune prior to the release of our full water modeling report in the spring. ATSDR is also on schedule to release its mortality study and birth defect and childhood cancer studies in spring 2013. While we finalize our water modeling and these epi studies, I will make certain that we brief the Department of Veterans Affairs staff on our findings. I would also like to recognize the efforts of your -- your department in supporting ATSDR's work and serving Camp Lejeune veterans and their families who were exposed to contaminated drinking water."

Did I read that correctly?

A. Yes, you did.

Q. Okay. Does that -- does that paragraph in particular reflect -- refresh your recollection at all as to sort of whether the water modeling efforts made by you and your team and the epi studies by ATSDR were used to help make policy decisions?

MR. DEAN: Object to the form of the question.

THE WITNESS: Again, I just was not involved in any of the legislation or legislative -- so I don't know what documents or analyses were provided before the official publication of our reports to congressional staffers, so I really could not answer. And then this talks about the veterans affairs, and I never was involved with anything to do with the veterans affairs from -- representing ATSDR. Other people were, but I was not.

BY MR. ANWAR:

Q. Okay. Understood. Do you know who was involved in those conversations?

A. I know at least Dr. Bove was at some point in time and probably Dr. Tom Sinks who was

deputy director of ATSDR and NCEH.

Q. Fair enough. Thank you.

I wanted to quickly turn back to -- and we can take this exhibit down.

We, a few moments ago, discussed the -- the Janey Ensminger Act. Do you recall that?

A. Yes.

Q. And I believe you testified Janey Ensminger was the daughter of Jerry Ensminger, correct?

A. That's correct.

Q. And he was on the CAP, correct?

A. That is correct.

Q. Did you talk with Mr. Ensminger at all about the Janey Ensminger Act before it was passed in 2012?

A. No.

Q. You called Mr. Ensminger an activist. Why -- why is that?

A. Because he was very proactive because he saw the cause for the death of his daughter at age nine a result of the water contamination at Camp -- Camp Lejeune.

Q. And in what ways was he proactive?

A. I believe he helped in some ways to get

Congress to fund -- maybe to fund ATSDR to conduct the health studies, okay? And if we were in need some of information for the water modeling or for the epi studies in terms of base logistics and things like that, he was a good source of information.

Q. Is -- is that -- or would it be fair to characterize what Mr. Ensminger did as sort of lobbying Congress related to Camp Lejeune?

MR. DEAN: Object to the form of the question.

THE WITNESS: I really did not have any experience in lobbying Congress or what one does to lobby Congress, so I couldn't answer that.

BY MR. ANWAR:

Q. But you are -- I guess a moment ago you said he helped, I guess, working with Congress to get funding or --

A. Yeah, yes, he would -- let me back up. From ear to ear there may be questions as to how much funding was available or reduce the funding, the typical congressional budget activities. So he spoke up on behalf of ATSDR as to why we needed the full amount of our budget and why we needed it in a timely manner.

Q. Do you know if he was having conversations with Congress members or senators?

A. I don't know. I don't have any direct knowledge of that.

Q. Okay.

A. Could I ask for a bathroom break real quick?

MR. ANWAR: Sure. Let's take -- let's five.

THE WITNESS: Thank you.

THE VIDEOGRAPHER: Going off the record. The time is 1:29 p.m.

(A recess transpired.)

THE VIDEOGRAPHER: Going back on the record. The time is 1:35 p.m.

BY MR. ANWAR:

Q. We are back on the record from a short break. Mr. Maslia, are you okay to continue?

A. Yes, I am.

Q. Okay. Did you, during the break, speak about your substance of your testimony with your counsel?

A. No.

Q. Okay. I just wanted to put on the record the VA letter that I showed a moment ago as,

I believe, Exhibit 8 has been produced at CLJ, underscore, water modeling, underscore, 01-0000076 158-59 and we are happy to substitute a copy of the Bates-stamped version of that as the exhibit.

So I would like to show you now what had been previously marked as Exhibit 6, but we kind of went out of order, so this is Exhibit 6, but the first time we'll be discussing this document.

MR. DEAN: Okay.

(DFT. EXHIBIT 6, ATSDR document entitled "Camp Lejeune, Summary of the Water Contamination Situation at Camp Lejeune", was marked for identification.)

BY MR. ANWAR:

Q. I'll represent to you that I'm showing you a water modeling summary from ATSDR's website entitled "summary of water contamination situation at Camp Lejeune." Did I read that correctly?

A. That is correct.

Q. Okay. And are you familiar with this page?

A. No, I'm not. It must be a newer page because when I was at ATSDR they never used scan codes, QR codes.

Q. Okay. Do you know if you were involved in providing information or populating the information on this page?

A. Yes, I was.

Q. Okay. And we can sort of scroll through it, at least up there and then your counsel can scroll through it for you, but I wanted to ask you to take a look at it, and based on your review of it, is the information contained within this website summary, the water modeling website summary, true and accurate to the best of your knowledge?

MR. DEAN: All right. So let's just start at the top and then you tell me to scroll.

THE WITNESS: Okay. Go ahead and scroll. Okay. Go ahead and scroll. Okay. Go ahead and scroll. Okay. I've read it.

BY MR. ANWAR:

Q. Based on your review of this page, is the information contained on the modeling summary true and accurate to the best of your knowledge?

A. Yes.

Q. And so I just want to now talk through it in a bit more detail and then we'll walk through it. According to the page it says there were eight

water distribution systems that supplied finished water to family housing and other facilities at Camp Lejeune, right?

A. That is correct.

Q. Then it lists eight water distribution systems. In the middle of the page it states "three water distribution pants, Hadnot Point, Tarawa Terrace, and Holcomb Boulevard have historically supplied finished water to the majority of family housing units at the base and were contaminated with volatile organic compounds, VOCs. Information about these three water treatment plants is provided below. Other non-based treatments plants were not contaminated."

Did I read that correctly?

A. Yes.

Q. Okay. So it lists the eight water distribution plants there, and I just wanted to confirm with you, based on your understanding, the water distribution system for Courthouse Bay was not contaminated with VOCs, right?

A. I would not be able to answer that without looking at documents because we really did not look at areas other than Tarawa Terrace, Hadnot Point, and Holcomb Boulevard, okay, which were the

family housing areas as the website points out. So we really did not do -- gather any information or data to be able to make that statement yes or no for any of the other areas.

Q. Is the reason that you didn't gather information related to those other areas -- and I'll just read them quickly. Courthouse Bay, Rifle Range, Onslow Beach, Montford Point/Camp Johnson, New River. Is the reason you didn't gather information related to those water distribution systems and did not model those water distribution systems because you're not aware or you have no reason to believe that they were contaminated?

MR. DEAN: Object to the form of the question.

THE WITNESS: No, that's not the reason.

BY MR. ANWAR:

Q. Okay. Tell me the reason.

A. The reason why Congress funded ATSDR through the Department of Navy to analyze family housing areas, and that's the three that we have previously mentioned here, those are not family housing areas. And when we went on base in July 2003 and toured around, we -- I, in fact,

mentioned to my points of contact, I said, well, if we're going to do water modeling on those three areas, we can just as easily do it on the whole base, and I was told that that was not going to happen.

Q. Okay. Would it be fair to say, then, as it relates to the water modeling efforts that you performed, the water modeling does not reach any conclusions about water contamination -- VOC contamination, water contamination, at these other water distribution systems, Rifle Range, Courthouse Bays -- Courthouse Bay, Onslow Beach, Montford Point/Camp Johnson and New River in the air station?

A. Just roll that back right there. Okay. One thing I did notice, based on our analysis, we did look at Montford Point and Camp Johnson because it was connected to Tarawa Terrace through a pipeline.

Q. And --

A. And -- well, that's what -- I just want to correct the record for that.

Q. Did you make any determination about whether Montford Point/Camp Johnson was providing water to Tarawa Terrace or Tarawa Terrace was

providing water to Camp Johnson?

A. There's -- that's been a subject of controversy, I will say, because there's some people who believe, based on certain documents, that Tarawa Terrace, which was contaminated, provided drinking water to Montford Point and Camp Johnson. Though all the investigation that we did and their documents that show that Tarawa Terrace was so short on water that Camp Johnson provided water to Tarawa Terrace.

Q. That's what -- based on your investigation --

A. Right.

Q. -- you believe Camp Johnson provided water to Tarawa Terrace?

A. Yes, yes, when needed. When needed by Tarawa Terrace.

Q. When needed.

A. Yes.

Q. Okay. And your water model -- the water modeling efforts related to Camp Lejeune didn't examine Courthouse Bay, correct?

A. That is correct.

Q. And the water modeling efforts related to Camp Lejeune didn't examine the Rifle Range,

correct?

A. That is correct.

Q. The water modeling efforts related to Camp Lejeune didn't examine Onslow Beach, correct?

A. That is correct.

Q. The water modeling efforts that you -- you landed on related to Camp Lejeune didn't examine the Montford Point/Camp Johnson's water distribution, correct?

A. Say that again. Sorry. I didn't understand.

Q. Okay. Let me -- you did not -- the water modeling efforts that you and your team performed related to Camp Lejeune do not show that Montford Point/Camp Johnson's water distribution system were -- was contaminated or affected by VOCs?

MR. DEAN: Object to the form of the question.

THE WITNESS: We investigated Camp Johnson/Montford Point from a water distribution side because they had a pipeline connecting that was Tarawa Terrace. So to understand the operations at Tarawa Terrace, we had to instrument certain pertinences at Camp Johnson and Montford

Point.
BY MR. ANWAR:
Q. Okay. And I think earlier you stated based on your investigation you believe that Camp Johnson provided water to Tarawa Terrace and not the other way around, correct?
A. That is correct.
Q. Okay. And do you, as you sit here today, have any reason to believe that the water distribution system at -- or do you have any evidence that the water distribution system at Camp Johnson was affected by VOCs or contaminated from '53 -- 1953 to 1987?
MR. DEAN: Object to the form.
THE WITNESS: No, I do not.
BY MR. ANWAR:
Q. Okay. And what was it about your investigation that led you to the conclusion that Camp Johnson was providing water to Tarawa Terrace?
A. We looked at the present day, meaning 2004 water distribution system because that's when we came on base, okay? Initially said we -- they had -- because the Marine Corps and most of the military bases do not meter their water. So we had to find out how much water was flowing through the

system, so we had to instrument the distribution system. And one of the controlling tanks was over at Montford Point/Camp Johnson for Holcomb -- by 2004 it was Holcomb Boulevard that it was controlling for.

Q. Okay.

A. So we would have to -- we did, in fact, instrument a tank, a controlling tank, there based on the water level at Camp Johnson and Montford Point, that's when the pumps at either Tarawa Terrace or Holcomb Boulevard would come on.

Q. Okay. And the -- your and your team's efforts related to Camp Lejeune water modeling, the water modeling does not show or does not examine New River Air Station, correct?

A. That is correct.

Q. The water modeling also does not examine Camp Geiger, right?

A. Is that correct.

Q. Do you have any reason or evidence to believe that Camp Geiger was impacted by VOCs or water contamination?

A. We just never looked at it, so I couldn't say. I did not review any -- any data.

Q. Okay.

A. Okay? So I could not say whether it was contaminated or not.

Q. I want to turn back quickly to the Montford Point/Camp Johnson issue. And I will show you what we'll upload -- what we're marking as Exhibit 9.

(DFT. EXHIBIT 9, e-mail correspondence Bates-stamped CL_MASLIA_0000000817 and 818, was marked for identification.)

MR. DEAN: So for the record, just to clear this up while he's bringing that up, Exhibit No. 8 that you marked, which was that ATSDR un-Bates-stamped document.

MR. ANWAR: Yeah.

MR. DEAN: For the record is CLJA, underscore, VA, underscore, RFP, underscore, fourth set underscore, 4109. And I'd ask that we replace and use that version for his depo.

MR. ANWAR: Okay. We'll take a look at a break and we can -- assuming it's the same thing, that shouldn't be an issue.

MR. DEAN: Okay.

MR. ANWAR: Is the exhibit up? Okay. If you'll go ahead and display it, please.

BY MR. ANWAR:

Q. Okay. We are pulling up what has been marked as Exhibit 9 or will be marked as Exhibit 9.

MR. ANWAR: And I will just note for the record before we start talking about this document that we -- we -- this -- so this was produced to us in response to the subpoena issued to Mr. Maslia, and we provided notice to the Plaintiffs Leadership Group who did not object to us holding onto the document or seek to --

MR. DEAN: I agree.

BY MR. ANWAR:

Q. Okay. So --

MR. DEAN: And for the record, the reason I told you I provided it to you -- because this is an e-mail from Jerry Ensminger to Mr. Maslia during his consulting with us. He then forwarded it to me, so I had the communication. Therefore, I felt the need and obligation to produce it to you.

MR. ANWAR: Okay.

BY MR. ANWAR:

Q. So let's scroll down to the bottom of the e-mail.

A. Okay.

MR. DEAN: Oh, the bottom one?

MR. ANWAR: Yeah, the one from Mr. Ensminger.

BY MR. ANWAR:

Q. So it looks like the chain starts -- the first e-mail on the chain is dated April 29, 2024, and it is an e-mail from Jerry Ensminger, Mr. Ensminger, to you, Mr. Maslia.

A. Right.

Q. Is that correct?

A. Yes, that's correct.

Q. Okay. And from my review of it and just from the subject it says "I am sharing CLW1191 with you" and then he provides a link to, I think, the document; is that right?

A. Hold on. I'm not seeing -- i am sharing --

MR. DEAN: That's in the subject line.

THE WITNESS: Oh, I'm sorry. Okay. Yes, yes, that is correct.

BY MR. ANWAR:

Q. And to the best of your recollection, is that what the link was, the link to that document?

A. It was a link to a CLW Camp Lejeune water document.

Q. Okay. And do you know why he was sending that document to you?

A. I guess he -- my understanding is that there were individuals who believed Tarawa Terrace, because it was contaminated with contaminated drinking water and contaminated wells, was -- was supplying water to Camp Johnson and Montford Point.

Q. Okay. And so that's what he -- was being sent to you to look at that question?

A. To look at that document. He felt that that document proved their point.

Q. Okay. Do you recall what that document is, CLW1191?

A. Yes, it's a document that describes -- if you could scroll down to the top part -- scroll up to the top part of the letter, that in the document it describes the pipeline going -- there's a pipeline going from Tarawa Terrace to Montford Point/Camp Johnson and that a Tarawa Terrace was -- and the capacities of how much each system in terms of million of gallons per day were producing or needed, and that Tarawa Terrace was substantially short on water.

Q. Okay. And so I'm just going to read the document. It says at the top of -- so the top

of the chain is dated April 30th, 2014 and it's from you, Mr. Maslia, to Mr. Dean, counsel, and -- is that right?

A. That -- yes. And somebody from the outside would contact me about work that was consulting on, then I would contact counsel to see if they wanted me to respond or they should respond or...

Q. Understood. And so your e-mail to Mr. Dean states "received from Jerry Ensminger. Have not responded to his e-mail. I am aware of the CLW1191 document. We have always said there is a pipeline connecting Tarawa Terrace and Camp Johnson. It is shown in Figure A-4 and Plate 1 of the Tarawa Terrace Chapter A report."

Did I read that correctly?

A. That is correct.

Q. Okay. And then the next paragraph states "the issue is did Tarawa Terrace provide drinking water to Camp Johnson or did Camp Johnson provide drinking water to Tarawa Terrace?"

Did I read that correctly?

A. Yes.

Q. Okay. And the last paragraph states "the answer is Tarawa Terrace was very short on

drinking water, especially in the summer as indicated in CLW1191, so Camp Johnson provided uncontaminated drinking water to Tarawa Terrace. Camp Johnson is at a higher elevation than Tarawa Terrace, so that a pump would need -- would be needed for Tarawa Terrace to provide water to Camp Johnson, which did not exist. Additionally, the controlling tank for Tarawa Terrace's tank SM-63 -- 623, excuse me, an elevated storage tank. Thus, based on the water demand and water level in the elevated tank, Camp Johnson would provide uncontaminated drinking water to Tarawa Terrace."

Does I read that correctly?

A. Yes.

Q. And is that still your conclusion today?

A. Yes, it is.

Q. Okay. We can remove that exhibit and go back to Exhibit 6. Okay. Do you have that exhibit in front of you?

A. I think we need to scroll up.

MR. DEAN: I'm sorry. It's at 6 again?

THE WITNESS: Yeah, right there. Okay.

BY MR. ANWAR:

Q. And so looking at Exhibit 6 again, only

the water distribution systems at Tarawa Terrace, Hadnot Point and Holcomb Boulevard were affected with contaminated water, right?

MR. DEAN: Object to the form of the question.

THE WITNESS: The three -- the three that you mentioned were contaminated with volatile organic compounds and BTEX compounds. Again, the others we did not specifically look at. That would be, I think, incorrect to make a determination as to whether they were contaminated or not contaminated.

BY MR. ANWAR:

Q. In the middle of the page, that middle paragraph that we went to, it says "information about these three water treatment plans is provided below. Other on-base treatment plants were not contaminated."

Would you -- would you agree with that statement, "other on-base treatment plants were not contaminated?"

A. If that's the agency's position, then I would agree with that.

Q. Okay. As you sit here today, you have no reason to dispute that statement, which is on

ATSDR's website?

A. No.

MR. DEAN: Object to the form of the question.

BY MR. ANWAR:

Q. Was that a "no"?

A. That was I have no reason to doubt this -- the text on the web -- webpage.

Q. Great. So with respect to Tarawa Terrace, Hadnot Point, and Holcomb Boulevard, what were the VOCs and contaminants at -- or chemicals at issue?

A. At Tarawa Terrace the primary source contaminant was tetrachloroethylene or perc or perchloroethylene, which is a dry cleaning and the degradation products from that. At Hadnot Point and Holcomb Boulevard, they had a number of source contaminants. Again, you had perchloroethylene, PCE. They had an on-base dry cleaner. You also had TCE or tetrachloroethylene, and you also had BTEX products.

Q. Which is benzene?

A. Benzene, toluene.

And then at Holcomb Boulevard they had intermittent contamination because of opening a

pump in the Marston pump 742 and Marston Pavilion valve to provide Hadnot Point water to Holcomb Boulevard on an intermittent basis.

Q. Okay. And I just wanted to quickly just walk through each of the -- the treatment systems with respect to -- and starting with Tarawa Terrace, since I think your report for Tarawa Terrace came first. It says here "began operation in 1952"; is that right?

A. Yeah.

Q. Okay. And then it says -- and when it says "began operation", is it referring to the water distribution system for Tarawa Terrace?

A. That would be our understanding.

Q. Okay. And then it says "the Tarawa Terrace water distribution system was shut down in March of 1970 -- or 1987"; is that right?

A. That's correct.

Q. And that's your understanding as well, right?

A. Yes.

Q. Okay. And it says "the Tarawa Terrace water distribution systems" --

A. Can you scroll up a little? That's good. Okay.

Q. It says "areas served for the Tarawa Terrace water distribution system, TT, family housing, Knox Trailer Park; is that right?

A. That's correct.

Q. Okay. And is that your understanding as well?

A. That's my understanding as well.

Q. Are there any other areas within Tarawa Terrace that you -- that are -- you're aware of that were impacted by the water distribution systems in Tarawa Terrace?

A. No, I'm not.

Q. Okay. You mentioned that PCE was the main contaminant at Tarawa Terrace, right?

A. That is correct.

Q. And then you mentioned degradation products of PCE, correct?

A. That's correct.

Q. It says in -- on the page, the source of contamination was ABC One Cleaners, an off-base dry cleaning firm; is that right?

A. That is correct.

Q. All right. And the degradation products for PCE with respect to Tarawa Terrace that I, at least, saw that the model -- your

modeling for Tarawa Terrace looked at were DEC, TCE and vinyl chloride?

A. That is correct.

Q. And those three particular chemicals, again, were only as degradation products of PCE, correct?

A. Yes, that's correct.

Q. Okay. ATSDR's water modeling for Tarawa Terrace didn't model benzene concentrations for Tarawa Terrace, right?

A. That is correct. Although we documented benzene contamination at one or two locations for data -- data discovery purposes and that's included in some of the reports.

Q. If I understand your prior deposition testimony correctly, you-all didn't model or look at benzene in the Tarawa Terrace model because any benzene samples that were discovered didn't -- weren't high enough to cause you any concern, correct?

A. I recall we didn't model benzene because we could not identify a source for benzene even though there were water samples that showed hits of benzene. I don't recall specifically their -- their levels. I do recall them being low,

but whether they were above or below an MCL just without looking at our reports, I could not say, but the primary reason not modeling it was we could not identify the source of that benzene.

Q. Okay. And your -- and I'm just going to, like, read it verbatim. Your prior deposition testimony on this particular topic you state, quote, after reviewing the data and the analyses that we did based on the underground storage tanks, we did not -- number one, we thought number one that whatever gasoline -- because at Tarawa Terrace there were gasoline holding tanks leaks was small enough in nature that it did not impact any of the supply wells, so there was no major source of benzene and, in fact, the results there are, I think, two or three samples at the water treatment plant that are, say, one to four, maybe there's a seven micrograms per liter were substantially low that it did not, again, indicate there was a source at Tarawa Terrace for benzene contamination of groundwater supplies that would impact drown -- impact drinking water.

MR. DEAN: Object to the form. If you have -- I can get me a copy of it, but I believe the witness is entitled to review the transcript.

MR. ANWAR: We can pull it back up. It's marked as an exhibit.

BY MR. ANWAR:

Q. But my -- just -- and I'll pull it up here in a second for you to take a look. Based on having just read your -- your deposition testimony there, is that still your understanding today?

MR. DEAN: So --

THE WITNESS: Let's just see the deposition.

MR. DEAN: I believe he needs to have an opportunity to take a look at the transcript. So if you give me just a second, I'll --

MR. ANWAR: We can pull it up. It's up now.

THE WITNESS: Okay.

MR. ANWAR: It's page 71.

MR. DEAN: What exhibit?

MR. ANWAR: It was Exhibit 3.

MR. DEAN: And what page are you on?

MR. ANWAR: Page 71.

MR. DEAN: I'll go to page 70. So let me just do this so you can scroll through it, okay? You might want to look a page or two before and a page or two after. He said it's on page -- what

did you say?

MR. ANWAR: Starts at 71 to -- that's his response. You can look -- is that -- yeah.

THE WITNESS: Can you scroll that one down to a page number so I can see the corresponding page number on my...

MR. DEAN: Go by the Bates-stamp number. He's at 9579.

THE WITNESS: Okay. Hold on. 9579. Oh, okay. I'm not even close to there. Okay.

BY MR. ANWAR:

Q. The deposition transcript page number on the right-hand corner is 71.

A. Yeah, I'm there. I'm at 65. Hold on. Okay. Here we go. Okay. Here we go.

Q. And starting at line seven.

A. Yeah. Okay. I'm reading. Okay.

Yes, I would -- I would still stand by my deposition.

Q. Okay. Fair enough. Okay. Let's go back to Exhibit 6, please. Thank you.

MR. DEAN: Okay.

BY MR. ANWAR:

Q. At the top of the page -- could we scroll up a little bit? Okay. So on Exhibit 6

it's says "the water distribution system at Hadnot Point began operation in 1942"; is that right?

A. Yes.

Q. Okay. And then it says "the areas served were Mainside barracks, Hospital Point family housing, and then family housing at Midway, Paradise Point, and Berkeley Manor until 1972"; is that right?

A. It also served the Navy -- the old Navy hospital that was located at Hospital Point, okay?

Q. Okay.

A. It was both family housing and the hospital.

Q. Understood. Is that reflected in your -- your reports?

A. It's on the maps that -- that we produced as part of the reports, yes.

Q. Okay. So Mainside barracks, Hospital Point family housing and the hospital, and then the family housing at Midway, Paradise Point, and Berkeley Manor until 1972; is that right?

A. I suppose I'm a little confused here because Hadnot Point is still operating.

Q. Are you --

A. It seems to indicate that family

housing at Midway until June 1972. They're either missing some text there or -- because I know Midway Park and -- okay, okay, okay, let me correct that. Yeah, 1972, that's when Holcomb Boulevard came online, so that's correct.

Q. That is correct?

A. Yes.

Q. Okay.

A. Sorry for the confusion.

Q. It's okay. And you said TCE was the main contaminant or the main VOC of concern at Hadnot Point, correct?

A. At Hadnot Point, yes.

Q. And then I think you also said you considered PCE and benzene, correct?

A. That is correct.

Q. Do you recall the sources of contamination at Hadnot Point?

A. There are multiple sources. For the TCE it would have been the landfill at Hadnot Point. For the PCE it would have also have been the landfill. They had an on-base dry cleaner, so there was some assumptions we had to make, but, in other words, PCE cannot be a degradation product of TCE, so it had to be a source, okay?

Q. Understood.
A. And then you would have the fuel farm, which -- where you would have the benzene contamination.
Q. So my understanding of the sources were underground leaking storage tanks and waste disposal sites; is that right?
A. That would have been -- the underground storage tanks would have primarily been for the fuel farm.
Q. Okay.
A. And then the landfill is, you know, where things -- industrial items and things like that would have been dumped into, so that would have been the source for the TCE and the PCE as well.
Q. In the three specific areas I have down and you mention in your prior deposition are the Hadnot Point industrial area, Hadnot Point landfill, and then HP-645 area, Building 645?
A. That's part of the -- well, what we were -- we did the analysis referring to the HP fuel farm and the industrial area.
Q. Okay.
A. So it was just a specific building in

that area.

Q. So the -- okay. Understood. And so for -- I think I missed this, but it said further down for Tarawa Terrace -- I'm sorry that I'm jumping back to Tarawa Terrace.

A. Okay.

Q. It says "most contaminated wells were shut down in February 1985."

A. That's correct.

Q. Okay. Are you aware of any contaminated wells that weren't shut down?

A. They were all shut down by -- during 1987, but they'd shut down the -- I think three primary contaminated wells, TT-26, TT-23 and, I think, TT-25 in '85 and that's actually one of the graphs in our Chapter A report for Tarawa Terrace, will tell you when the wells shut down.

Q. Based on your understanding, is there evidence or a factual basis for there being VOC contamination in the Tarawa Terrace water distribution system between February 1985 and December 1987? So like the --

A. It would be a small amount, yes, because the -- besides those three big contaminated wells that were shut down, the other wells, which

were pulling contaminated groundwater up were not shut down.

Q. So is it your understanding that there was sort of remnant contaminated water from the three wells that were shut down from 87 -- '85 to '87?

A. No, I would describe it as the aquifer underlying Tarawa Terrace was contaminated, okay? And you shut down the three big supply wells going into the distribution system in '85, but the remaining wells were still putting water into the distribution system along with uncontaminated wells, but their concentrations were substantially lower than the three big ones that were shut down in '85, so it would have been diluted down.

Q. After those three wells -- the most contaminated wells were shut down from '85 to '87 is -- is there sampling data related to -- do you recall the -- showing that the aquifer and other wells were still contaminated?

A. I would have to look back -- look through our reports.

Q. Okay. Would you defer to what your reports say about observed data?

A. Yes.

Q. Okay. And so jumping back to Hadnot Point, for Hadnot Point the most contaminated wells were shut down by February 1985 as well, correct?

A. I'm not seeing where you're reading that or...

Q. It's pages --

A. Oh, okay. Most contaminated wells were shut down. This is for Hadnot Point, yes.

Q. And for that period between February 1985 and December 1987, is your -- do you have any evidence or sort of factual basis for believing that there were other wells at Hadnot Point that were still contaminated?

A. There was contamination. We carried out the historical reconstruction simulations through 2008. So if you go to -- again, I'm going to refer to our reports because they have graphs in there showing the concentrations in the wells and the finished water past '85.

Q. Okay. Got it. And then Holcomb Boulevard it states "began operation in June 1972"; is that right?

A. Yes, that -- that is our estimate.

Q. And it says "family housing at" -- or "areas served family housing at" --

A. Let me just scroll, scroll up. Kevin, if you can scroll down to Holcomb Boulevard for me. There you go. Okay.

Q. Under Holcomb Boulevard it says "areas served family housing at Midway Park, Paradise Point, Berkeley Manor, and Watkins Village and then served Tarawa Terrace family housing after March 1987"; is that right?

A. That is correct.

Q. It says "Holcomb Boulevard wells were generally not contaminated"; is that right?

A. That is correct.

Q. But the last two bullet points "contaminated water from Hadnot Point water treatment plant supplied the drinking water system when the Holcomb Boulevard plant was shut down during January 27 to February 7, 1985?"

A. That is correct.

Q. And then the last bullet point, "contaminated water from Hadnot Point water treatment plant was used intermittently to supplement the Holcomb Boulevard drinking water supply during dry spring and summer months when demand was high in 1972 and 1985?"

A. Yes, that is correct.

Q. Okay. We can go ahead and take that exhibit down.

MR. DEAN: Haroon, can we take a bathroom break?

MS. BAUGHMAN: We need to take another --

THE WITNESS: I've got a cold and --

MR. ANWAR: Oh, no worries.

THE VIDEOGRAPHER: Going off the record. The time is 2:17 p.m.

(A recess transpired.)

THE VIDEOGRAPHER: Going back on the record. The time is 2:20 p.m.

BY MR. ANWAR:

Q. We are back on the record from a short break. Mr. Maslia, are you okay to continue?

A. Yes, I am.

Q. Okay. I'm going to quickly revisit Exhibit 6, which we just had finished discussing before the break and I wanted to clarify, I think you agreed with a question that I asked but I misspoke in my question. That last question, that last bullet point under Holcomb Boulevard says "contaminated water from Hadnot Point water treatment plant was used intermittently to

supplement the Holcomb Boulevard drinking water supply during dry spring and summer months when demand was high 1972 through 1970 -- or 1985?"

A. That is correct.

Q. Okay. And I think I accidently said '72 and 1985 before and what I meant to say was '72 through '85.

A. That is correct.

Q. Okay. And we had briefly had a discussion, I had asked you sort of the basis for why wells in Tarawa Terrace were still considered contaminated after the main wells were shut down in '85. And I think you mentioned sort of the aquifer and the other supply wells pulling from -- from that aquifer; is that right?

A. That is correct.

Q. Okay. Do you -- can you identify any specific wells, like other wells that were still contaminated?

A. I would have to look at our reports to tell you the well numbers.

Q. Okay. And we'll take a look at the reports. Is -- do you recall if -- do you recall if -- one second. Let me look at my outline. Sorry. Just one second.

Do you recall if those -- if there was, in fact, observable data from '85 to '87 with respect to other wells in Tarawa Terrace or if that was based on model simulation?

A. I would really have to look at the report.

Q. Okay.

A. That was the tail -- tail end of our simulation. It's in the reports, though. They're graphs of the wells.

Q. Why don't we go ahead and mark exhibit -- or Chapter A to the Tarawa Terrace report as Exhibit 9.

MR. DEAN: The summary?

MR. ANWAR: Correct.

(DFT. EXHIBIT 10, document entitled "Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions Chapter A: Summary of Findings", was marked for identification.)

MR. ANWAR: And --

MS. BAUGHMAN: Are you putting it up

or...

MR. ANWAR: Yeah.

MR. ANTONUCCI: Sorry about that.

MS. BAUGHMAN: Is it here as Exhibit 9?

MR. ANTONUCCI: It is Exhibit 10.

MR. ANWAR: Oh, I'm sorry. We're putting up the Tarawa Terrace, Chapter A, summary of findings as Exhibit 10. And for the record, Mr. Maslia is looking through Chapter A, summary of findings.

BY MR. ANWAR:

Q. Is there a particular page that you're looking at?

A. Yes, I'm looking at page A-39, Figure A-18.

Q. We're getting there.

A. That's -- yes, that's the graph I'm looking at.

Q. Okay. So from '85 -- February '85 to December '87, with respect to Tarawa Terrace, is there any observable data -- observed data of water contamination with respect to other wells at Tarawa Terrace?

A. Not -- not that I see on the graph and not that we published.

Q. So would that have been, then, based on that statement that said -- suggested that other wells may have had some contamination remaining, is that based on the computer simulation?

A. Yes, it is.

Q. Okay. Let's take that down for a moment. We'll put it back up shortly.

So I want to switch gears and now ask you specific questions about the modeling work that you performed.

A. Sure. Okay.

Q. So we may jump around a bit, and I apologize. And if you need to look at any of your reports, just let me know.

A. Okay.

Q. And we can mark them as an exhibit and walk through them together.

A. Okay.

Q. So we've been referring to water modeling and the water modeling efforts that you and your team at ATSDR performed related to Camp Lejeune. But when we say "water modeling" are we really referring to groundwater modeling, fate and transport modeling, and water distribution modeling?

A. It's a catchall phrase or a generalized characterization that we thought would enable the public to more generally understand or nontechnical people to understand what we were undertaking, but, yeah, that.

Q. What is groundwater modeling?

A. Groundwater modeling uses numerical methods or analytical methods to solve mathematical equations that describe the flow of groundwater from point A to point B.

Q. What is fate and transport modeling?

A. Fate and transport modeling is determining the fate and the movement of a contaminant or contaminants through a groundwater system.

Q. And what is water distribution modeling?

A. Water distribution system modeling is the movement of water through pressurized pipelines in the distribution of the water through the pipeline network.

Q. We've talked about this a little already, but are you familiar with the term of a hindcast model?

A. I'm familiar with the term.

Q. What is a hindcast model?
A. I disagree with the term.
Q. Okay. What is -- what is your understanding of the term?
A. My understanding is that you start, let's say, in 2024, go back to 2023, '22, '21 and that. Some people have equated that with historical reconstruction, but we have published in a peer review journal a discussion as to why that's not the same.
Q. Are hindcast models used to recreate past conditions based on limited or nonexistent data?
A. I really couldn't speak about hindcasting. I can speak about historical reconstruction.
Q. In your mind, how does a hindcast model differ from a historical reconstruction?
A. A historical reconstruction you might use present day information or historical information and then march forward in the time. So for example, at Tarawa Terrace we may know what the groundwater conditions were prior to wells being installed 1950 to '53. Then as the wells pump, we go forward in time until the wells were shut down.

So that's historical reconstruction.

Q. And for Camp -- for Tarawa Terrace, did you have -- you did not have sampling data back to 1953, right?

A. Not contaminant data, but there are some water level data and based on geohydrologic investigations where -- when they were drilling the wells back then, they would take water samples and indicate where the groundwater level was, so you could have that -- those limited data. And because there was no pumping going on, you knew, for example, that New River was at zero elevation or at sea level, so you could, with reliability, simulate and estimate the predevelopment conditions, pre-pumping conditions, at Tarawa Terrace in the aquifer.

Q. And I think we discussed this earlier, but just to be -- to be clear, the first Tarawa Terrace model, the purpose was to sort of reconstruct estimated concentration -- monthly concentrations of primarily PCE, but also it's degradation products from roughly '53 to '87; is that right?

A. That is correct.

Q. Okay. And the second model, the Hadnot

Point/Holcomb Boulevard model, was it historical reconstruction to estimate monthly contaminant concentrations for Hadnot Point/Holcomb Boulevard for roughly 1953 to 1987; is that correct?

A. We actually carried out the Hadnot Point historical reconstruction through 2008 because there was remediation data onsite at Camp Lejeune that helped us calibrate the models out to that, so that one was carried out to 2008.

Q. Okay. And that was -- Hadnot Point/Tarawa Terrace was primarily looking at TCE, PCE --

MS. BAUGHMAN: You said Tarawa Terrace.

MR. ANWAR: I'm sorry. Thank you for that correction.

BY MR. ANWAR:

Q. Hadnot Point/Holcomb Boulevard, that model was primarily looking at TCE, PCE, benzene --

A. Yes.

Q. -- and vinyl chloride; is that right?

A. That is correct.

Q. And the purpose of both of those models was to estimate monthly contaminant concentrations for use in epi studies?

A. Estimate mean monthly concentrations

for use by the health studies or the epidemiological studies.

Q. Okay. Why did you land on mean monthly concentrations?

A. Based on an analysis of the available data, groundwater data, geohydrologic data, contaminant data, we felt that -- and supply data -- that we could reliability obtain results on a monthly basis. And the assumption was that at the end of each month you would get a water level in the groundwater aquifers and that level we consider to be an average that would -- equally likely to occur on the last day of the month, the first day of the month, the middle of the month. So that's how we -- we -- and that was as refined as we could get, okay? So we could not -- because of the data of limitations, we did not feel justified scientifically to go any finer than a month period at a time.

Q. Did Dr. Bove or Perri Ruckart, did they request estimated mean monthly contaminant concentrations or that was -- was that the best that the model could provide?

A. My recollection is that they initially requested trimester data, but we told them that we

could provide mean monthly and they said then they would prefer to go with that because that would account for uncertainty for them.

Q. Okay. Do you have any understanding of what they meant when they said it would account for uncertainty for them?

A. That health studies in general have a large uncertainty associated with them because of a lot of unknowns. Specifically, for example, exactly how much water an individual digests, stuff like that. And so if you need trimester data, if you could get monthly data, then that can show you how it may vary through the trimester. And so we gave them -- provided more refinement than they initially requested.

Q. Okay. And I just wanted to make clear that the -- neither the Tarawa Terrace nor the Hadnot Point/Holcomb Boulevard models show or were intended to show actual exposure in individuals, correct?

A. The models were intended to show the mean monthly concentrations in the finished drinking water.

Q. Okay. And they don't show how much any individual person was exposed to, correct?

MR. DEAN: Object to the form of the question.

THE WITNESS: We did not look at populations or people in the water modeling phase of the project.

BY MR. ANWAR:

Q. Because it -- as far as I can tell, it doesn't take into account things like where people lived on base necessarily or how many showers they took or deployments, how much water they drank?

A. That's an exposure assessment and we were not tasked with conducting an exposure assessment.

Q. Okay. And that was kind of the point I was getting at. The water modeling was not an exposure assessment, correct?

A. That is correct.

Q. Were the estimated monthly contaminant concentrations for both of the models, were they intend to be used as quantitative or qualitative?

MR. DEAN: Object to the form of the question.

BY MR. ANWAR:

Q. And again, I'm not interested in -- this can, you know, this carries on through the

entire deposition, I'm not interested in any discussions that you've had with counsel since you've been retained as a consultant.

A. I understand. Could you repeat the question again?

Q. Sure. Were the estimated monthly contaminant concentrations for both of the models intended to be used as quantitative or qualitative results?

MR. DEAN: Same objection.

THE WITNESS: We felt, from a water modeling standpoint, that they were of substantial accuracy, that they could be used quantitatively.

BY MR. ANWAR:

Q. And do you believe that to be true for the entire period from 1953 to 1987?

A. Yes.

Q. What -- were the two models, the one for Tarawa Terrace and the one for Hadnot Point/Holcomb Boulevard, were they peer reviewed?

A. Yes, they were.

Q. Who peer reviewed them?

A. We had another -- excuse me. We had a formal and informal peer review process. For, let's say, for Tarawa Terrace to start with, we

brought together a panel of national and international experts in March 2005 to evaluate the work that we had done to that point and provide us guidance going forward.

Then when using their suggestions or their recommendations modifying our approach, we then finished the Tarawa Terrace analyses in 2006, let's say, and so then the Office of Science at ATSDR would send them out to external peer review.

Okay. And the same thing for Hadnot Point, we had an expert panel in 2009, I think, and, again, based on feedback, I mean, they are, in essence, peer reviewers, but they were not blinded to the panel members, but then when the Office of Science sends it out, we are blinded to the name of the peer reviewers just like a scientific journal.

Q. Understood. So the -- you would consider the internal review to be the panels you discussed the modeling with?

A. In combination there was also an internal ATS -- or technical staff review.

Q. Do you know who on the technical staff reviewed the two models?

A. No, I do not.

Q. And you were blinded from the peer

review of any external review?

A. Other than responding to the reviews.

Q. What do you mean by responding to the reviews?

A. Well, once the Office of Science selected a set of peer reviewers, and there were a number of them because of the number of chapters, and people have different expertise, so there was -- they would review and then they would send back review comments to the Office of Science. They would forward us the review comments not knowing -- without names on them, and then we would respond that we would accept or not accept their recommendations and have to explain why we either accepted or didn't accept the peer reviewers' recommendations. Similar process that if someone submits a manuscript to a peer review journal.

Q. So you don't -- if I'm understanding you correctly, because you were blinded, you don't know the identities or the names of the external peer reviewers?

A. I know some of the members as a pool because as with everything, the Office of Science may not have known specifically about groundwater modeling or fate and transport, so we provided them

a list, but who on that list they selected, I don't know.

Q. Oh, I see. Do you recall who was on -- in the pool or on the list?

A. I recall some of them.

Q. Who do you recall?

A. Dr. Leonard Konikow of the U.S. Geological Survey. I believe -- I'm trying to think of some others. There's a list on my ATSDR files somewhere, the list of all the reviewers. For example, for Tarawa Terrace, I think Dr. Barry Johnson. He had retired from ATSDR.

Q. Okay.

A. So he was a reviewer on -- may have been reviewing, for example, public health or public health policy, not necessarily groundwater modeling. There were some other former U.S. Geological groundwater modelers that reviewed different aspects of the groundwater modeling for us.

MR. DEAN: Could we ask you to spell the first one he mentioned.

MR. ANWAR: Sure.

THE WITNESS: Dr. Leonard Konikow, K-O-N-I-K-O-W.

BY MR. ANWAR:

Q. Do you know if that list of peer reviewers, the pool, would -- would have likely been included in your EDRP files?

A. Yes.

Q. Okay.

A. For Hadnot Point, I definitely remember that. I don't know -- for Tarawa Terrace, I don't remember if I -- if it was as formalized as it was for Hadnot Point.

Q. Okay. So I'm going to ask you the same question about both models, but I'm going to start with Tarawa Terrace.

A. Okay.

Q. How much observed or real-world data was available upon which to base the Tarawa Terrace model?

A. It was -- could you be more specific as to the type of data?

Q. Say sampling data for measured PCE concentrations.

A. Okay. There were data from, I would say, the early 1980s through '85 or '87 for that. And, again, in a groundwater flow fate and transport model it's not just the observed data,

but you also need to include the pumping scheduling and the pumping operations as well as the hydrogeologic properties.

Q. With respect to the sampling data, my understanding is there was limited data from 1982 and 1985. Does that sound right to you?

A. That is correct.

Q. And when I say limited, in your mind, how much data did you have, do you recall?

A. Well, there may have been several dozen data points. I would have to go to a specific table and look and tell you a number on that. I believe, for example, in the -- for the water -- for the fate and transport modeling at Tarawa Terrace we may have had, like, 36 data points.

Q. Okay. Do you know if all of those data points were used for calibration?

A. Yes, they were all used for calibration.

Q. Okay. And we can look at a table. Of the 36 data points, do you know how many of them came from pre-1985 -- or pre-1982?

A. I would have to look at the table.

Q. Okay. Is there a table in Chapter A that you could look at?

A. Let me see here. For example, in Table A-10, which is on page A-28.

Q. Let's pull that up.

A. I'm sorry. Let's go to the previous page, Table A-9 on page A-27.

Q. Okay.

A. Okay. Are we there? Yes. Okay. This is at supply wells and that's the list of data that we had going from '85 to '91.

Q. Did you -- so for some of these supply wells there's an ND listed there. What is ND?

A. ND stands for non-detect.

Q. And did you consider the -- the non-detect when calibrating the model?

A. We used it as a comparison, okay? In other words, the observed data are not put into the model to calibrate the model. Rather you put in your source concentration. You put in the operational schedule of the wells, and then the model comes out with -- it's simulated concentration since you compare those with what you have observed.

So we -- we considered the non-detects from the standpoint, for example, if it had a non-detect on April 9th, 1985 for supply well

TT-23, the detection limit is ten at that time. That was the best the technology could do. And we're simulating -- I'm sorry. Oh, these are -- this is just the PCE concentrations. Yeah, this is just the observed data, okay? Okay. Okay. So yes, the answer is we did consider non-detects, okay --

Q. Okay.

A. -- because we knew the detection limit.

Q. Okay. And then now focusing on Hadnot Point/Holcomb Boulevard, do you recall how much observed real-world data was available upon which to base the Holcomb -- the Hadnot Point/Holcomb Boulevard model?

A. It would be a little bit more than at Tarawa Terrace because we took it out in 2008.

Q. Okay.

A. Okay. So we -- we did that because we had the 2008 data or remediation data from a consultant working on base.

Q. The -- I think we discussed earlier that the most contaminated wells were shut down in 1985, correct?

A. That is correct.

Q. Do you recall how much data -- and when

I say data, sampling data or observed or real-world sampling data was available for Hadnot Point/Holcomb Boulevard model prior to 1985?

A. Not right off the top of my head. I would have to go through the report and -- and see.

Q. My -- and we can look through the report, too, and you're welcome to look through it and we can mark it, is that there was -- like Tarawa Terrace, there was only limited sampling data for measured TCE, PCE, DCE, vinyl chloride, and benzene concentrations at Hadnot Point between 1982 and 1985?

A. I would agree with that.

Q. Okay. You would agree with that?

A. Yes.

Q. And I think maybe -- we can mark Chapter A for Hadnot Point as the next exhibit, which I think will be 11.

(DFT. EXHIBIT 11, ATSDR document entitled "Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina

Chapter A: Summary and Findings", Bates-stamped CLJA_HEALTHEFFECTS0000221326 through 221535, was marked for identification.)

BY MR. ANWAR:

Q. And I think for Chapter A it might be A-62, Table A-18.

A. Which table number?

Q. A-18.

A. Okay. I'm there. Okay. Let's see. This is for the -- this is at the water treatment plant.

MS. BAUGHMAN: Did you upload this one yet?

MR. ANTONUCCI: It will be uploaded in about five seconds.

THE WITNESS: Okay.

MR. ANWAR: And we can wait for the exhibit to load.

MR. DEAN: If it's the one he's got in his hand, I'm fine to proceed.

MR. ANWAR: Okay.

THE WITNESS: Yeah, I've got A-18 pulled up. I just wanted to make -- understand that was for the water treatment plant at Hadnot Point -- water treatment plant, not supply wells.

BY MR. ANWAR:

Q. Okay. Is there a table in here for the observed data for, I guess -- pulled for the -- like the sampling data pulled from the source?

A. In the supply wells?

Q. Yeah.

A. I don't believe there is one specific here. Let me just -- they're -- they're graphs and I want to say Table A-13, contaminant, that's the sources, and then they are -- the following page, A-46, Figures A-18, there's some graphs there showing the observed and the contaminated. And I believe that in the chapter of supplement -- and Hadnot Point I went to supplements. I have to look up the supplement name, the letter designation.

Q. Okay. We can --

A. But in the various supplements that dealt strictly with the groundwater modeling and the fate and transport modeling at Hadnot Point, they would have tables of the observed data as well. The focus of the summary chapters that I put together to gather the information from the other technical chapters and then present it in terms of the -- what were the final mean monthly concentrations being delivered by the water

treatment plants and finished water.

Q. Got it. Thank you.

Just give me one second. I'm trying to find myself. I think on page -- I'll come back to that. So one of the labs where this -- I guess this sampling data came from was Grainger Labs; is that right?

A. That is correct, for Tarawa Terrace.

Q. For Tarawa Terrace.

A. In particular that's -- yes, that's...

Q. Okay. Did any sampling data come from Grainger Labs for Hadnot Point/Holcomb Boulevard?

A. I'll have to look at their letter again, okay? I definitely recall Tarawa Terrace.

Q. Was Grainger Labs accredited or certified to perform VOC testing, do you know?

A. I don't know the answer to that.

Q. If Grainger Labs lacked the certification necessary to perform VOC testing, would that impact the reliability of the sampling data from them?

MR. DEAN: Object to form.

THE WITNESS: I could not answer one way or the other.

BY MR. ANWAR:

Q. If -- would it be fair to say if the sampling data turned out to be different, the model would turned out to have different results, potentially?

MR. DEAN: Same objection. Assumes facts not in evidence.

THE WITNESS: Not necessarily because you don't put the sampling data into the model. Again, it's used for comparison purposes. And water quality data typically are characterized by some substantial variations.

BY MR. ANWAR:

Q. So the -- my understanding with respect to the reports is that the wells were assumed to operate continuously?

A. No.

Q. That's not right?

A. That's not -- not correct. We had operating schedules, most based on my calibrating the model and based on some other methods to determine which wells operated when. So on a monthly basis they may have operated -- we assumed they operated for the entire month, in other words. But whether they operated for two months straight and then stopped for a month or a month straight,

it would depend on whether you're looking at Tarawa Terrace or Hadnot Point and Holcomb Boulevard.

Q. Did you have operating schedules for the entirety of the '53 to -- 1953 to 1987 time period?

A. No, we did not.

Q. And how did you determine what the, you know, whether a well was operating or not when you did not have data available to --

A. Well, we did have some water utility logbooks that mentioned when certain wells may have been turned off or turned on. And then we also had the well construction information, so we knew when the wells went in, what their capacities were, and we knew the volume of water that was required. And so we -- we then were able to synthesize the operational schedule of the wells.

Q. Okay. Let's take a look at page A-18.

A. For Hadnot Point or --

Q. For Tarawa Terrace.

A. A-18.

Q. Chapter A, page A-18 for Tarawa Terrace, which should be Exhibit 10.

A. A-18. Okay.

MR. DEAN: Oh, Exhibit 10?

THE WITNESS: Page A-18. Okay. I'm there.

BY MR. ANWAR:

Q. At the bottom of the -- sorry. I thought I was there myself. So in the left-hand side, last paragraph --

A. Right.

Q. -- there's a sentence that says "once a well was put in service."

A. Right.

Q. "Once a well was put in service it was assumed to operated continuously for modeling purposes until it was permanently taken offline, the exception being temporary shutdowns for long-term maintenance."

A. Right. Okay.

Q. What does that mean? We were --

A. That means in the groundwater model you would initiate the well pumping whenever the data indicated that it went online, and you would keep pumping it on a monthly basis unless the records indicate that it was shut down for maintenance or until it stopped operating completely.

Q. Would it impact the ultimate mean monthly concentration and finished water if you --

if you hadn't made this assumption?

A. It would have affected the volume of water. In other words, we knew how much water we needed on a monthly basis based on records provided to us by Camp Lejeune as well as the well characteristics. So if, in fact, for example, they said a certain well was not operating, we would try that in the model, and the if model corroborated that, that's great. If the model did not, we would have to operate the well. So that's the calibration process.

Q. Okay. We will get to that. Do you know what method Grainger Labs used to test for TTHM?

A. No, I do not.

Q. And when I say "TTHM" do you know what I'm referring to?

A. Yeah, total trihalomethanes.

Q. Okay. Could you take a look at page -- still on Exhibit 10, Tarawa Terrace.

A. Okay. Okay.

Q. Chapter A, page A-25.

A. Okay. Yes.

Q. It's -- so in the middle of the page it says "a second reason for computing a selected

geometric bias" --

A. Yeah, I'm trying to see where -- is this the right-hand column or left-hand column?

Q. Sorry. Right-hand column, top paragraph. It is -- there is a section highlighted right there in the --

A. Hold on. Okay. Okay. I see "such greatly enhanced biodegradation would result in much lower PCE concentration" -- oh, "a second reason", yes, I'm there.

Q. Okay. It says "a second reason for computing a selected geometric bias and the omitting data from water supply well TT-23 is bias introduced into analytical results caused by incomplete or inadequate sampling methodology."

A. Right.

Q. What does that mean?

A. Well, there are different ways that they sampled both water quality and water level data. For example, with water level data you can use an air line, which is far less accurate, or you can use a tape measure and do that. And so the ability of the model to match observed data would be dependent on what sampling methodology was used and the accuracy and whatever error is associated

with that sampling methodology.

Q. Did the Tarawa Terrace model generate two geometric model biases?

A. I believe if we go over one more to page A-26, sample line -- row or calibration level three and four of calibration level three, you would see that there -- there was two geometric biases, 5.8 and 3.9, and I believe the footnote explains with and without TT-23.

Q. How does geometric model biases relate to the model's accuracy?

A. Okay. If you go -- let's go back to the previous page, okay, left-hand column, top part. A model bias is a numerical indication whether the model underpredicts, predicts exactly, or overpredicts, okay? So we take the simulated concentration and divide it by the observed concentration. If it's less than one, that means the model is underpredicting. If it's equal to one, there's an exact match. And if it's greater than one, that means the model is overpredicting based on the observed.

And because the distribution of that bias is -- is skewed -- it's skewed normally. In other words, it cannot be less than zero, okay, but

it can be much greater than one depending how poor of -- how much overprediction the model -- that's basically, like, a little normal distribution, so you want to use a geometric bias.

Q. And I think you --

A. Okay.

Q. For well TT-23 I think the -- there was a geometric model bias of 5.9 and 3.9. Does that mean both -- both are overpredictive?

A. Yes, yes.

Q. Okay.

A. One, I've referred to the following Table A-8. The geometric bias of 5.8 was including TT-23 and 3.9 was excluding TT-23.

Q. Would you agree that there was -- there were data limitations with respect to ATSDR's modeling of the mean monthly concentrations at Camp Lejeune because there was a small number of drinking water contaminant results from actual samples taken at the water treatment plant or the point of exposure?

MR. DEAN: Object to the form of the question.

THE WITNESS: There are always data limitations with any modeling analyses, especially

going back historically in time. That is one of the reasons why we went to the historical reconstruction process. If we could calibrate the models to the data that we had, then we would have confidence where we didn't have the data going backwards in time, which is the same thing as using a model in a predictive sense. For example, if you wanted to design a remediation operation, you don't have that data because you haven't started remediating. You collect what data you have and then you use the model to go forward in time.

Q. What are -- you mentioned there are always limitations. Are there limitations with respect to the Tarawa Terrace and the Hadnot Point/Holcomb Boulevard models?

A. Yes.

Q. What are those limitations?

A. It's the limited number of -- of data. It's specific water supply well operations. When I say specific, on a daily or hourly value.

Q. What does that say about the limitations as it relates to the results produced by the model?

A. Basically it tells you once you believe you have a calibrated model, there -- you need to

establish how reliable that is through some type of probabilistic uncertainty analysis. Because it would give you the range compared to where your data are of where your, say, reconstructed concentrations would be. And so you have limited data as we did and others do for this type of analysis. And by conducting a probabilistic uncertainty analysis it not only gives us, but when we present the results to the epidemiologist, it tells them what the range and the concentrations should be or could be.

Q. We'll talk a bit more about calibration, but do you believe you had calibrated models for both the Tarawa Terrace and Hadnot Point/Holcomb Boulevard models?

A. Yes, I do.

Q. What is your, like -- I guess, what is a basis for believing that each of the models was calibrated?

MR. DEAN: Object to the form of the question.

THE WITNESS: We -- we used accepted model calibration procedures as described in ASTM guidelines, described in American Waterworks Association handbook on model calibration, and

procedures established by the U.S. Geological Survey and we followed those. And for example, if you go to the Chapter A report, page A-24, I'll just hold it up here.

BY MR. ANWAR:

Q. Okay. That's fine.

A. You can see these scatter diagrams of graphs. That's one of the methods described in one of the ASTM documents that we referenced that they say you need to be able to produce and conduct to do a proper groundwater flow model calibration. So we followed the accepted modeling procedures, okay, and expressed our results both in terms of the mean monthly values as well as the uncertainty analysis, which, again, is part of a generally-accepted modeled calibration and fate and transport model simulation approach.

Q. Okay. We'll talk more about calibration here in a few minutes. I wanted to ask you a few other questions. In your prior deposition you referred to the model sort of -- and this would have been at the time that the Tarawa Terrace model had been completed.

A. Right.

Q. Novel -- you described it as novel

application, edge of the envelope in terms of what has been done. What did you mean by that?

MR. DEAN: What -- what -- hold on a second. Hold on. Can you tell me what page you're referring to?

MR. ANWAR: Yeah, page 45.

MR. DEAN: What's -- what's the exhibit number?

MR. ANWAR: It's 3.

MS. BAUGHMAN: This is the deposition?

MR. ANWAR: Yeah.

MS. BAUGHMAN: Can you show him -- let him see the testimony.

MR. DEAN: Hold on. Hold on. Hold on. What page are we on?

MR. ANWAR: I said 45.

MR. DEAN: 45. Sorry. Okay. It should be on the screen, page 45.

THE WITNESS: Okay.

MR. DEAN: What line and question?

MR. ANWAR: It's 45, nine through 46, 14.

THE WITNESS: Line 14. Okay.

MR. DEAN: Hold on one second.

THE WITNESS: Okay. Those were not --

those were not my words.

MR. DEAN: That's what I was going to say. I don't know what your question was, but your question --

THE WITNESS: Yes, those were not -- that was --

MR. DEAN: Hold on. Your question did not accurately depict what's in the transcript, which is why we wanted to see the transcript.

MR. ANWAR: Page 46. I believe his testimony is --

MR. DEAN: You told me 45.

MR. ANWAR: I said 45 to 46.

MR. DEAN: Okay.

MR. ANWAR: And it says "so from that standpoint that's probably, you know, edge of the envelope of what has been done."

MR. DEAN: You're mischaracterizing his testimony, though, but go ahead.

THE WITNESS: Can I read the -- okay.

MR. DEAN: Here, take this so you can scroll look at 45 and 46.

THE WITNESS: Oh, okay.

MR. DEAN: So when you're finished reading 45 --

THE WITNESS: Yes.
MR. DEAN: -- just let him ask his questions again.
BY MR. ANWAR:
Q. Yeah. So you certainly referred, I think, to it as edge of the envelope.
MR. DEAN: So object to the form of the question. You say "it" --
BY MR. ANWAR:
Q. In terms of what has been done --
MR. DEAN: Again, object to the form of the question because you have to clarify what it is and what was being done being referred to, so --
MR. ANWAR: Look, I'm not going to argue with you, but the testimony reads "so from that standpoint that's probably, you know --
MR. DEAN: I agree with what the transcript says, but that's not what your initial question was when you first asked this and we asked for the transcript. So I'm just pointing out an objection to the form of the question because you keep saying "it" and neither one of us know what you're referring.
MR. ANWAR: And you can object to form, but I'm going to ask you to stop speaking -- make

speaking objections and waste my time.

MR. DEAN: I'm trying to give you -- help you with your questions. That's all I'm doing.

BY MR. ANWAR:

Q. What did you mean when you were referring to edge of envelope in the context of that discussion?

A. I think at the time I was referring to being able to go backwards in time, reconstruct based on either available data in the 1980s or current day information. Many modeling remediation-type studies collect field data present day and then, of course, project forward in time, but this was a unique application of -- of going backwards in time.

Q. Okay. Thank you.

What was your role in selecting source locations and strength for the two models? And let's start with the Tarawa Terrace model.

A. My role?

Q. Yeah.

A. I deferred to the person conducting the modeling itself. In the case of Tarawa Terrace it would have been Mr. Robert Faye. I provided him

with documents that indicated where the sources were for Tarawa Terrace. That would have been ABC One-Hour Cleaners, which are -- which is based on the reports by Shiver 1985 out of North Carolina also west -- some Weston reports.

Q. Okay.

A. And -- and so -- but the actual quantitative determination of the strength of the source, the timing of it, that would be up to the person conducting the modeling.

Q. In this instance it was Robert Faye?

A. That is correct.

Q. Was that also true for the Hadnot Point/Holcomb Boulevard?

A. No, we had -- we had Mr. Rene Suarez-Soto and also a hydrologist from the U.S. Geological Survey, Elliott Jones. But again, that would have been with information I -- I provided them.

Q. Okay. And for the Hadnot Point/Holcomb Boulevard model, do you recall the type of information you provided to determine the source and the strength?

A. Basically the location, the type of contamination, and then the model calibration

process would help quantify, you know, how long the source, how deep the source, and things of that nature. They had information on the construction of the landfill or the depth of the landfill, so...

Q. How did you determine the source strength in both models?

A. Well, in Tarawa Terrace we used a technique that's in the literature because we could actually plot the PCE plume aerially and then we compute a weighed volume and then determine a minimum annual amount of PCE going into the groundwater system. And so we did it that -- that way, okay? And their computations are provided in the Chapter F report of Tarawa Terrace.

Q. Okay.

A. If -- for Hadnot Point we assumed a constant source and turned it on and turned it off depending -- and at depth there were multiple aquifer layers.

Q. What was the basis for the assumption of the constant source?

A. It was -- everything was dumped into a landfill, and we really did not have as specific information as we did at ABC One-Hour Cleaners. And so that's a standard modeling approach, is to

assume that the source -- the source is the same from one time step to the other unless you, for example, start remediating, then you would reduce the source strength.

Q. Were model results for either of the models used to locate some of the sources?

A. We had -- and this is, I think, in the Chapter A or Chapter C report. I'll have to find exactly where, but we had identified some sources that we called apparent sources, okay, and that's because of the model results indicated that there may be a source -- a source there, okay, a high concentration value. And let me see if I can see -- oh, and for Hadnot Point -- oh, no -- yeah, Hadnot Point, Chapter A-45 -- chapter -- page A-45, Table A-13, those are the documented sources right there.

Q. Okay.

A. And let me see if I could -- okay. Okay. If you go to Table A-7, let's start with that.

Q. Okay.

A. Okay.

Q. This is Tarawa Terrace?

A. No, this was Hadnot Point.

Q. Okay.
A. Tarawa Terrace was only one source and that was ABC One-Hour Cleaners.
Q. Understood. You're on page A-7?
A. Page A-26, Table A-7.
Q. Okay. I'm there with you.
A. Okay. You're with me. Do you see that last column, potential source locations? Because you had multiple buildings and multiple locations, we refer to them as potential because, you know, it would not necessarily be that every single building listed would have been a source, okay? As compared to, say, the landfill where we knew that was a source, okay, because it was, you know, a landfill, so stuff went into the landfill.
Q. And I'm sorry if I missed it. So the original question was were model results used to locate some of the sources. Is that a yes or --
A. Not model --
MR. DEAN: Object to the form of the question. You're asking him for an opinion.
MR. ANWAR: I'm asking for his opinion in his role developing the model.
THE WITNESS: Okay. I'm looking now and I think it was just on the initial

characterization that we referred to as potential source locations, in other words, okay? Then we would use the model or, as we were calibrating the model, we would determine from that list, exhaustive list, of potential sources which ones were actual sources. We did not identify any new area, in other words, that -- that we said, oh, this is contaminated and there's -- you don't have any information on this area.

MR. ANWAR: Okay. Why don't we take a quick break?

THE WITNESS: Okay.

MR. ANWAR: Thank you.

THE VIDEOGRAPHER: Going off the record. The time is 3:24 p.m.

(A recess transpired.)

THE VIDEOGRAPHER: Going back on the record. The time is 3:39 p.m.

BY MR. ANWAR:

Q. We --

A. Could I qualify some things that were said in the previous --

Q. Sure. Let me just -- we're back on the record from a short break. Are you ready to continue, Mr. Maslia?

A. Yes.
Q. And did you speak with your counsel about your testimony during the -- during the break?
A. No, I did not.
Q. Okay. And it sounds like there's something you want to clarify. Go ahead.
A. Yes, clarify. When we're talking about the questions being asked about sources at Tarawa Terrace and then Hadnot Point, they're entirely two different approaches because at Tarawa Terrace there's only one identified source, ABC One-Hour Cleaners, okay? That was easy to identify and there was substantial more investigation done at -- by EPA contractors at ABC, and so we did -- that's why we used one method for characterizing the source for the model at Tarawa Terrace.
At Hadnot Point, and I'll refer you to Table A-7 on page A-26.
Q. This is Hadnot Point?
A. Hadnot Point.
Q. What was the page again, I'm sorry?
A. A-26.
Q. Okay. I've got you.
A. Do you see that's -- that's the table

-- there are many, many buildings that a supply well could have been contaminated from. And then the following page on Table A-8 sort of boils that down to which -- which buildings were contaminated based on historical events. And so there are many, many more sources at Hadnot Point.

And then if you flip to page A-20.

Q. Okay.

A. That's Figure A-10. That's basically the landfill area. Yeah, that's it. You see there are many more source -- sources, source locations in there, so there was not a single source like there was at ABC One-Hour Cleaners. So we have to use a different modeling approach to characterize the sources in the model.

Q. Okay. Thank you for that clarification. I wanted to ask you, generally speaking, since the water modeling for both Tarawa Terrace and Hadnot Point/Holcomb Boulevard were used to support epi studies, when it came to assumptions that were used or, I guess, to some degree the uncertainty, did you -- your team err on the side of being conservative? And when I say conservative, I mean sort of health protective.

A. I would say we did not consider

health -- health criteria or health standards. What we considered were what were the maximum contaminant levels of certain contaminants, in other words. That's what our guidelines were. If it came to concentration data, just because we may have had an exceedingly high concentration data, we did not force the model to reproduce that high concentration data. We took an objective scientific approach that could be defended by the public -- by the reviewers, by the scientific community, as to the approach that we did for modeling.

Q. Okay. Would you agree that calibration is -- the intent of calibration is to measure model accuracy?

A. I would define -- or the intent of calibration is to test out and compare your model assumptions from geohydrologic to well operations to source to the available field data that you have and give you a sense of reliability.

Q. Would calibration include comparing observed data with simulated data to the extent those data points exist?

A. Yes.

Q. Okay.

A. And then performing some statistics on that.

Q. So I wanted to have you turn to -- actually let's mark it as an exhibit. It is Chapter F for the Tarawa Terrace.

A. For the Tarawa Terrace, Chapter F. Okay. It's over here.

MR. DEAN: Oh, yeah, that's right.

THE WITNESS: Okay.

(DFT. EXHIBIT 12, document entitled Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions. Chapter F:Simulation of the Fate and Transport of Tetrachloroethylene (PCE), was marked for identification.)

BY MR. ANWAR:

Q. Do you have Chapter F in front of you? Is it loaded? Let's go ahead and display that. Give me one second to get back to it.

Okay. So let's turn to page F-34.

A. Okay. I'm there.

Q. And we can actually start on page F-33.

A. Okay.

Q. And so on F-33 there's a Figure 12 there that is a graph that I believe is intended to compare observed data versus simulated data. And there's only a couple of data points -- data points where the observed data and the simulated data actually line up with each other. And then let's go ahead and look at the next page.

A. Okay.

Q. There's Figures F-13, F-14, F-15, F-16. And you can see the simulated data, what the model came up with, and then you can see what the observed data is, and almost in every instance it's much lower than what the simulated data is. And I wanted to ask you, like, how do you -- how do you explain the -- like, I think you've said you believe the model was appropriately calibrated. Why do you believe it was appropriately calibrated when the observed data doesn't match the simulated data and the simulated data appears to overpredict by quite a bit?

MR. DEAN: Object to the form of the question.

THE WITNESS: First, if you go back to Figure F-12.

BY MR. ANWAR:

Q. Sure.

A. And I have not come across any studies where the -- they line up on the 45-degree line there, okay? They will either be above or below, okay? So the fact that a data -- a simulated versus observed does not line up on the line is not -- not an issue. And it does show that -- and we acknowledge that, in fact, the simulated data tends to be higher than the observed data, okay?

Q. So you would agree that the model --

A. And we said that, if you looked at our model bias calibrations that the bias was greater than one, so the model would overpredict slightly, okay?

Q. Okay.

A. But again, the other thing you need to remember is, you know, let's take Figure F-16, okay. Look at the data. You've got the data ranging from 1600 all the way down to maybe 100 there where it says observed. And so, you know, the data are extremely variable as well. That's the observed -- that's the observed data. And so the model simulation sort of splits the difference.

Q. Well, with respect -- I think another

question that I have, with respect to the accuracy of the calibration or -- and so it sounds like you acknowledge that the model tends to overpredict; is that right?

A. It overpredicts, but not -- not in an unacceptable manner or unacceptable -- we actually conducted -- that would be a reason for conducting, say, an uncertainty analysis. So you could look at your confidence bands in -- in the model and see whether you're plus or minus an order of magnitude, half an order of magnitude, three orders of magnitude, whatever it would be. So in other words, we accepted the calibration, but then we also went to a further analysis to test our confidence in that calibration.

Q. For instance, if you look at Figure F-15, one of the things that I don't think I understand, you see the simulated value --

A. Right.

Q. -- and you see the observed on the zero axis for 1187?

A. Right.

Q. And then you see the observed going up?

A. Right.

Q. If I remember correctly, for Tarawa

Terrace, the wells were taken out of service in 1985, and so the model should reflect the -- the estimated concentrations going down, but uniformly in all of these figures, for the most part, the -- the concentrations continue to go up --

A. Right.

Q. -- even after the wells are taken out of service.

A. Right.

Q. Why is that?

A. Because -- and actually, let's see if it's in this report or the -- he may not have put -- I did it in -- yeah, in this report. If you -- if you go forward to Figures F-18 through F-21 -- actually, I'm sorry, yeah, through F-23, okay, flip up a couple of pages. I'm sorry. Keep going forward. Go to page -- this will be pages F-36 through F-38. There you go. Okay. That's the aerial distribution of the plume, of the PCE plume, okay. That first one is from 1960.

And let's keep flipping forward. Keep going, keep going. Okay. The wells are pumping. Now the -- keep going. And then the wells are taken out, okay? Even though the wells -- we can stop right there. Even though the wells are taken

out, the aquifer is still contaminated, okay? So while you may not have a supply well that's pumping there, the aquifer is still contaminated and the contaminant is still moving through the aquifer. And so the results are reflecting that.

Q. Shouldn't --

A. Okay. Reflecting at the location where, for example, TT-25 used to be, they took it out. So in fact, there could be a higher or increasing as -- as the plume migrated from northeast to southwest because it would be migrating under natural groundwater flow once the wells were removed.

Q. Wouldn't it be fair -- so, you know, I understand your point that there may still be contaminants in the aquifer, but when the source is removed, shouldn't the simulation be showing -- even if there's still contaminants in the aquifer, that the monthly concentration is sloping down?

MR. DEAN: Object to the form.

THE WITNESS: It would -- it would really depend on the location. In other words, the -- the contaminant migration migrates, especially once you remove all the wells, at a slower velocity than when the wells were pumping.

So you take the source out of the model and then the immediate vicinity of where the source was, that it should go down decrease.

But as the contaminant source migrates under the natural groundwater flow conditions now that you have no pumping, you will still get high hits of -- of PCE until it moves, you know, completely out into wherever it's going to move past Tarawa Terrace.

BY MR. ANWAR:

Q. You would agree that at least on Figures F-13, F-14, F-15, F-16 that the simulation doesn't match the observed data in most of the, you know, most of the observed points in relation to the simulated data? It's not even close.

MR. DEAN: Object to the form.

THE WITNESS: I would say the model overpredicts; however, again, what our objective was, was to present finished water concentrations, okay, not necessarily water supply well concentrations. So what you have to do is -- and that is why we went to a multiple-phase calibration is if we go back to the summary of findings in Chapter A for Tarawa Terrace, what will you note is that the -- let me just get this one. Hang on.

That's not it. I can't find it here. Maybe he put it in Chapter F. Hold on just a second.

Ah, there you go. I'm sorry. Chapter F, go to page F-43. Okay. That graph. I mean, if you want to blow that up you can. But that -- that is the finished water concentrations, and for the available data it is -- it is spot on.

BY MR. ANWAR:

Q. The way I'm reading Chapter F is if you look at January 1985, the commuted data appears to still be significantly higher than most of the observed data.

A. January '85? No, I see three or four data points at the top -- top there and that's where the simulated line is. And if you move over to January -- or to 19, say, '86 or '7, the very last line, you see the data are lining up with the simulated value.

Q. Okay. So I wanted to ask you, in terms that you mentioned that the model overpredicts, does it --

A. Fate and transport. Again, I think we need to distinguish because from the fate and transport model we used a simple mixing model to mix all the wells at the treatment plant, and then

without adjusting anything, we just compared it to the measured data at the water treatment plant and it fell right on as far as we were concerned.

Q. You use a mixing model for the water treatment plant, so if it overpredicts to the -- in the fate and transport model to the wastewater treatment plant, doesn't that necessarily result in higher concentrations at the water treatment plant?

A. No, because you've got multiple wells mixing in. Some are not contaminated, some are contaminated, and some are highly contaminated.

Q. But if you have multiple wells mixing in regardless and if it underpredicted, wouldn't that result in the numbers being lower?

A. All I can answer is we had this independent set of data, which were the finished water concentrations, okay, and as we went to our calibration process from steady state groundwater flow to transient to fate and transport and then did the mixing model, the simple mixing model, it ended up that we obtained what we felt were acceptable results because what we were to provide to the epidemiologist were finished water concentrations.

So if, in fact, we were way, you know,

way off, either overpredicting, underpredicting at the water treatment plant, then that would have been a concern, but, again, the fate and transport, while they don't match and they overpredict somewhat, we felt that through the use of a mixing model where you assumed instantaneous mixing --

Q. Okay.

A. So basically our -- our criteria for accepting or not was what was happening at the water treatment plant.

Q. Okay. I just want to ask you a couple more questions.

A. Sure.

Q. Specific questions about the model, and due to time and some other things I would like to cover --

A. Right.

Q. -- I'll try to get through this quickly.

A. Sure.

Q. First, I believe the Tarawa Terrace model assumes that the dry cleaner was contaminating the wells from 1953 -- that the contamination existed as of 1953. What's the basis for that assumption?

A. Based on the deposition of Victor Melts who was the owner of ABC One-Hour Cleaners and based on the operational records that -- or it's in the deposition that he gave when he began operations. And knowing dry cleaners of that generation back then, he, in fact, said that he would take the waste, the sludge, PCE, and use it to -- put it outside, you know, where it was covering some ground or putting it in a drain field or whatever, so yes.

Q. Another -- so if -- if it turned out that the dry cleaner started leaking -- or contaminants at a later period in time, would that impact the Tarawa Terrace model?

A. It would impact the -- any -- any model, but, again, the information we received from the reports done at ABC One-Hour Cleaners told us when the dry cleaners started operating and so -- which we believe to be in 1953.

Q. Would you agree that -- so I believe you indicated you have reports that state that the dry cleaners started operating in 1953?

A. Yes.

Q. Do those reports state that the dry cleaner starting leaking PCE in 1953?

A. Well, nobody knew it was leaking PCE because at the time there were -- the environmental laws weren't in place to say you had to do that, but based on the deposition of Victor Melts that is available to anyone, you know, his practices were to dump or place the waste PCE just outside the -- on the grounds of the dry cleaner. That's described actually, I believe, in the Chapter E report of Tarawa Terrace in a lot more detail. So that's where we, you know, obtain the assumption that he started in 1953.

Q. If no one knew for sure when the PCE started leaking -- or when ABC Cleaners starting leaking PCE, wouldn't you agree it's a conservative assumption to assume that PCE started leaking as soon as the dry cleaner opened?

MR. DEAN: Object to the form of the question.

THE WITNESS: You have to understand the geohydrology of the area. You've got sandy soils there, so whatever you spill on the ground is going to instantaneously leak. So --

BY MR. ANWAR:

Q. I would like to ask you quickly about another assumption. The -- I believe in your

models it's assumed that the -- the concentration levels at the wastewater treatment plant are the same as in finished water, correct?

MR. DEAN: Object to the form of the question. Which models?

THE WITNESS: We define what finished water is early on, and maybe I should just read it for the record.

BY MR. ANWAR:

Q. No.

A. Okay.

Q. Sorry. I'm not asking you to look through. Just to the best of your recollection. If you don't recall, it's fine.

A. Well, we defined finished water as the concentrations from the -- at the water treatment plant that would have been delivered to residents or people living.

Q. I think I was a bit imprecise. For the Tarawa Terrace model I believed it was assumed --

A. Right.

Q. -- that the concentrations, after the mixing model was performed --

A. Right.

Q. -- coming out of the wastewater

treatment plant were the same as in sort of the finished water coming out of the faucet?

A. That's correct.

Q. Okay. What was the basis for that?

A. That was based on advice from our expert panel in 2005, March of 2005, specifically Doctors Tom Walski and Dr. Walter Grayman who noticed that throughout the history of operation of Tarawa Terrace all the wells mixed at the water treatment plant. So if all the wells, every single one of them, went into -- the contaminated and non-contaminated went into the water treatment plant, then you can use a simple mixing model also known as a CSTR, continuous stirred tank reactor model, and the concentration resulting from the mixing model would also be the concentration at any location within the distribution system.

Now, we tested that out, we tested that assumption out, and it is in Chapter I of the Tarawa Terrace reports, and we do a comparison of a very rigorous water distribution system analysis through looking at locations and looking at the mixing model. And after about a week or ten days, they're identical. They're identical. And because we were looking at monthly mean concentrations,

that meant within a month they -- we had no issue.

Q. Okay.

MR. DEAN: Just one second. I understood your question and so did the witness because he obviously just answered it. Just for the record you used the word wastewater, so I just want to --

MR. ANWAR: Oh, I apologize.

THE WITNESS: Water treatment. Water treatment.

BY MR. ANWAR:

Q. Water treatment plant. So the question for the record for the prior -- my question was, I believe the Tarawa Terrace model assumes that water that goes for the mixing model that you run in the wastewater treatment plant --

MS. BAUGHMAN: You did it again.

BY MR. ANWAR:

Q. Oh, waste treatment plant.

A. No, water treatment plant.

Q. Water treatment plant. Long day.

A. Okay. You can start over.

MR. DEAN: I'm not going to fuss.

BY MR. ANWAR:

Q. So I believe the Tarawa Terrace model

assumes that the concentrations in the water treatment plant are the same as in finished water, correct?

A. No, it assumes that the drinking water distributed throughout the water distribution system is the same as the concentration of the water in the water treatment plant.

Q. Okay. That is what --

A. That's the same assumption that was used for Hadnot Point also.

Q. Do you -- for -- okay. That's helpful as well. Do you know for Tarawa Terrace there's a Chapter J and K, and I did not see them online.

A. No, no, there was not. Those were supposed to be -- because of budget and timing, the last chapter in the Tarawa Terrace series is the Chapter I, which is about sensitivity uncertainty and that's where we do the verification testing of the water distribution system model versus the simple mixing model, if that's in that chapter.

Yes, there were plans, but it was decided -- I think Chapter J was going to talk about our field testing of the water distribution system, that was put over into supplement eight of the Hadnot Point, okay? So there's only -- Chapter

I is the final chapter in the Tarawa Terrace report series.

Q. Okay. Understood. I wanted to quickly ask you about the uncertainty analysis that you ran. And my understanding is that as part of the uncertainty analysis, you chose a range with which you -- you -- and my term of art may not be correct, so you can -- you can correct me if I'm saying this wrong, but you chose plus or minus half on order of magnitude range with which you wanted -- you were aiming for the simulated results to fall within?

A. Let me clarify --

Q. Sure.

A. -- something. That was the calibration target range and that's not an uncertainty analysis.

Q. Okay.

A. Okay. That's two different things. So I guess my question is, do you want to talk about calibration targets or do you want to talk about uncertainty analysis?

Q. What did you do for your uncertainty analysis?

A. For our uncertainty analysis we used

what we refer to as a two-stage Monte Carlo simulation where we use Monte Carlo simulation to assign and to simulate probability density functions for different model parameters. And then each time the groundwater or the fate and transport model ran, when it would call for a certain parameter, for example, hydraulic conductivity or dispersivity or whatever, it would go out and randomly select from the PDF, probability density function, that -- that value. And so you have a -- a series, what we refer to as realizations of a whole bunch of different runs, like 800 different runs.

Q. Sure.

A. Okay. And so using Monte Carlo simulation, therefore, we can look at the range of them by looking at -- taking the 2.5 percentile, looking at the 97.5 percentile, and the difference gives you 95 percent confidence of all simulations. So it's a more rigorous approach than just doing a simplified confidence limit.

Q. So my understanding is the Navy had an opportunity to -- to review the model as well; is that right?

A. They critiqued the Chapter A report or

the final report. They did not review it. No one actually, except for the peer reviewers, reviewed a report before it was publicly released.

Q. And I think they ended up sending a letter sharing some feedback, and some of the concerns they raised related to calibration in terms of observed versus simulated data, which we've discussed.

A. Right.

Q. And they also discussed the Monte Carlo simulation. And I think they described that only 510 of the 840 runs resulted in viable realizations.

A. Okay.

Q. And I understand that you disagree with the Navy's critique; is that right?

A. That is correct.

Q. Okay. Why do you disagree with that?

A. Okay. The Monte Carlo simulation did exactly what we wanted it to do. If you -- if a parameter changes, let's say pumping, okay, and you, you know, triple the pumping rate -- and I'm just using hypothetical examples -- well, then it may dry out the aquifer, okay? That's not a viable solution because we know the aquifer doesn't dry

out. It's still there.

So we put filters on stopping criteria on our Monte Carlo simulations that if it -- the aquifer dewatered or it went dry, that it would stop the realization or the Monte Carlo simulation right there because that's not a realistic solution. So the fact that five hundred were viable solutions and we did -- actually conducted 800 realizations, all that meant is that those three hundred or so did not produce realistic results and that's what you would want. You know, I wouldn't say throw them out, but to have the Monte Carlo simulation or the model stop running once it's dried out, that just means that probability density -- the functions that you assign to the different model parameters, the combination of those did not result in a physically realistic result.

Q. Okay. I understand that Congress mandated the National Research Counsel to also review the epidemiological study and the Tarawa Terrace modeling; is that right?

A. I'm not sure who mandated it, okay? I know the Navy contracted with the National Research Council to review our work at ATSDR.

Q. And, you know, I can represent to you that in your -- I think in your prior deposition --

A. Right.

Q. -- you -- you indicated that Congress had mandated the Navy to fund it.

A. Okay. Okay. It's been a few years since...

Q. No, I hear you.

A. Okay. So...

Q. What is your recollection about the -- so let me back up for a second. What is the NRC?

A. NRC is the National Research Council, part of the National Academies of Science.

Q. Okay. And is the National Research Council an arm of the National Academy of Science?

A. That's my understanding by going to the NAS website.

Q. The NAS is a nonprofit institution that advises on science issues in the country?

A. I don't know about the nonprofit part, okay? It's -- I do not believe it's a government agency.

Q. Okay. It is an institution that advises on scientific issues --

A. Okay.

Q. -- in the country; is that -- would you agree with that?

A. Yes, yes.

Q. Would you agree that the NAS is generally highly respected?

MR. DEAN: Object to the form of the question. Are you talking about prior to this case?

THE WITNESS: I have -- I have really not dealt with the NAS. I've read some of their publications and reference materials, but I cannot make a recommendation as to whether they, you know, pro, con, or otherwise.

BY MR. ANWAR:

Q. What is your understanding of the NRC's evaluation of the Tarawa Terrace model?

A. In terms of what they were charged with or the results?

Q. The results.

A. Well, they were critical of the ATSDR modeling approach and felt that models or the models could not be used to reconstruct historical concentrations. We, of course, disagreed with that and we did write an internal document. I don't know if it's ever been made public or not, but

pointing out what we felt were the misclassifications, erroneous assumptions, not considering the Chapter I report, for example. They critiqued us of not doing uncertainty analysis, but there's the report right there. And --

Q. Were you -- my understanding is that you had an opportunity to attend a meeting in D.C. for the first NRC meeting?

A. That is correct.

Q. And did you present about the Camp Lejeune -- I guess at that time it was the Tarawa Terrace model -- at that meeting?

A. We -- that was in 2007, so -- I believe it was in 2007. We may have been in the final stages of -- so I probably presented our approach. I'm not sure if we presented any results or not. I would have to look at the presentation to see what we presented.

Q. And, you know, we don't need -- I'll represent to you that the meeting and the documents indicate the meeting took place on September 24th, 2007. Does that sound right?

A. Yes, yes.

Q. Okay. Did you have an opportunity to

communicate with anyone from NRC about your -- the Tarawa Terrace model?

A. Yes, a number of people. Specifically the person who was, I guess, in charge of their -- what they refer to as Chapter 2, which is exposure assessment. We provided information as he needed, whether it was data or analyses. Wanted to know how we were classifying the source at ABC One-Hour Cleaners, so there's e-mails back and forth.

Q. Who was that person?

A. That was Dr. Prabhakar Clement.

Q. Okay.

A. And then I also communicated with the executive secretary. I forget her name right off the bat, but -- Martel. Susan, Susan. I believe she's a doctor, Susan Martel. And I communicated with her both in terms of attending that meeting and issues that I saw that the committee should consider.

Q. Okay. I'm marking an exhibit. It will be marked Exhibit 13.

(DFT. EXHIBIT 13, e-mail correspondence Bates-stamped CLJA_ATSDR_BOVE_0000108607 and 108608, was marked for identification.)

BY MR. ANWAR:

Q. It is -- I'll represent to you it's an e-mail communication from you -- well, it's an e-mail exchange. The top e-mail is from you to what appears to be your ATSDR team.

A. That's correct.

Q. And the body of the e-mail says "look at the second paragraph from Dr. Clement, a member of the National Research Council Committee on contamination of drinking water at Camp Lejeune. It's nice to get words of praise from unbiased and technically competent colleagues about our abilities and work."

Did I read that correctly?

A. That is correct.

Q. Do you -- do you believe Dr. Clement to be an unbiased and technically competent colleague?

MR. DEAN: Object to the form of the question.

THE WITNESS: In his correspondence with me, in that I felt he was objective and competent, but that's what sort of -- that is, in fact, what caught us by surprise when the report came out and it was basically 100 percent opposite of what he and I had been communicating about.

BY MR. ANWAR:

Q. When you say -- you mean the NRC report?

A. Yes, yes, yes, yes, the one that was published in June -- or released in June 2009.

Q. And in 2010, Dr. Clement, I believe, issued an article himself and it was entitled "Complexities in Hindcasting Models When Should We Say Enough is Enough." Do you recall that article?

A. Yes, I do.

Q. What do you -- what is your understanding about it? What do you recall?

A. I recall that we responded to it. Our agency allowed us to respond to it because, again, like the NRC report, we found a number of issues that were either mischaracterized or were presented not in the way that we thought they should have been presented. And so the journal Groundwater where he published his article, the editor -- which they usually do not let you do a ten-page response, they allowed us -- they recognized of the complexity and -- and the, I guess, political sensitivities of the whole Camp Lejeune issue, and so they allowed us to respond, which -- which we did, and I forget the exact date that we sent a response in, but we can find that if you need it.

Q. Wasn't the thrust, to the best of your recollection, of Dr. Clement's article calling into question the value of historical reconstruction due to the limited data and uncertainty of historical reconstruction?

MR. DEAN: Object to the form of the question.

THE WITNESS: My understanding is, or at least started out, I think, to -- to make a philosophical discussion as to how much funding and how long of a time should projects that go on, in other words, and should we be using simpler models or more complex models, in other words. And when -- when there's -- you're not obtaining any return for your investment.

Q. Okay. And I understand that you responded and then Dr. Clement had a response to your response, correct?

A. Yes, yes, yes. And that's the article or our response where we challenge the use of -- or disagreed professionally with -- with -- with the term hindcasting.

Q. Do you still consider Dr. Clement to be a technically competent and unbiased colleague?

A. Competent, yes, and -- I mean, I

haven't dealt with him on issues like that to say biased or unbiased, but one would make the assumption he's in academia that, in fact, you would like your work to be considered unbiased.

Q. And the -- the issue the NRC had with the Tarawa Terrace modeling was what it described as uncertainty as well, correct?

A. That was one of them. They -- they had an issue about the characterization of the source at Tarawa Terrace, that they insist -- the NCR report described it as a dense non-aqueous phase liquid or a DNAPL and the data just did not support that. And we felt that was especially egregious if they're complaining about not having sufficient field data. We had a lot of field data at ABC that demonstrated it was a dissolved phase. And on top of that, as we pointed out in our -- I think it was 37-page response NRC report, the remediation system approved by the State of North Carolina and USEPA was only valid for dissolved -- pump and treat can only deal with dissolved phase liquids. That's not treat. It's -- cannot be used for DNAPL.

And so we felt there was a complete mischaracterization of the source at ABC One-Hour Cleaners and then, of course, the uncertainty,

okay? And I believe the Chapter I report was available in March of 2009. I'll have to look it up and see what the date is, but it was before the NRC report was released. And I am sure if the NRC -- in fact, there's an e-mail where I told -- communicated to Dr. Clement that we had an uncertainty analysis report, completed report, that I thought the NRC committee should see. But if the NRC committee had wanted to see it, even if it's unpublished form, I'm sure our agency leadership would have allowed them to do that.

Q. Okay. I'm showing you what we're -- we're pulling up what is being marked as Exhibit 14. It should be uploaded to the exhibit platform.

(DFT. EXHIBIT 14, e-mail correspondence Bates-stamped CLJA_WATERMODELING_01-0000080493, was marked for identification.)

BY MR. ANWAR:

Q. So this is an e-mail from you to Susan Martel dated May 15, 2008?

A. That is correct.

Q. That's correct?

A. That's correct.

Q. Okay. Who is Susan Martel?

A. She was the -- I knew of her as the executive secretary of the NRC committee and was looking at contaminated drinking water at Camp Lejeune. And I believe she is the one that sent me the invitation to make a presentation at -- in Washington D.C.

Q. So here in this e-mail you write, "Dear Susan, since ATSDR presented information to the committee on September 24th pertaining to our agency's current health study including water modeling activities at Camp Lejeune, I and my colleagues at ATSDR have provided additional information and responses to inquiries from committee members and we continue to be very supportive of the NRC's charge and mission with respect to the Camp Lejeune issues."

Did I read that first paragraph --

A. Yes.

Q. I read that first paragraph correctly?

A. That is correct.

Q. Okay. Second paragraph says "I have become aware, however, in responding to inquiries and information requests that all of the NRC committee members may not have -- may not be fully aware or appreciate the technical issues,

logistical, and budgetary constraints faced by ATSDR, especially within the last six months."

Did I read that correctly?

A. Yes.

Q. What did you mean in that paragraph?

A. This is 2008. So it appeared to me that they were focusing solely on Tarawa Terrace, but we were still going through the data for Hadnot Point, and they were going to make, you know, their -- their goal or mission, from the title of the report, "is contaminated water at Camp Lejeune." It didn't say "contaminated water at Tarawa Terrace", but it said "at Camp Lejeune." So they should have considered or at least asked what data we had for Hadnot Point in that -- that area.

And then also I think around that time is when we had some substantial budgetary issues with the -- the Navy either delaying funding or whatever, and so my concern was that would be reflected in, you know, negatively on the progress of the modeling and I thought that was important for committee members to also understand.

Q. Okay. The third paragraph reads -- "therefore --

A. Kevin, can you put up the third

paragraph? Okay.

Q. "Therefore, I am requesting that you and the NRC committee consider convening a closed-door meeting with ATSDR health study and water modeling staff so that we are able to address any and all questions committee members may have. We feel this would be a useful time for the NRC committee members in preparing its draft report and recommendations."

Why did you request a closed-door meeting?

A. I just -- because we had attended the public meeting, okay, where we made the presentation, and I -- I -- perhaps that was a bad choice of words, but I wanted it to be a scientific, highly technical meeting and thought that the closed-door meeting -- my definition of closed-door meeting meant for scientists and technical people working on Camp Lejeune to get together and discuss technical issues. I was thinking it in terms of, like, our expert panels that we had at ATSDR, whereas, if we held an open public meeting, you know, you would have other issues being brought -- brought -- brought in that would detract from the technical and scientific

issues we wanted to cover.

Q. The fourth paragraph reads "this meeting could take place at ATSDR's Chamblee campus at NRC headquarters at a location -- or at a location of mutual convenience to the NRC committee members."

A. Right.

Q. I read that correctly?

A. Yes.

Q. And then the last paragraph there says, "I cannot stress strongly enough that the ATSDR health study staff including water modeling staff want the NRC committee members to have all information it needs and requires to fulfill its mission and we believe that additional time spent with ATSDR staff will greatly help accomplish this mission."

Did I read that correctly?

A. Yes.

Q. What did you mean there?

A. Just what it says, is that, again, we did not feel the -- based on e-mail communication, primarily from me and Dr. Clement, I assume they may have been similar to the health scientist, the request for information and -- and all of that,

that they were not getting the complete picture, okay? And we wanted to make sure they had all information and all data available as to the most current time, which would have been the date of that letter, May 2008.

Q. At this time did you -- did you discover or get a sense when you -- at the time that you were writing this e-mail that the NRC's report may come out negative towards the water modeling?

A. Not at all. Not at this time. Again, that is what took us by -- by surprise, to be quite honest.

THE VIDEOGRAPHER: I need to go off record within five minutes.

MR. ANWAR: What's that?

THE VIDEOGRAPHER: I just need to go off record within five minutes.

MR. ANWAR: Okay. Let's go off now.

THE VIDEOGRAPHER: Going off the record. The time is 4:32 p.m.

(Off the record.)

THE VIDEOGRAPHER: Going back on the record. The time is 4:35 p.m.

BY MR. ANWAR:

Q. Okay. We are back on the record from a short break. We're marking -- you're about to be shown what is being marked as Exhibit 15.

(DFT. EXHIBIT 15, e-mail correspondence Bates-stamped CLJA_ATSDR_BOVE_0000160913 and 160912, was marked for identification.)

BY MR. ANWAR:

Q. And let me know when you can see it. Can you see it?

A. Yes, I can see that. I'm sorry. Yeah.

Q. Okay. So this -- appears to be an e-mail communication from you dated January 12th, 2007 to the -- what looks to be the water -- the water modeling and epidemiology team at ATSDR; is that right?

A. That is -- well, let me -- can you see who it's sent to and I'll tell you. Yes, yes, that's correct.

Q. Okay. And so I'll just work through this e-mail. Subject is "finalizing modeling activities for Tarawa Terrace," correct?

A. Right, that's correct.

Q. And then the importance is high. And the opening line in blue "an open e-mail, slash, letter to those conducting groundwater flow, fate

and transport modeling at Tarawa Terrace and vicinity. This e-mail comes as a result of what I perceive is differing opinions, each valid, I am convinced, from perceived data limitations and modeling assumptions, as to what, quote, calibrated parameter values should be used, depending on the model being used and its level of sophistication.

In this particular case there is apparently a discrepancy on the value of the biodegradation rate for PCE between 0.0006 per day to 0.0004 per day. There are two different levels of sophistication of models used. MT3DMS versus TechFlowMP and a lack of definitive data to compare modeling results against, non-detects ranging from two milligrams per -- micrograms per liter to ten micrograms per liter, in my opinion, do not constitute a definitive standard by which to compare modeling results."

Did I read that correctly?

A. Yes, yes.

Q. Can you -- can you tell me what biodegradation rate is?

A. When a constituent -- or contaminant such as PCE goes in groundwater, it has degradation products. So for example, PCE degrades to TCE and

then degrades to DCE, one of the forms, trans or cis DCE, and then degrades down to VC, vinyl chloride, okay? So that's degradation.

The approach ATSDR took initially using the MT3DMS model was not to degrade to PCE, okay? What we wanted to check out was that a gross error was that, you know, giving a higher concentration -- a substantially higher concentration to PCE than had we degraded it so I asked our corporative agreement partners, who I knew had a model, and did multi -- multiphase flow so they could degrade PCE to run it as -- as well and look at the degradation products and look to see, then I compare if there was a substantial difference or not.

Q. Does it -- is it fair to characterize -- strike that.

Would you agree that a higher degradation rate means more of the PCE is degrading away as water is moving towards wherever it's heading, the water treatment plant or the finished -- the water distribution system?

MR. DEAN: Object to the form of the question.

THE WITNESS: It would degrade at a faster rate.

BY MR. ANWAR:

Q. And here it says "non-detects ranging from two micrograms per liter to ten micrograms per liter, in my opinion, do not constitute a definitive standard by which to compare modeling results."

Why, in your opinion, do non-detects not constitute a definitive standard by which to compare modeling results?

MR. DEAN: Object to the form of the question. You're asking for an opinion, which he's not yet completed his work in this case.

BY MR. ANWAR:

Q. And let me reframe the question. Why at this time when you wrote this e-mail did you think that in your -- did you hold the opinion that non-detects do not constitute a definitive standard by which to compare modeling results?

A. At the time that I wrote that there was a -- as I pointed out, a difference of opinion between, I believe, the modeling team at Georgia Tech and the ATSDR modeling team as to what the degradation rate should be for PCE not having any measured values. And so I didn't want to just look at the samples that said non-detect, okay, because

that really wouldn't tell you the impact of the degradation of the PCE, okay? If you had samples that, you know, 10, 20, 30 or whatever and then one model is predicting higher or lower, then that could help you assess which value to use.

Q. Aren't non-detects data also that should be considered?

A. Oh, we considered it in our calibration, in our analysis, but for this particular issue I -- I did not want it considered because I did not believe as a science technical project officer for this project that that would give us a definitive resolution of the parameter value. This is -- this type of discussion goes on and on in all model calibration efforts or model simulation and calibration efforts. Whether it's complex is you don't have -- especially, like, degradation rates. Unless you've gone into the laboratory and measured them, out in the field you don't have them, so you use the model to determine what value should be -- should be used, and we were coming up with two different -- two different rates, okay?

Q. The second paragraph reads "as the agency is under tremendous pressure, if not,

outright criticism to immediately, all caps, provide a report on Tarawa Terrace we no longer have the time to debate this matter any further. I'm calling a tie in the battle of models. Therefore, as project officer for this -- for this project, I have made the following decision and I am requesting everyone involved abide by my decision."

I wanted to ask you, what was the tremendous appreciate, if not, outright criticism?

A. Could you scroll to the date of that letter?

MR. DEAN: Yeah, that's what I was looking at.

THE WITNESS: That was January 2007.

BY MR. ANWAR:

Q. So just for the purpose of the record, my question is what was the tremendous pressure, if not, outright criticism that the water modeling team was facing and the agency was facing, meaning ATSDR?

A. Yeah, ATSDR. We were facing from the public and -- and the CAP why there was a delay in producing modeling results to be released to the public. And there were, you know, the agency

leadership would come to us and say what's taking so long and why haven't you completed the report and put it out? And again, because we -- we wanted to cover all aspects of the contaminant fate and transport, that's why we asked our university partner to do a degradation analysis, not just the single source that we used, okay? I felt that was critical to understand if, in fact, we were way overestimating PCE concentrations or not.

And so there was pressure to complete the Tarawa Terrace, you know, and quarterly reviews and things like that, pressure to -- to complete the Tarawa Terrace modeling.

Q. Do you -- you say here "we no longer have time to debate this matter any further." Did the pressure that you were facing impact the scientific process that you were undertaking in performing water modeling related to Camp Lejeune?

A. I don't believe it did because, again, they were two different values from two different models. And this is a typical discussion that has gone -- that anyone or any team that goes through fate and transport modeling conducts. It's not -- this is not an unusual occurrence, this type of discussion, and we had similar discussions with

Hadnot Point. And I felt that there was really no -- no way in a rapid sense to say whether the 0.006 was more acceptable or the 0.004. So I said we needed to make a decision, okay?

Q. On -- thank you.

On 0.3 it states "no quantitative comparisons will be made using non-detect ND samples. As the detection limits for these samples range from two micrograms per liter to ten micrograms per liter, using these values is a double edge sword that will come back to attack us because those who review our modeling results will pick an ND value to justify their point of view and contradict our results."

Did I read that correctly?

A. That is correct.

Q. I wanted to start with the first sentence, no quantitative comparisons will be made using non-detect ND samples." What did you mean by that?

A. A number of the samples, as you can read in the report, had non-detects in them, which means they were below the detection limit. My concern was that depending on your point of view, non-detect -- and we had numerous discussions, say,

for -- with our point of contacts at Camp Lejeune, they assume non-detect meant zero concentration, okay. On the other hand, because you have a detection limit of say one to ten micrograms per liter, you could have others that say, well, non-detect just meant it fell within or outside the detection limit, so you've got just differing opinions. So initially I -- I said let's just use what I call, you know, the real data, the data that's above the detection limits.

Q. Why is non-detect not real data?

A. I didn't say it wasn't real data. I said -- and actually we reversed that because -- in our report we do go back to that. And it's not that I'm a believer that non-detect -- that should be used, but I think I was referring to this specific -- this specific issue of the biodegradation rate.

Q. And what did you mean when you said "using these values as a double edge sword that will come back to attack us because those who review our modeling results will pick an ND value to justify their point of view and contradict or results?"

A. That's exactly what I said before and

perhaps I can explain it better. If -- if you -- say a model simulation is at five micrograms per liter, okay, if your detection limit is ten, it's below the detection limit, okay? Five is below the detection limit. It's just a real, real number. So those who, say, want to except your modeling results, they will say, oh, yeah this is great, it's below the detection limit, but it's, you know, five is greater than zero.

On the other hand, as I pointed out, you'll have those that will say, well, if the sample says it's below the detection limit, that means it's zero, okay? So you can't win either -- either -- either way.

Q. Is those differing view points that you're describing, would -- would that be considered sort of reasonable scientific debate and was -- go on.

A. Yeah, I would say there's difference of scientific opinion. Again, this is dated January of 2007. By the time we moved on later in the year and solved the issue of degradation rate, we did, in fact, did use the non-detects to compare modeling results with, so we did not discard non-detects, okay? We looked at the detection

limit. So I'm -- I'm probably convinced at this point that this e-mail was written at the height -- height of the differing of opinions which, you know, technical teams go through in...

Q. Based on the timing of this e-mail, it's January 2007, correct? And I think you stated earlier it was June of 2007 where you were called to a senate hearing --

A. Right.

Q. -- on Camp Lejeune, right?

A. Right.

Q. Were you feeling political pressure when you're referring to the pressure in the e-mail?

A. I did not have -- I was not in any direct communication with politicians, but our agency leadership probably were or at least got feedback from them, and so they were pressuring us to finish up.

Q. At the end I wanted to ask you about this last paragraph, "the bottom line, it is time to stop modeling and, quote, fine tuning models as we do not have the data to justify further modeling analysis."

A. Right.

Q. "The agency does not have the time to devote to additional modeling analyses --

A. Oh, I'm sorry. I'm not seeing that. There we go. Okay.

Q. And then the last sentence, "we have a CAP meeting scheduled in the beginning of March and I must have a completed draft report."

So I wanted to first ask you about the first sentence in that last paragraph, "the bottom line, it is time to stop modeling and fine tuning modelings as we do not have the data to justify further analyses."

What did you mean by "we do not have the model to justify further modeling analysis?"

A. Well, the sample on the top of the page, in other words, the degradation rate, we can go back and forth and do additional, additional, additional simulations trying to see which parameter value would -- would be more acceptable or more realistic, and you can do that with all model parameters. And typically, you know, you want to, again, try to get your calibration values as close as possible to your observed values.

So at a certain point you have to accept that we're all only going to be within plus

or minus five feet of water level instead of plus or minus three feet of water level. If not, you can keep modeling adding an item and that's what I did not want to see, and I felt because of having reviewed the Tarawa Terrace data, knowing the limited data that we had, that we probably would not be able to refine modeling to make, you know, additional decisions as to parameter values and things of that nature.

Q. And then that last sentence reads, "we have a CAP meeting scheduled in the beginning of March and I must have a completed draft report."

A. Right.

Q. Were you feeling pressure from the CAP to complete --

A. It was communicated to me that the CAP would be expecting a report.

Q. Who communicated it to you?

A. I don't have a specific individual necessarily. It may have come up in our branch meeting or division meeting, okay, in other words, just to make us aware that we're having a CAP meeting and the CAP has, I'll say, requested or said they are expecting to have a final report. And the reason it's a final report is because the

CAP wanted to see modeling results and it was agency policy not to release modeling results publicly until a report was publicly released.

Q. Wouldn't you have preferred to have built consensus among your team and made sure all of the modelers on your team were in agreement on the parameters to make sure what you were -- you were giving to the CAP, you felt confident as opposed to rushing to get it done?

A. This was the only real parameter that there was a question about, and the reason why is because, again, we went to a more sophisticated model that -- the degradation, the degradation byproducts. So I don't -- I don't think I was rushing them. We had people doing model simulations and looking at the various values and seeing what impact they had at different locations in the model.

And you know, we were not coming up with a definitive result as to which specific value, and to me that seemed to be a small range, 0.006 to 0.004, and so I just made a, you know, project officer decision that, well, let's just take the average or go with the -- the mid -- midpoint value.

Q. The 0.0005 biodegradation rate is the rate that ended up in the Tarawa Terrace model, correct?

A. That is my understanding. I would have to look in -- in Chapter F, okay?

Q. I can tell you I've looked and that's what I saw.

A. Okay. Well, then that's -- that's -- you know, and all the team members were -- I think in part they were looking for a decision to be made, okay, in other words.

Q. Okay. Can we pull up the next exhibit. Is this 15?

MR. ANTONUCCI: 16.

MR. ANWAR: 16.

(DFT. EXHIBIT 16, e-mail correspondence Bates-stamped CLJA_WATERMODELING_010000075306 and 75307, was marked for identification.)

BY MR. ANWAR:

Q. We're showing you what is being marked as Exhibit 16. Can you see it?

A. Yes.

Q. This is an e-mail dated January 13, 2007 from Robert Faye to you, Morris Maslia. Do you agree with that?

A. Yes.

Q. Okay. The subject is "MT3DMS results" and the Morris -- or excuse me, the e-mail starts, "hi, Morris, I've rerun the fate and transport model with a biodegradation rate of 0.0005 as required. The results are only marginally acceptable and certainly do not represent our best calibration. Nevertheless, I intend to finish the report with the current simulation results and explain to them -- explain them to the best of my ability. Because of the marginal results several issues have come to mind that I need to share with you and which I hope to discuss with you in the future. I have listed these issues below."

Did I read that correctly?

A. Yes.

Q. In number one he says "I find it will be -- I find it very difficult to defend these results to my technical peers or in a court of law. Consequently, I would like to write a letter to the record to you and to ERG explaining what has happened, why the results are what they are, and addressing my concerns. I will send a draft of this letter to you first and ask for your comments."

Did I read that correctly?

A. Yes, yes, you did.

Q. Did you receive a draft of this letter to the record from Robert Faye?

A. I do not recall.

Q. Okay. I will represent to you that I did not find it in the water modeling project files.

A. Okay. Then it was not sent.

Q. Okay. Number two, "I believe we have violated a fundamental rule of good modeling procedure. We let the tail wag the dog and assigned extraordinary credibility to simulated numbers rather than to well-established concepts."

When -- did I read that correctly?

A. Yes.

Q. And when he says "we let the tail wag the dog", what he's really saying is we -- we pushed to get to a certain result, right?

MR. DEAN: Object to the form of the question.

THE WITNESS: I think he may have been referring to the push to finish, finish the modeling analyses, okay, by a deadline, by a deadline.

BY MR. ANWAR:

Q. Okay. So you think he was referring to the deadline and not furthering the debate?

A. Yes, yes.

Q. What -- he says "we have violated a fundamental rule of good modeling procedure." Do you know what fundamental rule of good modeling procedure he's referring to here?

MR. DEAN: Object to the form of the question.

THE WITNESS: I do not.

BY MR. ANWAR:

Q. The e-mail goes on, "when a choice must be made between accepting less than a -- than desirable model results or violating or compromising valid conceptual models, I believe we should accept the undesirable results and explain the limitations of the simulations in that context."

Did I read that correctly?

A. Yes.

Q. And based on those two sentences, he's clearing talking about the results and not the timing, right?

MR. DEAN: Object to the form of the

question. Ask the person who had drafted the e-mail.

THE WITNESS: I couldn't say whether he's talking about the timing or -- again, I don't -- when I say I don't recall, it's been so long, I don't recall specifically this -- this e-mail other than it exists. And reading it, I do recall having a conversation with Mr. Faye and, you know, that was his -- his, you know, opinion.

BY MR. ANWAR:

Q. Do you recall the conversation that you had with Mr. Faye?

A. No, I do not.

Q. Number three says, "I would like to insert a statement in the fate and transport report that ATSDR -- ATSDR required 100 percent agreement between the MT3DMS model and the Georgia Tech model regarding fate and transport parameters. As a result, the biodegradation rate assigned to both models was a compromise between the best rates determined by individual model calibration."

Did I read that correctly?

A. That's correct.

Q. Do you -- do you know what he's referring to there?

A. No. I -- looking at this e-mail -- and I've known Mr. Faye for 40-some-odd years since our time at -- as with any person conducting modeling or whatever, you sometimes blow things out of perspective, okay, and I believe he thought that his best modeling or calibration approach may have been questioned by our university partner, okay, and vice versa, okay? They may have felt that he was trying to tell them what the best parameter values were, okay?

So now that I see that and the length of it, and knowing Mr. Faye, it was letting off steam, okay, because there was no such statement, to my knowledge, put in the fate and transport report.

Q. 0.4 states, "from a technical point of view, I believe most or all of this unfortunate, quote, mess has evolved from flawed concepts and applications on the part of Georgia Tech. Specifically they applied the calibrated mass loading rate from the M3DMS [sic] model to the unsaturated and saturated zones represented in their model.

I assume initially they also applied the calibrated MT3DMS degradation rate to the

unsaturated and saturated zones. Degradation in the saturated zone is aerobically driven and occurs at rates that are possibly several orders of magnitude greater than anaerobic degradation. The degradation rate that I computed at well TT-26 was reasonably an anaerobic rate also applying the calibrated mass loading rate from the MT3DMS model to the unsaturated zone directly equates the actual, quote, real-world PCE loss rate at ABC One Cleaners to the MT3DMS mass loading rate.

Such an equation is absurd as it does not account for retention and degradation within the unsaturated zone. The MT3DMS code requires that mass loading be applied directly to the water table and thus can represent at best only at the minimum loss rate at ABC One-Hour Cleaners. I believe if Georgia Tech had calibrated instead to simulate PCE concentrations at the water table at the loading elements and had applied a reasonable aerobic degradation rate to their unsaturated zone, then a mass loading rate significantly greater than the calibrated MT3DMS rate would result for the Georgia Tech model.

This rate would more directly equate to the PCE loss to -- due to operations at ABC

One-Hour Cleaners. In addition, these approaches would result in a correspondingly greater PCE mass in the saturated zone and quite possibly the calibrated biodegradation rates assigned to the MT3DMS and Georgia Tech model would be highly similar."

Did I read all of that correctly?

A. Yes.

Q. What is your recollection or your understanding of what he's saying here?

A. Basically he's letting off steam as to, you know, the differences in the modeling approach, yeah, and you did have two different models. The MT3DMS is a saturated zone. Only from the water table Georgia Tech model went from land surface down. And I believe this whole discourse was basically eventually resolved, okay? And I don't know if it was a formal meeting or not, but we did -- I mean, between Mr. Faye and Georgia Tech and myself.

So, again, this was one of those things that I believe knowing Mr. Faye in the elongated e-mail, I think he was just frustrated that he had felt he had a calibrated model, Georgia Tech felt they had a calibrated model, and, you know, it's --

that happens I would say often in these types of analyses. Not necessarily just historical reconstruction, but just modeling analyses when you're trying to compare a simpler model or a model making certain assumptions versus a more complex model.

Q. And so the last paragraph there states "the application of the anaerobic degradation rate to the unsaturated zone and the direct equation of the actual PCE loss due to operations at ABC One-Hour Cleaners to the mass loading rate calibrated for the MT3DMS model violates sound reasoning and hydraulic principles. I am not at all surprised that Georgia Tech found less PCE mass than required for a reasonable simulation. The fault, however, was not in the assigned degradation rate, but rather in their flawed concepts and reasoning. I suspect a through technical review" --

A. Yeah, can you -- hold on. Can you scroll up? Okay.

Q. Okay. I apologize. "I suspect a thorough technical review by my competent peers will point out these issues."

Did I read that correctly?

A. Yes.

Q. Okay. And then the last paragraph, "let me emphasize, I do not intend to change the current model results and I'm not asking for any dispensation to do so, however, I would like to follow through on my letter to the record and my other requests as soon as possible. Please let me know your thoughts at your earliest convenience."

Did I read that correctly?

A. That is correct.

Q. Did you -- do you recall ever responding to this e-mail?

A. No, I do not.

Q. And I think you --

A. I do not recall receiving a letter either. And again, this was, I think, you know, Mr. Faye was not physically located at our headquarters. He was at his office, which was in North Georgia, so we did everything by phone or by e-mail. And I think it's just an expression of frustration. I think we eventually sort of got -- got together.

Q. Okay. I wanted to shift gears a little bit. I know I'm running up probably on the hour, so I would like to --

A. It's fine.
Q. -- get through this.
Do you have any family or friends that have filed legal claims related to Camp Lejeune?
A. Not that I'm aware of.
Q. Okay. Aside from serving as an expert now for the plaintiffs, have you ever received any compensation from someone other than ATSDR related to your Camp Lejeune water modeling work?
A. No, I have not.
Q. Let's pull up the next exhibit. This will be the January 17, 2009 -- actually this might be the wrong one. I apologize. Give me one second. Let's do -- actually I think it's the right one.
(DFT. EXHIBIT 17, e-mail correspondence Bates-stamped CLJA_WATERMODELING_01-09_0000034863 through 34866, was marked for identification.)
BY MR. ANWAR:
Q. Okay. I wanted to ask -- so what you should be seeing now is an exhibit that we're marking as Exhibit 17.
A. Right. Okay.
Q. It's an e-mail exchange with the last e-mail dated June 17, 2009. Do you see that?

A. Yes.

Q. Okay. And among the recipients in this e-mail, you are -- your e-mail is copied there in the middle of the recipients.

If we scroll down the chain, the first e-mail on the chain starts June 17, 2009 and it is an e-mail from Richard Clapp, who I believe was a CAP member, right?

A. He was -- I don't know if he was a CAP member at that time or not, but he was a CAP member and also worked at -- was a professor at -- I believe it was Boston University School of Public Health.

Q. And he's forwarding to three individuals, one of whom appears to be Jerry Ensminger, Mr. Ensminger, a statement in response to the National Research Council on Camp Lejeune.

A. Right.

Q. And then --

MR. DEAN: Actually you're miss -- just honestly, I see what you're doing, but you're misinterpreting how this occurred. This is a post -- it's clear that this is a copy and post by J -- Joe Anderson that went to Jerry Ensminger on July the 17th, 2009. And he's pasting in the e-mail

that's below. Because if you go to the end of the e-mail, you will see J. Panglia -- I mean Joseph Anderson's signature at the end of the e-mail. So he did not -- this e-mail was not sent by Richard Clapp.

MR. ANWAR: That's not where I'm going with this.

MR. DEAN: Okay.

MR. ANWAR: And I would appreciate if you don't --

MR. DEAN: No, I just want to make sure -- you're misrepresenting who sent what e-mail. This -- but anyway, go ahead.

BY MR. ANWAR:

Q. What it appears to me -- and Mr. Maslia, if you understand it differently, I would appreciate hearing from the witness and letting the witness testify. There -- the chain above is certainly an e-mail dated June 17, 2009. It's from a Janderson@andersonpangia.com to a Jensminger@hotmail.com.

A. Right.

Q. And somewhere in the middle there, and we can find it if you need to, but it's on the right-hand side in the middle. There's

MMmaslia@CDC.gov.

A. Okay. I'll --

MR. DEAN: I see it.

THE WITNESS: Okay.

BY MR. ANWAR:

Q. My question for you was do you -- Joseph Anderson was the lawyer that took your deposition in June 2010.

A. That is my recollection.

Q. Okay. And this is a year before your deposition and you're being copied on an e-mail by a lawyer -- a plaintiff's lawyer that took your deposition a year later. Do you know why you were copied on this e-mail?

A. No, I do not.

Q. Prior to your deposition in June 2010, had you ever spoken with Joseph Anderson?

A. No, I have not.

MR. DEAN: I also object on the record that this e-mail has not been produced by the DOJ in the manner which it originally existed. If you look at Bates stamp 34 -- let me finish.

MR. ANWAR: You can make your objection.

MR. DEAN: No, sir, you're

mischaracterizing that this is an e-mail and this is not an e-mail in the sense it's sent. If you look at 3486 --

MR. ANWAR: You're not entitled to testify.

MR. DEAN: Yes -- I'm not. I'm making an objection.

MR. ANWAR: If we need to call the magistrate and I get another hour for this deposition --

MR. DEAN: You are misrepresenting this e-mail. 34863, if you look at the last e-mail, EPA.gov at the top, then it is a conversation that ends in the second -- at the top of the second page, it says "outstanding, J." This is not the full chain of this e-mail and I object to your using this e-mail in the sense that you have.

MR. ANWAR: Great. You can make that objection in court.

MR. DEAN: Okay.

BY MR. ANWAR:

Q. Let's move on to the next exhibit dated October 26, 2009.

(DFT. EXHIBIT 18, e-mail correspondence Bates-stamped CLJA_WATERMODELING_01-09_0000035889

and 35890, was marked for identification.)

MR. DEAN: Exhibit 18?

MR. ANWAR: Correct.

BY MR. ANWAR:

Q. And let me know when you see it.

MR. DEAN: Okay.

BY MR. ANWAR:

Q. Exhibit 18, if you -- at the top of the last e-mail on this chain is an e-mail dated October 26, 2009, so this is while the water modeling is still ongoing. It's an e-mail from Jerry Ensminger to you and it copies what appears to be a paralegal from the Bell Legal Group. And if you scroll down --

A. I'm sorry, Bell...

Q. If you scroll down to the bottom of the chain, there's an e-mail dated October 26, 2009.

A. Right.

Q. Do you see that?

A. From Elle Brigman.

Q. Correct, to Mr. Ensminger.

A. Right.

Q. And you're copied there?

A. Uh-huh.

Q. And it says "subject banner request."

And the e-mail states, from Elle, "hello, this is Elle. I just spoke with you on the phone. This e-mail is also carbon copied to Mr. Jerry."

Did I read that correctly?

A. Yes, yes.

Q. So you can let me know if you disagree, but the way I interpret that first two lines or three lines right there is that Elle Brigman is referring to speaking to you on the phone and he's -- he or her has copied this e-mail to Mr. Ensminger. Would you agree with that?

MR. DEAN: Object to the form of the question.

THE WITNESS: I don't recall at all who this is or, obviously, the e-mail you can -- because it's got my e-mail address on there, but I just don't recall the topic or the subject matter or the person that sent it.

BY MR. ANWAR:

Q. So the rest of the e-mail reads, "Jerry first let me say, those boiled peanuts rocked. I had them on the way home", you know it's a personal --

A. Right.

Q. -- story about peanuts. The second

paragraph reads "anyway, the banner, slash, poster you have and showed us, we would like to have a copy for the city council meeting in December. I was not sure of the title of the items, so I wanted to ask you if it is a combination of various documents, which ones? Anyway, guidance would be great and thank you again for your knowledge and the boiled peanuts. I am sure I will be talking to you soon."

And again, since the request is for a banner, it appears to be directed at you. Would you agree with that?

MR. DEAN: Object to the form of the question.

THE WITNESS: I have -- I have no idea what banner the e-mail is referring to.

BY MR. ANWAR:

Q. Do you know why you -- so do you know who the Bell Legal Group is?

A. At that point?

Q. At that point or now, do you know who they are now?

A. Now I know who the Bell Legal Group --

Q. Who are they?

A. I've been retained for them as an

expert witness or expert consultant, okay?

Q. Is the Bell Legal Group the -- the lead counsel in this litigation? Are we sitting at the Bell Legal Group right now?

A. We're sitting at the Bell Legal Group offices. As to their responsibility or assignment, I've really not gotten into that, okay?

Q. So can you -- can you explain to me why you're being copied on e-mails as the water modeling is being performed --

A. Okay. Hold on.

Q. -- in 2009 with a paralegal from the Bell Legal Group?

A. Okay. Well, describing people and their positions that I have no knowledge of so, again, I just don't recall this e-mail. It, obviously, was received by -- by me.

Q. Do you like boiled peanuts?

A. I've had them.

Q. Is that something you would give as a gift?

A. Not if I want to still stay married to my wife.

Q. And then at the top of the chain Mr. Ensminger responds to you, "Morris, don't worry

about the poster. I'll let them use mine. They do not need all of the chapters for the Tarawa Terrace model. I gave them Chapter A, but they need the entire report."

Did I read that correctly?

A. Can you scroll down? I mean -- or up probably for you. You read that correctly. Again, I do not know what banner or poster they are referring to.

Q. Okay. Let's move to exhibit -- what we'll call 19.

(DFT. EXHIBIT 19, e-mail correspondence Bates-stamped CJLA_WATERMODELING_01-09_000003613, were marked for identification.)

BY MR. ANWAR:

Q. It is an e-mail communication dated January 21, 2010. Let me know when you see it.

MR. DEAN: Okay.

BY MR. ANWAR:

Q. This is an e-mail communication dated December 16, 2009. The subject is "CAP meeting, January 21, 2010", and it's an e-mail from an individual named Vanessa Bertka to you, Mr. Maslia. Would you agree with that?

A. Yes.

Q. Okay. In the body of the e-mail -- well, let me start -- the -- at the bottom of the e-mail Vanessa Bertka is identified as a paralegal for the Bell Legal Group, correct?

A. That is correct.

Q. And the e-mail states, "Mr. Maslia, I write in regard to the CAP meeting currently set for January 21, 2010. I would like to know how we go about getting an invite into this meeting. Please contact me at your earliest convenience."

Did I read that correctly?

A. Yes.

Q. Do you recall this e-mail exchange with Ms. Bertka?

A. No, I do not.

Q. Did you have a conversation with Ms. Bertka?

A. Not that I recall.

Q. Not that you recall. Did you extend an invitation to the Bell Legal Group to the CAP meeting set for January 21, 2010?

A. That would not have been in my job assignment. It could have been agency leadership. It could have been other people, but I really did not deal at all with extending or inviting people

to CAP meetings.

Q. That e-mail goes on to state, "as I understand, you are on vacation at this time. I hope you and your family have a Merry Christmas and Happy New Year." Does -- do you have any understanding of how she knew you were on vacation at that time?

A. No, I do not. Nor do I celebrate Christmas.

Q. Fair enough. Let's pull up -- let's pull up the next e-mail April 13, 2020. You should be seeing --

MR. DEAN: We're good.

BY MR. ANWAR:

Q. -- what we're marking as Exhibit 20.

A. Okay.

(DFT. EXHIBIT 20, e-mail correspondence Bates-stamped CLJA_WATERMODELING_010000074373 through 74375, was marked for identification.)

BY MR. ANWAR:

Q. This is an e-mail exchange. The very bottom of it is dated April 13th, 2010.

A. Right.

Q. It doesn't look like you're copied on the bottom of the e-mail circulating --

A. I'm copied on the top of the e-mail.
Q. Correct.
A. Okay.
Q. But I was just referring back for context.
A. Okay.
Q. And then you end up being copied at the top of the e-mail?
A. Right.
Q. And the e-mail is from Frank Bove and -- to a group of individuals at ATSDR --
A. Right.
Q. -- and you and Barbara Rogers are copied, correct?
A. Right.
Q. Okay. And so the -- the top of the e-mail is dated April 13, 2010, right?
A. That's correct, yes.
Q. And so the e-mail states "I can guarantee that the CAP meeting will be a complete chaos if Jerry's presentation is left off the agenda. All the CAP community members have endorsed the previous draft agenda, which Jerry had on -- which had Jerry on for one hour. I have negotiated with Jerry to reduce his presentation to

30 minutes. Morris and I will work with him to make sure his presentation is tight and he does not exceed his time unless he gets questions.

The previous agenda was developed by Perri and myself. We know what works and the agenda reflects our best judgment on the issues the CAP meeting needs to cover and the appropriate orders -- order of the issues, i.e. Jerry's presentation following Morris's update after the morning break period.

Given my over 40 years as a political activist just like Jerry, as well as my seven years as a full-time community organizer, I think I have the experience necessary to know what will work and what won't work when it comes to community meetings like the CAP. This CAP has been a model for other CAPs to follow. It has been extremely successful publicizing the issues. It has provided valuable comments to our water modeling work and our epi studies. It has been instrumental in getting funding and in general has been a model for successful community participation. ATSDR has gained public trust, media trust, congressional support through the efforts of the CAP."

Let me stop right there. Did I read

that correctly?

A. Yes, you read that correctly.

Q. Do you recall this particular, I guess, incident or incidents situation that he's describing?

A. Not this specific one.

Q. What is your understanding of what's being said in the e-mail?

MR. DEAN: Object to the form of the question.

THE WITNESS: My understanding is that Mr. Ensminger was allotted a certain amount of time to make a presentation at the CAP meeting. Someone, and I don't know who, but someone who reviewed the agenda took him off of there, okay? And I'm sure that met with displeasure. And so it's an e-mail to explain why he should be put back on the agenda.

Q. And the e-mail starts out, "I can guarantee that the CAP meeting will be complete chaos if Jerry's presentation is left off the agenda." Do you recall what Frank Bove was referring to here?

A. No, I do not. Again, I was never directly involved with the administration or the

logistics of CAP meetings. I was simply invited there as an ATSDR's technical expert in water modeling.

Q. The middle of the e-mail says -- and this is Dr. Bove speaking, "given my over 40 years as a political activist just like Jerry, as well as my seven years as a full-time community organizer." Would you -- do you -- do you know Dr. Bove to be a political activist?

A. Yes.

Q. And how so?

A. Oh, he will tell anyone who asks him that, that he is a community organizer and a political activist. I mean, he does not hide it, in other words. I have not seen him in action, okay, but I know he'll, you know, work with community organizations based on whatever political, you know, opinions they may need or may want. And he -- I mean, he has stated, you know, directly to me and others that he is a community organizer.

Q. Do you know Dr. Bove to be a political activist as it relates to Camp Lejeune?

MR. DEAN: Object to the form of the question.

THE WITNESS: I never observed any political activist activity on his part with respect to Camp Lejeune. He was passionate about -- from the scientific standpoint in getting funding, getting and providing community members with transparent information.

BY MR. ANWAR:

Q. And then he says "I'm a political activist just like Jerry." I think earlier you agreed, do you understand or do you know Mr. Ensminger to be a political activist?

MR. DEAN: Object to the form of the question.

THE WITNESS: I have not been observed or been told about Mr. Ensminger being, you know, a political activist. Like, Dr. Bove had told me directly, so it's not been told to me directly by Mr. Ensminger that's what he is, but obviously the Janey Ensminger Act got signed, okay, and so that would take some amount of political activism to get that done.

BY MR. ANWAR:

Q. Do you consider yourself an activist?

A. No, I do not.

Q. The -- the first sentence of the second

paragraph says "I've heard that a congressional staffer from Miller's office is considering personally attending the CAP meeting."

Do you know who Dr. Bove is referring to when he says Miller's office?

A. No, I do not.

Q. During your time at ATSDR and sort of involvement with the CAP and attendance to CAP meetings, has a congressional staffer ever attended a CAP meeting that you've attended?

A. I don't -- I don't recall a congressional staffer at a CAP meeting, but then again, I did not attend all sessions of each CAP meeting, okay? In other words, when they got into the health studies or some agency budgetary issues maybe towards the end of a CAP meeting, you know, I was not needed there, so I can't say if there were congressional people there or not, but during the time that I made presentations at the CAP, there were no congressional representatives there, or staffers.

Q. Okay. Should be appearing shortly what we're marking as Exhibit 21.

(DFT. EXHIBIT 21, e-mail correspondence Bates-stamped CL_MASLIA_0000000173 and 174, was

marked for identification.)
BY MR. ANWAR:
Q. Do you see that e-mail in front of you?
MR. DEAN: Yes.
THE WITNESS: Yes.
BY MR. ANWAR:
Q. Okay. So the top of the chain is from you to Mr. Ensminger. It's dated July 13, 2022. The start of the chain is an e-mail from you to Mr. Ensminger. It's dated July 12th, 2022. So let's -- let's start at the bottom of the chain. It says there -- and is that your e-mail address, H2Oboy54@gmail.com?
A. That's, yes, my e-mail address.
Q. Okay. And the e-mail is dated July 2012 -- or July 12, 2022, correct, to Jerry Ensminger?
A. Right.
Q. And it is a -- it appears to be an e-mail of you passing along a published article to Mr. Ensminger about Camp Lejeune; is that right?
A. That is correct.
Q. Okay. And then at the bottom of the e-mail you say "also I have been contacted by another law firm about Camp Lejeune. No

discussions yet, but just wanted to give you a heads-up." Did I read that correctly?

A. That is correct.

Q. Why did you want to give Mr. Ensminger a heads-up?

A. Some -- somewhere and I don't recall where, but, I mean, it was during this time frame he had asked me would I be interested in doing consulting work as an expert. And he said, I know of a law firm that may be interested in your services. I said, fine, give them my name, I can send them my CV or resume.

And then I was also contacted by another law firm. I don't recall the name at this time. I don't know where they got my name from, but maybe from the reports or wherever. And so just thought I would let him know that, you know, business was hopping.

Q. The chain goes on to a response from Mr. Ensminger dated July 13th, 2022. It states, "Morris, please don't take any meeting with other law firm until you meet with Ed Bell. The bill hadn't passed Congress yet, let alone being signed into law by the POTUS. I will see if I can get Ed to give you a call today, Jerry."

Did I read that correctly?

A. Yes.

Q. And then the top of the chain, the last chain, is a response to Mr. Ensminger's e-mail, "spoke with Kevin who works with Ed Bell this morning. They will be sending me a retainer form to sign."

Did I read that correctly?

A. Yes.

Q. Okay. And when you're referring to Kevin there, are you referring to Mr. Dean, here today?

A. Yes.

MR. DEAN: Not another one.

BY MR. ANWAR:

Q. And I understand that you were retained as an expert around July -- or June/July 2022, correct?

A. July. Mid July, 2022, yes, that's correct.

Q. My -- how -- how long have you known Ed Bell or professionals at the Bell Legal Group?

A. Professionally since July -- well, yeah, July of 2022.

Q. Okay. What about personally?

A. I was introduced to him -- I think it was earlier in 2022 maybe. There was a CAP meeting in Atlanta and there was a restaurant down in the Atlanta area, and I was introduced to him. Not his capacity or anything, but just as Ed Bell.

Q. How long have you known Mr. Ensminger?

A. I became aware of him sometimes during the final stages of perhaps the Tarawa Terrace modeling activities.

Q. So roughly 2008/2009?

A. Yes, somewhere around there. Maybe a little before because he was a member of the CAP and we would make presentations to the CAP and they would have his nametag, you know, there.

Q. Do you consider Mr. Ensminger a friend?

A. No.

Q. When is the last time you've communicated with him?

A. I think you brought up an e-mail earlier where I forwarded an e-mail from Mr. Ensminger to Mr. Dean.

Q. Okay.

A. This -- I don't recall the date, but that's the last time.

Q. You should be seeing what is being

marked as Exhibit 23, I believe. Sorry. Sorry. 22. Clarification for the record.

(DFT. EXHIBIT 22, e-mail correspondence Bates-stamped CL_MASLIA_0000000487, was marked for identification.)

BY MR. ANWAR:

Q. It is an October 4th, 2023 e-mail from you to Mr. Ensminger.

A. Right.

Q. And it appears that you're attaching photos from an award that you won in 2015?

A. Right.

Q. I was just curious or wondering, why were you sending photos of your award to Mr. Ensminger?

A. He had e-mailed me or called me and wanted to know if I had available the photos of the presentations from the award that we -- my team received from the American Association of Environmental Engineers and Scientists in 2015. And that's public information, so...

Q. Okay. We can take that exhibit down.

My understanding is the most recent -- are you familiar with -- let me back up for a second. Are you familiar with the recent cancer

incidence study that was published by ATSDR?

A. I have a copy of it, yes.

Q. Are you familiar with the mortality study related to Camp Lejeune?

A. I'm familiar with the journal articles.

Q. Okay. Well --

A. Not the nuts and bolts of it, not being a epidemiologist.

Q. Let's just focus on the cancer incidence study. My understanding is that study does not -- and a couple -- at least one other of the more recent studies does not rely on the Camp Lejeune water modeling for any sort of exposure response analysis. Do you know why that is?

A. You would have to speak to Dr. Bove who authored that study. He was -- once I retired from ATSDR, we were not in communication other than maybe having a lunch occasionally. But in terms of conducting any studies he was working on at ATSDR, I was not solicited for information nor privy to decisions that he made as to why he was making them and...

Q. Are you represented by counsel today?

A. I'm here being deposed as a fact witness.

Q. Are the lawyers, Mr. Dean and Ms. Baughman, on the other side of the table, are they representing you here at this deposition today?

MR. DEAN: Object to --

MS. BAUGHMAN: Object to the form.

THE WITNESS: I don't believe they're representing me. I'm an expert consultant for them or to -- for the firm. I have no attorney representing me at this deposition.

BY MR. ANWAR:

Q. What led you to decide to serve as a consultant in this litigation?

A. I felt all along -- and this goes back to when I was in ATSDR and the whole NRC report issue came up, being critical of our work, and I felt, and I was proved right, that the Department of Navy, which you said is the pinnacle of science, okay, which we disagreed with. And so as time -- time went on, I felt that perhaps an -- attorneys representing plaintiffs could use someone with my technical and scientific abilities to interpret the highly technical reports that we produced and if there were questions as to why there were differences between the NRC report and the ATSDR

reports, I could be valuable to them.

Q. Earlier we discussed the Navy critique. Do you recall that discussion?

A. Yes.

Q. Of the -- the Camp Lejeune or the Tarawa Terrace?

A. Okay. Weather service, tornado warning.

MS. BAUGHMAN: This is an interior room. We're probably fine.

MR. DEAN: Keep going. You've got five more minutes anyway.

MR. ANWAR: Yeah, no, I hear you.

BY MR. ANWAR:

Q. So earlier we discussed the -- the Navy critique of the Camp Lejeune water modeling, correct?

A. Yes, that is correct.

Q. And my recollection of the critique was -- and we discussed it earlier, was they had an issue with the calibration of the model and whether the -- whether the --

MS. BAUGHMAN: If we all turn our phones off.

MR. DEAN: Yeah, if you turn off your

phones, you know, it's not going to do that.
BY MR. ANWAR:
Q. My recollection of their critique -- Goddamn it.
MR. DEAN: You've got notifications on the -- on the -- if you turn off all alerts it will...
BY MR. ANWAR:
Q. -- took issue with the calibration and the sensitivity analysis relied upon in the model; is that fair?
MS. BAUGHMAN: Object to the form.
Q. Okay. We don't need to quibble about what they took issue with, but they took issue with the -- the reliability of the modeling, fair?
MR. DEAN: Object to the form.
THE WITNESS: Again, I would not consider that's what they took issue with.
BY MR. ANWAR:
Q. Are you familiar with -- do you know who Dan Waddell is?
A. Yes, I do.
Q. What is your relationship with Mr. Waddell?
A. He's a -- employed at least at the time

that I remember him, NFEC, which is the Naval Facilities Engineering Command, and he also made a statement or presented a statement at one of the expert panel meetings that we had at ATSDR.

Q. Okay. Was --

A. And we -- and there -- let me just add -- we don't need to go look through them. I think there's a couple of e-mails between him and me.

Q. Okay. Let's leave it at the Navy critiqued the Camp Lejeune water modeling, the Tarawa Terrace model, correct?

A. That's correct.

Q. And the NRC, the National Research Council, an arm of the National Academy of Science, also critiqued the Tawara Terrace water modeling, correct?

A. Correct.

Q. And then Dr. Clement, who I think at one time you referred to as unbiased, published an article sort of raising the question about whether hind -- or reconstruction efforts are -- have value. My question to you is, of those -- just those three people or organizations that have critiqued the model, is there any aspect of their

critique, their scientific critique, with which you believe is valid?

MR. DEAN: Object to the form of the question.

THE WITNESS: First I would like to respond by first saying we responded to the Navy's critique and it's officially on the ATSDR website available for anyone to read and, I believe, we responded point by point. That's typically what's done in scientific discourse is -- whether you publish a paper or --

BY MR. ANWAR:

Q. And my question is whether -- not whether you responded. My question is --

A. Well, we didn't have -- my point is we did not have an official opportunity to respond to the NRC report, okay? And I think you need to take the responses and -- and evaluate our responses, okay?

Q. And I'm asking you, as you sit here today --

A. Right.

Q. Well, let's say, I'm asking you not in your capacity as working for the plaintiffs, but I'm asking you in your capacity as a fact witness

that has worked on the Camp Lejeune water modeling for, you know, more than a decade, who did work, is there any aspect of the criticism or the -- that the model received that you believe is valid?

MR. DEAN: Object to the form. You're asking him for his personal opinion. His work is not yet completed on this case nor has he issued a report and reserves the right -- or we reserve the right, and the witness does, to address any issue needed in the report.

MS. BAUGHMAN: It's also a compound question.

BY MR. ANWAR:

Q. You can answer the question.

A. Okay. NRC suggested using simpler modeling approaches. We actually accepted that and did that for Hadnot Point. On the other hand, they critiqued us for not using more complex biodegradation. You can't have it both ways, okay, so, again -- but we did with NRC recommendation that we try some simpler modeling approaches. We accepted that, okay, for Hadnot Point.

MR. ANWAR: I believe I have one minute left. I will -- I think that's -- that's all I have for today. As I understand that you -- you

will be testifying in this case, I'm sure we'll meet again, so nice to meet you and thank you for your time.

THE WITNESS: Thank you.

MR. DEAN: Okay. I need a little bit of a break to use the restroom, confer with my -- and then we've got a few questions.

THE VIDEOGRAPHER: Going off the record. The time is 5:49 p.m.

(A recess transpired.)

THE VIDEOGRAPHER: Going back on the record. The time is 5:59 p.m.

MR. DEAN: Okay. Giovanni, I don't need it right at the moment, but I sent you one exhibit. If you don't mind dropping it in the folder.

MR. ANTONUCCI: Oh, sure.

MR. DEAN: And if you want to -- what was the last exhibit number?

MS. BAUGHMAN: 22.

MR. DEAN: So you want to call it 23?

MR. ANWAR: However you want to --

MR. DEAN: Yeah, whatever is next. I'm fine just using consecutive numbers.

MR. ANWAR: Okay. Do we want to close

that?

MR. DEAN: Okay.

MR. ANWAR: You said you sent the exhibit?

MR. ANTONUCCI: I have it.

MR. DEAN: Yeah, I sent it to you.

EXAMINATION

BY MR. DEAN:

Q. So let's go, Mr. Maslia, to Exhibit No. 6. Let's see here. All right. Do you remember Exhibit No. 6?

A. Yes. Sorry I'm...

Q. That's okay. And it indicates that this is a printoff of a webpage created -- last updated, it says, September the 18th of 2024 --

A. Right.

Q. -- at 3:02 p.m. at the top. Do you see that?

A. Yes, I do.

Q. Were you working with the ATSDR in September of '24?

A. No, I was not.

Q. Did you have any involvement in creating the information that is on Exhibit 6?

A. None whatsoever.

Q. Did anybody call since your requirement in 2017 and ask you to assist or consult with them about what ATSDR puts on its website in 2024?

A. No.

Q. Now, on Exhibit 6 there's a statement in the second full paragraph where it begins "treatment water distribution plants." Do you see that?

A. Yes, I do.

Q. And you were asked this by counsel earlier. At the end of that paragraph it says, quote, other on-base treatment plants were not contaminated." Do you see that?

A. Yes.

Q. It is true that the work done by ATSD [sic] water modeling professionals including yourself were operating under contracts that were being funded by the Navy for the work to be done?

A. Yes.

Q. Is that correct?

A. That's correct.

Q. Did ATSDR, between 2003 and the time you left in 2017, ever receive any funding -- funding and conduct any activities to evaluate contamination at any water treatment plants other

than the three reported in all of the reports we have here today?

A. Not that I'm aware of.

Q. You yourself never personally evaluated whether or not any of the other treatment plants were not contaminated, correct?

A. That is correct.

Q. Now, you answered a question earlier on in the deposition. I just want to clarify something and if Mr. Anwar has any follow-up questions. He asked you whether or not you met with anyone yesterday or what you did to prepare for your deposition, something along those lines. Do you remember that?

A. Yes.

Q. At my request, did you fly in Tuesday night to work on a proposed expert report and we met in this office yesterday?

A. Yes, that is correct.

Q. From time to time, whether it be a break or at lunch or from time to time about your attire, did you and I have some informal discussion about the timing and participation in today's deposition?

A. Yes, we had a discussion about the

logistics of today's deposition.

Q. All right. Now, I want to show you Exhibit No. 7. This Exhibit 7 is Bates-stamped COJ, underscore, water modeling, underscore, 13764. Do you see that?

A. Yes, I do.

Q. And it has a CDC sticker at the bottom right-hand corner. Do you see that?

A. Yes, the banner at the bottom, yes, I do.

Q. And I believe you testified you've never seen this PowerPoint before, right?

A. That is correct.

Q. Do you know whether or not this PowerPoint was created by anybody at ATSDR?

A. It wasn't created by anybody from the technical water modeling staff. I can tell by the language used or the verbiage used in there, but I don't know who created it, whether it was ATSDR or CDC or...

Q. Okay. And that's because some of the information, which you went over with counsel, is inaccurate?

A. That is correct.

Q. Okay. So I'm going to show you Exhibit

No. 22.

MR. DEAN: And Giovanni, do you mind dropping that exhibit in the folder, please.

MR. ANWAR: So it's been dropped into the folder and it's labeled Plaintiff's Exhibit 1.

MR. DEAN: Oh, let's see if I can find it. And the other -- it's just a suggestion, it's up to you, you might want to delete the ones that were not marked as exhibits so the court reporter can pull them up. Now, is it the one that says EX to EX7 metadata file, or did you call it Plaintiff's Exhibit?

MR. ANTONUCCI: I introduced it as Plaintiff's Exhibit 001 documents.

MR. DEAN: Okay. I see it. Got it. Thank you.

(PLF. EXHIBIT 1, screenshot of PowerPoint slide entitled CDC 24/7 Camp Lejeune Summary 2014, was marked for identification.)

BY MR. DEAN:

Q. All right. I want to show you Plaintiff's Exhibit to your deposition, Number 1. Do you see the --

A. Yes.

Q. -- screenshot?

A. Yes, I do.
Q. I'll represent to you during the deposition I went and located the native version of this document that council showed you, which is Exhibit No. 7, and I have a screenshot on the screen of that exhibit. Do you see that?
A. Yes.
Q. Do you recognize that as the same Bates stamp and the same page that was on Exhibit 7?
A. Yes.
Q. Now if you look in the right-hand corner, do you see that the author of the document -- well, first of all, do you see it was created December the 9th of 2014?
A. Yes, I see that now.
Q. Do you see that the author of the document is a lady named Barbara Reynolds?
A. Yes.
Q. Do you see that she was working for a company, CDC? Do you see it? Beside "company" it says CDC.
A. I'm looking for "company", which I don't -- oh, company, CDC.
Q. Do you see that?
A. Yes, I do.

Q. Do you know who Mrs. Barbara Reynolds is?
A. No, I do not.
Q. Have you ever heard of her?
A. No.
Q. I'm not going to mark this as an exhibit unless you want me to.
MR. ANWAR: What is it?
MR. DEAN: Something we used to identify who Ms. Barbara Reynolds is.
MR. ANWAR: Okay.
MR. DEAN: I mean, I'll mark the page as a separate --
BY MR. DEAN:
Q. Are you aware that Barbara Reynolds, the lady that is listed in that document creating that PowerPoint December of 2014, formerly worked with the CDC and she was the senior communications and crisis advisor to the Center for Disease Control? Did you know that?
A. No, I do not.
Q. So the PowerPoint you were shown earlier and any questions that may or may not have suggested who -- the creator of that document, would you agree with me that document was not an

ATSDR-created document, it was created by the CDC and Ms. Reynolds, a media senior crisis advisor?

MR. ANWAR: Object to form.

THE WITNESS: Yes, it was not created by people that I knew -- well, during 2014 I was at ATSDR and that never came through for either review or occurrence or any comments.

MR. DEAN: All right. Mr. Maslia, thank you for your time today.

THE WITNESS: Thank you.

MR. ANWAR: Thank you for your time.

THE VIDEOGRAPHER: That ends this deposition. The time is 6:07 p.m.

(The witness, after having been advised of his right to read and sign this transcript, does not waive that right.)

CERTIFICATE OF REPORTER

I, Lauren A. Balogh, Registered Professional Reporter and Notary Public for the State of South Carolina at Large, do hereby certify that the foregoing transcript is a true, accurate, and complete record.

I further certify that I am neither related to nor counsel for any party to the cause pending or interested in the events thereof.

Witness my hand, I have hereunto affixed my official seal this 29th day of September, 2024 at Murrells Inlet, Horry County, South Carolina.

_____

Lauren A. Balogh

My Commission expires

March 19, 2030

I N D E X

E X H I B I T S

1	DFT. EXHIBIT 3, deposition of Morris Maslia dated June 30, 2010 Bates-stamped CLJA_HEALTHEFFECTS-0000049487 through 49712	18	6
6	DFT. EXHIBIT 4, resume for Morris L. Maslia Bates-stamped CLJA_ATSDR_BOVE_0000073110 and 73111	22	1
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	Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina Chapter A: Summary and Findings", Bates-stamped CLJA_HEALTHEFFECTS0000221326 through 221535		
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EXHIBIT 36

From: Maslia, Morris (ATSDR/DHAC/EISAB) [/O=HHS EES/OU=FIRST ADMINISTRATIVE GROUP/CN=RECIPIENTS/CN=MFM4]
Sent: 1/12/2007 10:10:00 AM
To: Sautner, Jason (ATSDR/DHAC/EISAB) [/O=HHS EES/OU=FIRST ADMINISTRATIVE GROUP/CN=RECIPIENTS/CN=ZLC9]; Suarez-Soto, Rene J. (ATSDR/DHAC/EISAB) [/O=HHS EES/OU=FIRST ADMINISTRATIVE GROUP/CN=RECIPIENTS/CN=ETA6]; Krueger, Amy K. (ATSDR/DHAC/EISAB) (CTR) [/O=HHS EES/OU=FIRST ADMINISTRATIVE GROUP/CN=RECIPIENTS/CN=FRF7]; refaye@alltel.net; mustafa.aral@ce.gatech.edu; gtg730t@mail.gatech.edu
CC: Moore, Susan (ATSDR/DHAC/EISAB) [/O=HHS EES/OU=FIRST ADMINISTRATIVE GROUP/CN=RECIPIENTS/CN=SYM8]; Bove, Frank J. (ATSDR/DHS/SRB) [/O=HHS EES/OU=FIRST ADMINISTRATIVE GROUP/CN=RECIPIENTS/CN=FJB0]; Ruckart, Perri (ATSDR/DHS/SRB) [/O=HHS EES/OU=FIRST ADMINISTRATIVE GROUP/CN=RECIPIENTS/CN=AFP4]
Subject: Finalizing Modeling Activities for Tarawa Terrace

Importance: High

An Open Email/Letter to those conducting Groundwater flow, fate, and transport modeling at Tarawa Terrace and Vicinity:

This email comes as a result of what I perceive is differing opinions (each valid, I am convinced, from perceived data limitations and modeling assumptions) as to what "calibrated" parameter values should be used, depending on the model being used and its level of sophistication. In this particular case, there is apparently a discrepancy on the value of the biodegradation rate for PCE (0.0006/day – 0.0004/day). There are two different levels of sophistication of models used (MT3DMS vs. TechFlowMP) and a LACK of DEFINITIVE DATA to compare modeling results against (Non detects ranging from 2 μg/L to 10 μg/L, in my opinion do NOT constitute a definitive standard by which to compare modeling results).

As the Agency is under tremendous pressure (if not outright criticism) to IMMEDIATELY provide a report on Tarawa Terrace, we no longer have the time to debate this matter any further (i.e., I am calling it a "tie" in the "battle of the models"). Therefore, as the project officer for this project, I have made the following decision and **I am requesting that everyone involved abide my decision**.

1. Fate and transport results provided using the MT3DMS model will use a biodegradation rate of **0.0005/day**

2. Early and Late arrival of PCE, derived using the GTMESL developed PSOpS approach and MODFLOW/MT3DMS will use a biodegradation rate of **0.0005/day**

3. **NO quantitative comparisons will be made using NON-DETECT (ND) samples**. As the detection limits for these samples range from 2 μg/L to 10 μg/L, using these values is a "double edge" sword that will come back to "attack" us, because those who review or modeling results will pick a ND value to "justify" their point of view and contradict our results.

4. If you wish to compare simulated results with measured samples (including ND), you can do so in a **TABLE with 4 columns** (Sample Location, Date, Measured Value, Simulated Value, Detection Limit). You are free to discuss in the TEXT any implications you see from the data, but NO OTHER quantitative analyses are to be made (I am abandoning the use of the Geometric Bias as I have concluded we just do not have the data to justify its use)

5. Each report/analysis will also provide a **"graphical" comparison**, such as the one I am attaching as an example (I am providing both TIFF and JPG file formats). In your respective graphs you can plot simulated PCE versus time for a specific condition (e.g., calibrated, early arrival, late arrival, etc.) and overlay that with the MEASURED data only.

6. In the graph I have attached you can see that in "early times", there is NO difference in the parameter value used, and in later times, data are so limited that certain data fit a specific parameter value, but there is NO CONCLUSIVE evidence that there is a "best" parameter value. Thus, as I stated above, all models will use a value of **0.0005/day**.

The bottom line, it is time to stop modeling and "fine tuning" models as we do not have the data to justify further modeling analyses. The Agency does not have the time to devote to additional modeling analyses. We have a CAP meeting scheduled in the beginning of March and I MUST have a completed draft report.

I am sure I can count on everyone to support me in my request.

Thank you

Morris

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Morris L. Maslia, P.E., D.WRE, DEE
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EXHIBIT 37

From: Robert E. Faye
To: Maslia, Morris (ATSDR/DHAC/EISAB)
Subject: MT3DMS results
Date: Saturday, January 13, 2007 5:14:51 PM

Hi Morris,

I have rerun the fate & transport model with a biodegradation rate of 0.0005 as you required.The results are only marginally acceptable and certainly do not represent our "best" calibration. Nevertheless I intend to finish the report with the current simulation results and explain them to the best of my ability. Because of the marginal results, several issues have come to mind that I need to share with you and which I hope to discuss with you in the future, I have listed these issues below.

1. I will find it very difficult to defend these results to my technical peers or in a court of law. Consequently, I would like to write a letter to the record to you and to ERG explaining what has happened, why the results are what they are, and addressing my concerns. I will send a draft of this letter to you first and ask for your comments.

2. I believe we have violated a fundamental rule of good modeling procedure. We let the "tail wag the dog" and assigned extraordinary credibility to simulated numbers rather than to well established concepts. When a choice must be made between accepting less than desirable model results or violating or compromising valid conceptual models, I believe we should accept the undesirable results and explain the limitations of the simulations in that context.

3. I would like to insert a statement in the fate & transport report that ATSDR required 100 percent agreement between the MT3DMS model and the GA Tech model regarding fate & transport parameters. As a result, the biodegradation rate assigned to both models was a compromise between the "best" rates determined by individual model calibration.

4. From a technical point of view, I believe most or all of this unfortunate "mess" has evolved from flawed concepts and applications on the part of GA Tech. Specifically, they applied the calibrated mass loading rate from the MT3DMS model to the unsaturated and saturated zones represented in their model. I assume, initially, they also applied the calibrated MT3DMS degradation rate to the unsaturated and saturated zones. Degradation in the saturated zone is aerobically driven and occurs at rates that are possibly several orders of magnitude greater than anaerobic degradation. The degradation rate that I computed at well TT-26 was reasonably an anaerobic rate. Also, applying the calibrated mass loading rate from the MT3DMS model to the unsaturated zone directly equates the actual ("real world") PCE loss rate at ABC One-Hour Cleaners to the MT3DMS mass loading rate. Such an equation is absurd as it does not account for retention and degradation within the unsaturated zone. The MT3DMS code requires that mass loading be applied directly to the water table and thus can represent, at best, only the minimum loss rate at ABC One-hour Cleaners. I believe if GA Tech had calibrated, instead, to simulated PCE concentrations at the water table at the loading elements and had applied a reasonable aerobic degradation rate to their unsaturated zone, then a mass loading rate significantly greater than the calibrated MT3DMS rate would result for the GA Tech model. This rate would more directly equate to the actual PCE loss due to operations at ABC One-Hour Cleaners. In addition, these approaches would result in a correspondingly greater PCE mass in the saturated zone and quite possibly the calibrated biodegradation rates assigned to the MT3DMS and GA Tech model would be highly similar.

The application of an anaerobic degradation rate to the unsaturated zone and the direct equation of the actual PCE loss due to operations at ABC One-Hour Cleaners to the mass loading rate calibrated for the MT3DMS model violate sound reasoning and hydrologic principles. I am not at all surprised that GA Tech found less PCE mass than required for a reasonable simulation. The fault, however, was not in the assigned degradation rate but rather in their flawed concepts and reasoning. I suspect a thorough technical review by competent peers will point out these issues.

Let me emphasize, I do not intend to change the current model results and I am not asking for any dispensation to do so. However, I would like to follow through on my letter to the record and my other requests as soon as possible. Please let me know your thoughts at your earliest convenience.

Bob

EXHIBIT 38

To: Anderson, Barbara A. (ATSDR/DHAC/EISAB)[bha6@cdc.gov]; 'mustafa.aral@ce.gatech.edu'[mustafa.aral@ce.gatech.edu]; Maslia, Morris (ATSDR/DHAC/EISAB)[mfm4@cdc.gov]
Cc: Suarez-Soto, Rene J. (ATSDR/DHAC/EISAB)[eta6@cdc.gov]
From: Anderson, Barbara A. (ATSDR/DHAC/EISAB)[/O=CDC/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=BHA6]
Sent: Mon 9/26/2011 3:13:41 PM (UTC)
Subject: RE: Start date and LNAPL source functions for the HPFF/Bldg 1115 area - correction
SourceScenarios.docx

Rene noticed a mistake that I wanted to correct: for scenario 2, the source starts at 0% rather than 100%.

Scenario 2, ramp function

- **1951**: LNAPL source starts at 0% initial strength

Barbara Anderson, PE, MSEnvE
Environmental Health Scientist | phone: 770.488.0710
Agency for Toxic Substances and Disease Registry | Atlanta | Georgia

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From: Anderson, Barbara A. (ATSDR/DHAC/EISAB)
Sent: Monday, September 26, 2011 9:38 AM
To: 'mustafa.aral@ce.gatech.edu'; Maslia, Morris (ATSDR/DHAC/EISAB)
Cc: Suarez-Soto, Rene J. (ATSDR/DHAC/EISAB)
Subject: Start date and LNAPL source functions for the HPFF/Bldg 1115 area

All,
In last week's meeting we agreed to standardize the process used to determine the start date(s) for the sources we are using in our models. Rene and I worked together to review some references about leaking UST systems and how we could apply that info to the modeling effort. The results for the HPFF area are summarized below. The same method is being applied to determine start dates for the UST-related TCE sources in Rene's model.

We are also offering two scenarios for the source function conceptualization (see info below and details in the attached). It seems wise to run a couple of different source scenarios to see the overall effects of varying source characterization. Not sure how many scenarios we should ultimately run, but we selected two for consideration.

The first scenario is a simple step function. The second scenario incorporates some information we have about the HPFF area and conceptualizes the source strength/LNAPL area as increasing over time. In reality, the LNAPL footprint grew and spread as the UST system leaks and releases progressed. At some point in time, the LNAPL footprint grew to be the size that GT calculated from the free product data (1988-1998). But it was not that size from the beginning/start date; this is shown in scenario 2.

Please review the info below and the assumptions/details provided in the attached document and let us know if you have any questions.
We would be happy to come to your offices to discuss this further. I'm not sure how the source is currently built into your model -? It may help to discuss your conceptualizations alongside the ones presented here. Hopefully they are not too far apart ;)
Thanks,
Barb

START DATE will be January 1951

Start Date = Date of tank installation (or best approximation, usually rounding up to January of the next year if only year is provided) + 9 years (median leak time for UST system piping*)

Background information
1941: HPFF USTs were installed [UST #669 and #670]
1942: Earliest date for UST install at Bldg 1115 [UST #408, UST #504 and #507, UST #670]

Start date calculated as = Jan 1942 + 9 years = January 1951

The rationale for adding the 9 years to the tank install date is based primarily on an EPA study that evaluated 1,244 leak incident reports within the United States (EPA 1986 report findings, as discussed in Gangadharan et al 1988, p4, p10-13*). They found the mean and median age for piping leaks is 11 and 9 years, respectively. We decided the median is the best estimator for our purposes.

For more info on the leaking UST system references, see the attached email that I sent to GT some months ago. It contains relevant report excerpts. I believe I provided this info on CD as well -?

** Gangadharan et al. 1988. Leak Prevention and Corrective Action Technology for Underground Storage Tanks. Park Ridge, NJ, Noyes Data Corporation.*

SOURCE FUNCTION SCENARIOS

Background information

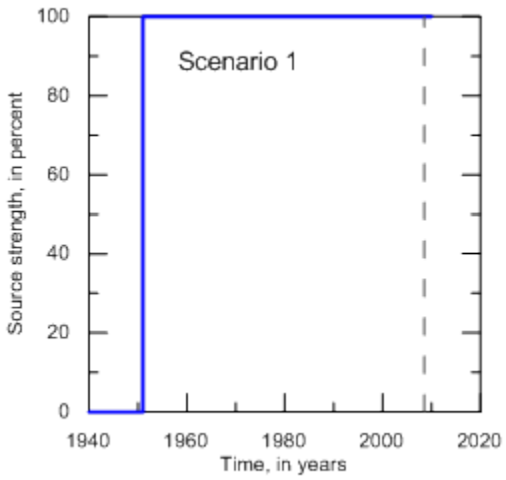
Jan 1993: USTs in the HPFF and Bldg 1115 area were removed [UST #1186 and #670]

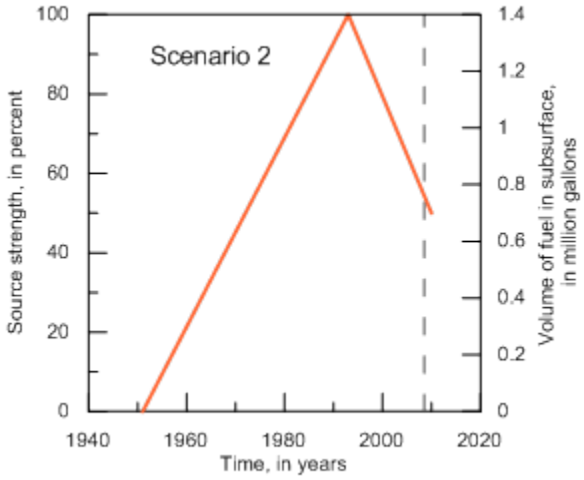
Dec 2000: Piping removal at HPFF/Bldg 1115 [UST #417] - see attached ATSDR figure for piping locations

Calculated fuel in subsurface: 1,400,000 gal [GT MESL 2011]

Potential source scenarios for consideration

[Note: Source strength could be programmed as LNAPL area/volume in the model -? This would be more consistent with how the LNAPL footprint probably developed and spread as the fuel leaks and releases progressed over time.]





Scenario 1, simple step function

- 1951: LNAPL source applied at 100% strength
- Constant source throughout simulation period
- LNAPL source persists even after HPFF/Bldg 1115 USTs removed in 1993

Scenario 2, ramp function

- **1951**: LNAPL source applied at 100% strength
- 1991: Remediation initiated at HPFF (4 recovery wells)
- **1993**: Max source strength/LNAPL volume of 1.4 million gal [GT MESL 2011]
  - 1.4 million gal/42 yrs = "leak rate" of 2,778 gal/mo
  - HPFF and Bldg 1115 USTs removed in 1993
- 1993–2000, 2005: Remediation steadily efforts increased at HPFF/Bldg 1115
- **2010**: Source strength approximately 70% of maximum
  - USMC reported 414,118 gal of fuel recovered as of July 2010, which equates to 30% of the 1.4 million gal total volume; 70% remaining in subsurface

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