Exhibit 43

Expert Report of

Morris L. Maslia, P.E., D.WRE, DEE, Fellow EWRI

Prepared by:

Morris L. Maslia



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M. L. Maslia Consulting Engineer
Registered Professional Engineer, GA #PE012689

3360 Norfolk Chase Drive, Peachtree Corners, GA 30092
Mobile: +1 (404) 431-0035 — Email: H2OBoy54@gmail.com
https://www.linkedin.com/in/mlmaslia/

Table of Contents

Table of Contents **2**

List of Figures **5**

List of Tables **7**

1.0 Introduction **9**

2.0 Details of Experience **9**

2.1 U.S. Geological Survey (USGS), 1980–1989 10

2.2 Geosyntec Consultants, 1990–1992 12

2.3 Agency for Toxic Substances and Disease Registry (ATSDR),1992–2017 12

3.0 Awards **16**

4.0 Professional Registration and Certifications **17**

5.0 Scope of Work **17**

6.0 Summary of Opinions **17**

7.0 U.S. Marine Corps Base Camp Lejeune, North Carolina: Reconstructing Volatile Organic Compound Contamination of Drinking-Water Supplies **19**

7.1 Introduction 20

7.2 Water Supply and Contamination at Camp Lejeune 22

7.3 Water-Modeling and Study Objectives 26

7.4 Historical Reconstruction Methods 27

7.4.1 Overview 27

7.4.2 Information and Data Discovery 29

7.4.3 Water-Modeling Approach and Simulation Tools 31

7.4.4 Model Calibration, Sensitivity, and Uncertainty 44

7.5 Historical Reconstruction Analyses and Results 45

7.5.1 Tarawa Terrace (TT) 47

Level 1 Calibration (Predevelopment Conditions) 48

Level 2 Calibration (Transient Conditions) 49

Level 3 Calibration (Contaminant Fate and Transport) 51

Selected Simulation Results: Tarawa Terrace 53

January 1958 54

January 1968 54

December 1984 54

December 1994 54
Well TT-26 57
Level 4 Calibration (Mixing Model) 58
Post-Audit of the Tarawa Terrace Models 61
Uncertainty 61
Water-Supply Well Scheduling Analysis 62
Sensitivity Analysis 62
Probabilistic Analysis 62
Conclusions Regarding Tarawa Terrace 68
7.5.2 Hadnot Point (HP) 69
Level 1 Calibration (Predevelopment Conditions) 72
Level 2 Calibration (Transient Conditions) 72
Level 3 Calibration (Contaminant Fate and Transport) 74
PCE and TCE 74
Benzene 80
Liner Control Model (LCM) Methodology 82
Level 4 Calibration (Mixing Model) 84
Uncertainty 87
Sensitivity Analysis 87
Uncertainty 88
Sensitivity Analysis 88
Probabilistic Analysis 90
Conclusions Regarding Hadnot Point 91
7.5.3 Holcomb Boulevard (HB) 93
Conclusions Regarding Holcomb Boulevard 94
7.5.4 Discussion and Conclusions 97
7.6 Peer Review of ATSDR Analyses, Results, and Reports 99
7.7 Scientific Discourse 99
7.7.1 Department of the Navy (DON) Comments on the Tarawa Terrace Models and ATSDR Response 100
7.7.2 National Research Council Report on Camp Lejeune and ATSDR Response 101
7.7.3 ATSDR Response to Ground Water Journal Article on Camp Lejeune 102
8.0 References 104

9.0 Glossary and Abbreviations 115

Appendix A — Curriculum Vitae for Morris L. Maslia, P.E. 120

Appendix B — The ATSDR Water Modeling Team for Historical Reconstruction at U.S. Marine Corps Base Camp Lejeune, North Carolina 144

Appendix C — Exposure-Dose Reconstruction Program: Overview of Strategy, Agency for Toxic Substances and Disease Registry, March 1993 146

Appendix D — Dover Township, Toms River, New Jersey Childhood Cancer Cluster Investigation 159

Appendix E — Information Sources Used to Extract Model-Related Data for Historical Reconstruction 165

Appendix F — Summaries of ATSDR's Tarawa Terrace Chapter Reports 174

Appendix G — Summaries of ATSDR's Hadnot Point–Holcomb Boulevard Chapter Reports and Supplemental Information 179

Appendix H1 — Tarawa Terrace Water Treatment Plant Reconstructed (Simulated) Mean Monthly Finished Water Concentrations for Single-Specie Tetrachloroethylene (PCE) Using MT3DMS Model and for Multispecies, Multiphase PCE (Trichloroethylene [TCE], *trans*-1,2-Dichlorothylene [1,2-*t*DCE], and Vinyl Chloride [VC]) Using TechFlowMP Model 185

Appendix H2 — Tarawa Terrace Water Treatment Plant Reconstructed (Simulated) Mean Monthly Finished Water Concentration of Single-Specie Tetrachloroethylene (PCE) and Range of Concentrations Derived from Monte Carlo Simulation 198

Appendix I —Reconstructed (Simulated) Mean Monthly Concentrations of Selected Water-Supply Wells, for Tetrachloroethylene (PCE), Trichloroethylene (TCE), *trans*-1,2-Dichloroethylene (1,2-tDCE), Vinyl Chloride (VC), and Benzene, Hadnot Point-Holcomb Boulevard Study Area 208

Appendix J — Hadnot Point Water Treatment Plant Reconstructed (Simulated) Mean Monthly Finished Water Concentrations 224

Appendix K — Holcomb Boulevard Water-Distribution System Reconstructed (Simulated) Mean Monthly Finished Water Concentrations 240

Appendix L — ATSDR Response to Department of the Navy's Letter on: Assessment of ATSDTR Water Modeling for Tarawa Terrace (ATSDR 2009) 246

Appendix M — ATSDR Response to National Research Council Report on Contaminated Water-Supplies at Camp Lejeune: Assessing Potential Health Effects (NRC 2009) 273

Appendix N — ATSDR Editorial Response in Ground Water Journal (Maslia et al. 2012) to the Article, "*Complexities in Hindcasting Models—When Should We Say Enough Is Enough*?" by T. P. Clement (2010) 310

Appendix O — Post-Audit of the Tarawa Terrace Flow and Transport Model, N. L. Jones and R. Jeffrey Davis, Integral Consulting, Inc., October 25, 2024 319

Appendix P — Reliance Materials 393

List of Figures[1]

Figure 7.1. Water-supply areas with focus on housing areas, barracks, and workplaces included in the Agency for Toxic Substances and Disease Registry (ATSDR) drinking-water exposure and health studies, U.S. Marine Corps Base Camp Lejeune, North Carolina (Maslia et al. 2013, 2016).

Figure 7.2. Operational chronologies of Tarawa Terrace water-supply wells, Tarawa Terrace study area, 1952–1987 (Maslia et al. 2007).

Figure 7.3. Operational chronology of Hadnot Point and Holcomb Boulevard water-supply wells, Hadnot Point-Holcomb Boulevard study area (Maslia et al. 2013).

Figure 7.4. A generalized process of identifying information, extracting usable model-specific data, and applying models to reconstruct historical drinking-water contaminant-specific concentrations (Maslia et al. 2013, 2016).

Figure 7.5. Three-stage process used for identifying relevant information and extracting data for databases and model development, Tarawa Terrace, Hadnot Point, and Holcomb Boulevard study areas, U.S. Marine Corps Base Camp Lejeune, North Carolina (Maslia et al. 2013).

Figure 7.6. Water-modeling approach used for reconstructing historical drinking-water contaminant concentrations at Tarawa Terrace (TT), Hadnot Point (HP), and Holcomb Boulevard (HB). (Details of the groundwater-flow and contaminant fate and transport models are provided in Maslia et al. [2007, 2009a, 2013, 2016] and associated reports.)

Figure 7.7. Groundwater-flow model domain and contaminate fate and transport model subdomains for the Hadnot Point Industrial Area (HPIA) and Hadnot Point landfill (HPLF). (Maslia et al. 2013).

Figure 7.8. Schematic node-link representations for water-distribution systems: *(A)* mixing-model approach used for the Tarawa Terrace and Hadnot Point water treatment plant analyses and *(B)* network-model approach used for the Hadnot Point and Holcomb Boulevard interconnection analyses (Maslia et al. 2013).

Figure 7.9. Simulated and observed predevelopment water levels, Tarawa Terrace and vicinity (Faye and Valenzuela 2007).

Figure 7.10. Simulated and observed transient water levels, Tarawa Terrace and vicinity (Faye and Valenzuela 2007).

Figure 7.11. Simulated and observed tetrachloroethylene (PCE) concentrations at selected water-supply wells. Tarwa Terrace and vicinity (Faye 2008).

Figure 7.12. Reconstructed (simulated) distribution of tetrachloroethylene (PCE), model layer 1: (A) January 1958, (B) January 1968, (C) December 1984, and (D) December 1994 (Faye 2008).

Figure 7.13. Concentration of tetrachloroethylene (PCE): (1) simulated at selected water-supply wells and in finished water at the water treatment plant and (2) measured in finished water at the water treatment plant, Tarawa Terrace (Maslia et al. 2007).

[1] In this Expert Report and in all published ATSDR reports and journal articles on Camp Lejeune, chemical names are referred to by their Common Name (e.g., tetrachloroethylene for PCE). Tables listing complete names for volatile organic compounds in groundwater are provided in Lawrence (2007).

Figure 7.14. Reconstructed (simulated) and observed tetrachloroethylene (PCE) concentrations at water-supply well TT-26, Tarawa Terrace (Faye 2008).

Figure 7.15. Conceptual framework for (a) a deterministic analysis and (b) a probabilistic analysis (Maslia and Aral 2004).

Figure 7.16a. Ratio of pumping rate to pumping capacity (Q_{TT-26} / QC_{TT-26}) for water-supply well TT-26 for calibrated model and Monte Carlo simulation, Tarawa Terrace (Maslia et al. 2009b).

Figure 7.16b. Concentrations of tetrachloroethylene (PCE) in finished water at the water treatment plant derived from the calibrated MT3DMS model, probabilistic analysis using Monte Carlo simulation for scenario 1 (pumping uncertainty excluded) and scenario 2 (pumping uncertainty included), Tarwa Terrace study area (Maslia et al. 2009b).

Figure 7.17. Locations of historically contaminated water-supply wells, Installation Restoration Program (IRP) sites, and above-ground and underground storage tank (AST/UST) sites, Hadnot Point–Holcomb Boulevard study areas (map area figures refer to the Chapter A report [Maslia et al. 2013]).

Figure 7.18. Steady-state groundwater-flow model results shown as observed and simulated potentiometric levels, and observed potentiometric levels and corresponding residuals, steady-state groundwater-flow model calibration, Hadnot Point–Holcomb Boulevard study area (Suárez-Soto et al. 2013).

Figure 7.19. Comparison of observed water-level altitude and simulated water-level altitude for well X24S6 for two cases of the transient groundwater-flow model: *case a* with temporal variability of recharge, and *case b* without temporal variability of recharge, Hadnot Point–Holcomb Boulevard study area (Suárez-Soto et al. 2013). [Note: Date range for measured and simulated water-level altitude for *cases a* and *b* is March 1988 to June 2008].

Figure 7.20. Reconstructed (simulated) and measured concentrations of trichloroethylene (TCE) at selected water-supply wells within the Hadnot Point Industrial Area, Handot Point-Holcomb Boulevard study area. Groundwater-flow simulation using MODFLOW (Harbaugh 2005) and contaminant fate and transport simulation using MT3DMS (Zheng and Wang 1999), see Figure 7.17 for well location(from Jones et al. 2013).

Figure 7.21. Reconstructed (simulated) and measured observed 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 (Jones et al. 2013).

Figure 7.22. *(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 (Jones et al. 2013).

Figure 7.23. Reconstructed (simulated) and measured concentrations of benzene at selected water-supply wells within the Hadnot Point Industrial Area, Hadnot Point study area, U.S. Marine Corps Base Camp Lejeune, North Carolina (Maslia et al. 2013).

Figure 7.24. Reconstructed (simulated) and measured concentrations of tetrachloroethylene (PCE) and trichloroethylene (TCE), trans-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at water-supply well HP-651 using numerical (MT3DMS) and linear control methodology (LCM; TechControl) models, Hadnot Point study area (Guan and Aral 2013, Maslia et al. 2013).

Figure 7.25. Reconstructed (simulated) finished-water concentrations of tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, and measured concentrations (Faye et al. 2010), Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study

area. (Note: See Appendix I for monthly mean finished-water concentration). (Maslia et al. 2013) [J, estimated; LCM, linear control model; LNAPL, light nonaqueous phase liquid].

Figure 7.26. Concentrations of tetrachloroethylene (PCE) and trichloroethylene (TCE) in finished water at the Hadnot Point water treatment plant derived from model calibration and hydraulic, fate, and transport model parameter sensitivity analysis, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. [*Kxx* , horizontal hydraulic conductivity; *I*, infiltration; *C*, source concentration; *nE*, porosity; α*L*, longitudinal dispersivity; *KD* , distribution coefficient; λ, biodegradation rate; J, estimated].

Figure 7.27. 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 (Maslia et al. 2013). [J, estimated].

Figure 7.28. Reconstructed (simulated) distribution of trichloroethylene (TCE) contamination within the Holcomb Boulevard water treatment plant service area resulting from supply of contaminated Hadnot Point finished water, June 1978, May 1982, and February 1985 (see Maslia et al. 2013, Figure A1 for location map of Holcomb Boulevard water-distribution system).

Figure 7.29. Reconstructed (simulated) and measured finished-water concentrations of tetrachloroethylene (PCE) and trichloroethylene (TCE) at the Tarawa Terrace and Hadnot Point water treatment plants (Maslia et al. 2016).

List of Tables

Table 2.1. Partners and team members supporting the Agency for Toxic Substances and Disease Registry's (ATSDR's) water-modeling activities for the Camp Lejeune drinking-water health studies

Table 7.1. Chronology of selected evens related to water supply and environmental contamination at U.S. Marine Corps Base Camp Lejeune, North Carolina, and vicinity.

Table 7.2. Analyses and simulation tools (models) used to reconstruct historical contamination events at Tarawa Terrace and vicinity (Maslia et al. 2007).

Table 7.3. Analyses and simulation tools (models) used to reconstruct historical contamination events at Handot Point-Holcomb Boulevard and vicinity (Maslia et al. 2013).

Table 7.4. Description and characteristics of model properties used to simulate three-dimensional groundwater flow and contaminant fate and transport, Hadnot Point- Holcomb Boulevard and Tarawa Terrace study areas (Maslia et al. 2013).

Table 7.5. Reports describing geohydrologic data, hydrogeologic data, water-supply data, analyses and results for the Tarawa Terrace study area.

Table 7.6. Reports describing geohydrologic data, hydrogeologic data, water-supply data, analyses and results for the Hadnot Point-Holcomb Boulevard study area.

Table 7.7. Summary of calibration targets and resulting calibration statistics for models used to reconstruct historical contamination events at Tarawa Terrace and vicinity.

Table 7.8. Calibrated model parameter values used for simulating groundwater flow and contaminant fate and transport, Tarawa Terrace and vicinity (Faye 2008).

Table 7.9. Summary of reconstructed (simulated) values and observed data of tetrachloroethylene (PCE) at water-supply wells, Tarawa Terrace (Maslia et al. 2007).

Table 7.10. Summary of reconstructed (simulated) values and observed data of tetrachloroethylene (PCE) at the water treatment plant, Tarawa Terrace (Maslia et al. 2007).

Table 7.11. Summary statistics for reconstructed (simulated) tetrachloroethylene (PCE) contamination of selected water-supply wells and the water treatment plant based on calibrated model simulations, Tarawa Terrace (Maslia et al. 2007).

Table 7.12. Computed and observed tetrachloroethylene (PCE) concentrations in water samples collected at the Tarawa Terrace water treatment plant and calibration target range, Tarawa Terrace (Fay 2008).

Table 7.13. Identification of documented source areas, primary contaminants, and location of major dissolved-phase sources, Hadnot Point area, U.S. Marine Corps Base Camp Lejeune, North Carolina (Figure references are to the Chapter A report [Maslia et al. 2013]).

Table 7.14. Calibrated model parameter values used to simulate groundwater flow and contaminant fate and transport, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Table 7.15. Selected measured and reconstructed (simulated) concentrations of tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene at the Hadnot Point water treatment plant, Hadnot Point study area (Maslia et al. 2013).

Table 7.16. Summary statistics for reconstructed contaminant concentrations at selected water-supply wells and the Hadnot Point water treatment plant, Hadnot Point study area (Maslia et al. 2013).

Table 7.17. Reconstructed (simulated) mean concentrations of tetrachloroethylene, trichloroethylene, *trans*-1,2-dichloroethylene, vinyl chloride, and benzene in finished water distributed to Holcomb Boulevard family housing areas for selected months, Hadnot Point– Holcomb Boulevard study area (Maslia et al. 2013, Sautner et al. 2013b).

1.0 Introduction

I am Morris L. Maslia, P.E. (a licensed professional engineer in the State of Georgia), and I have conducted consulting engineering, research, and scientific studies in the areas of environmental fate and transport, water resources (including water-distribution systems), hazardous waste remediation, environmental health, exposure assessment, and public health. I have worked with international organizations, non-profit organizations, U.S. federal agencies, state government agencies, engineering consulting firms, and private industry. I have developed and presented workshops, lectures, and training courses for international, government, and academic institutions (*e.g.*, University of San Luis Potosi, Mexico, Emory University, and Georgia Tech, Atlanta, Georgia). My areas of experience, expertise, and continued interests include public health, water resources and sanitation, global impacts of contamination of water resources, environmental analyses, epidemiological studies, exposure assessment, water-distribution system analysis, engineering and research report review, and volunteering and working with non-profit organizations.

2.0 Details of Experience

A summary and overview of my professional experiences and professional registrations are listed below. Specific details of my professional experiences are provided in my current curriculum vitae (CV), that is in **Appendix A** of this report.

My professional work experience and history are listed below in chronological order, beginning with the most recent professional experiences.

- **M. L. Maslia Consulting Engineer, Peachtree Corners, Georgia**
  Owner, 2018–Present
- **Agency for Toxic Substances and Disease Registry, Atlanta, Georgia**
  Research Environmental Engineer and Project Officer, 1992–2017 (December 31)
- **Rollins School of Public Health, Emory University, Atlanta, Georgia**
  Adjunct Faculty, Department of Environmental Health, 2000–2015
- **Geosyntec Consulting Engineers, Norcross, Georgia**
  Water Resources Group Manager and Hydrologist, 1989–1992
- **U.S. Geological Survey, Water Resources Division, Doraville, Georgia**
  Research Hydrologist, 1980–1989
- **Federal Energy Regulatory Commission, Washington, DC/Atlanta, Georgia (f/k/a, Federal Power Commission)**
  Civil / Hydraulic Engineer, 1976–1980

Throughout my professional career, I have participated in, contributed to, and directed several high-profile, public water resources, environmental and public health projects. A complete list is found in my CV (**Appendix A**). Below are summaries of sentinel projects and experiences.

One of the high-profile, public sites that I was the Technical/Scientific Project Officer for was the project for water-modeling of volatile organic compound (VOC) contamination of drinking water supplies at U.S. Marine Corps Base Camp (USMCB) Camp Lejeune, Noth Carolina. In terms of overseeing and managing this project, I was responsible for putting together a multidisciplinary team of scientists, engineers, and data analysts consisting of available staff from the Agency for Toxic Substances and Disease Registry (ATSDR); coordinating with a cooperative agreement University Partner (the Multimedia Environmental Simulations Laboratory in the School of Civil and Environmental Engineering at the Georgia Institute of Technology); hiring outside consulting experts for task-specific assignments; coordinating with an ATSDR contractor (Eastern Research Group) to provide engineering and hydrologic science sub-contractor support and project logistical and administrative support; and requesting and executing cooperative agreements with other federal agencies (U.S. Geological Survey [USGS]) to provide modeling and cartographic support personnel. In total, there were 21 people that I supervised and 3 outside organizations that I coordinated with (Eastern Research Group, a university partner, and the USGS) from 2003–2013 for this project. Table 2.1 lists the partners and team members by organization. **Appendix B** lists team members, their occupation, organization, and their respective technical and scientific expertise provided to the project.

Table 2.1. Partners and Team Members Supporting the Agency for Toxic Substances and Disease Registry's (ATSDR's) Water-Modeling Activities for the Camp Lejeune Drinking-Water Health Studies.

ATSDR	Consultants	University Partner[1]	Other Federal Agency
B.A. Anderson	Eastern Research Group[2]	M.M. Aral	U. S. Geological Survey (USGS)
F.J. Bove	J. Doherty[3]	B. Chang	L.E. Jones[7]
M.L. Maslia	R.E. Faye[4]	J. Guan	S. J. Lawrence[7]
S.M. Moore	W.M. Grayman[5]	W. Jang	K.A. Waltenbaugh[8]
P.Z. Ruckart	I.T. Telci[6]	I,T. Telci	C.J. Wipperfurth[8]
J.B. Sautner	J.W. Green, Jr.		
R.J. Suárez-Soto	C. Valenzuela		

[1]Multimedia Environmental Simulations Laboratory, School of Civil and Environmental Engineering, Georgia Institute of Technology
[2]Under contract to ATSDR for multi-site assistance and logistic support
[3]Watermark Numerical Computing
[4]R.E. Faye and Associates, sub-contractor to Eastern Research Group
[5]W.M. Grayman Consulting Engineer
[6]Sub-contractor to Oak Ridge Institute for Science and Education (ORISE)
[7]Georgia Water Science Center, USGS
[8]Science Publishing Network, USGS

2.1 U.S. Geological Survey (USGS), 1980–1989

Regional Aquifer Systems Analysis (RASA)
The major groundwater systems of the United States were investigated by the U.S. Geological Survey (USGS) through its Regional Aquifer-System Analysis (RASA) Program. During the first 15 years of the program (1978-92), 25 regional aquifer systems, including the most heavily pumped aquifers in the Nation, were intensively studied. One of the aquifer systems, the Floridan Aquifer

System, is located in southwest Georgia, southernmost Alabama, and all of Florida. I had the opportunity to develop and calibrate two-dimensional groundwater-flow models for southwest Georgia (an area of extensive agricultural pumpage) and northwest Florida (an area of extensive agricultural and water-supply pumpage). The results of the RASA studies are detailed in the series of USGS Professional Papers publications (1403 series for the Floridan Aquifer System). Two sentinel publications that I co-authored are Hayes et al. (1983) and Maslia and Hayes (1988). A peer-reviewed journal article that I co-authored was published in the journal *Ground Water* and was a result of research efforts conducted on the Floridan RASA program (Randolph et al. 1985).

Investigation of Groundwater Flow, Hyde Park Landfill, New York

Early in my tenure with the USGS Water Resources Division, I and a colleague were asked by the U.S. Environmental Protection Agency (USEPA) to assist them with evaluating and understanding the hydrogeologic controls on groundwater flow in a fractured rock aquifer at Niagara Falls, New York. The Hyde Park landfill, owned and operated by Hooker Chemical Company and located in the vicinity of Love Canal and the S-Area, had buried, toxic wastes underlain by a fractured rock aquifer. We applied a saturated-unsaturated finite element groundwater-flow model that I had developed as part of my Master's Degree dissertation (Maslia 1980) to conduct the analysis. The results of the analyses were used by the USEPA to determine the direction and travel time for groundwater (and hence groundwater contaminated with chemicals) from the Hyde Park landfill to the Niagara River Gorge. This research effort resulted in two publications (a USGS Open-File Report and a peer-reviewed journal article) that are described in Maslia and Johnston (1982, 1984). The resulting calibrated hydrogeologic and aquifer parameter values have stood the test of time and have been used by other researchers conducting groundwater-flow modeling in this area over the years. *Noteworthy of this research is that the results were used by the USEPA to support its first legal proceedings under the newly enacted CERCLA (Superfund) legislation*.

Determining Anisotropic Transmissivity Tensor Components of Two-Dimensional Groundwater Flow

The equations that represent the movement of water in an aquifer when water is being withdrawn from a well form the basis of methods used to analyze aquifer-test data. These equations were derived under the assumption of aquifer isotropy and are not valid for analysis of anisotropic aquifers that include, for example, flow in some secondary permeability terrains and fractured rocks. Thus, in conjunction with aquifer-test data, the anisotropic equations can be used to determine aquifer anisotropy and the components of the anisotropic transmissivity tensor. In this research, the method originally described by Papadopulos (1965) was applied to aquifer hydraulic data to determine the components of the anisotropic transmissivity tensor. In addition, this research described the development, codification, and use of the computer program TENSOR2D, which automates the solution of hydraulic parameters and tensor components of the anisotropic transmissivity tensor. This research resulted in two USGS publications (Maslia and Randolph, 1986, 1987) and has been incorporated into several public and proprietary desktop aquifer analysis programs used today by consulting engineers. An updated version of the TENSOR2D program was described in a note to the journal *Ground Water* (Maslia 1994).

Effects of Faults on Groundwater Flow and Chloride Contamination in the Upper Floridan Aquifer, Brunswick, Glynn County, Georgia

This research focused on the effects of inferred faults based on geophysical, hydrogeologic, and water-quality data within the Upper Floridan aquifer underlying Brunswick, Glynn County, Georgia.

This area has historically withdrawn large quantities of groundwater to support the chemical and pulp industries in Georgia, and in addition, provide drinking water to local municipalities. The research developed a unified, multidiscipline hypothesis to explain the anomalous pattern by which chloride has been found in water of the Upper Floridan aquifer. Analysis of geophysical, hydraulic, water chemistry, and aquifer-test data using the equivalent porous medium (EPM) approach were used to support the hypothesis and to improve further understanding of the fracture-flow system in this area. Results are described in a peer-reviewed journal article (Maslia and Prowell 1990) and two USGS publications (Jones and Maslia 1994; Jones et al. 2002).

2.2 Geosyntec Consultants, 1990–1992

Evaluation of Groundwater Flow Regime at a Landfill in New York
The High Acres Landfill is located southeast of Rochester, New York, in Monroe County, on the eastern border of the town of Perinton. The design, construction, and operation of a waste disposal facility requires owners and operators to comply with applicable state and federal regulations. These regulations require the owner/operator to demonstrate that a minimum distance can be maintained between waste and groundwater to assure that the waste is not placed in the saturated zone (zone at and below the water table). For this site, the owner/operator had to demonstrate that the seasonal-high water table could be maintained 5 feet below the liner system. A multilayer finite-element aquifer model was applied to the site to (1) simulate the mechanism by which groundwater moves through the landfill at the site, and (2) evaluate the average and seasonal high water-table conditions at the site with and without the liner system. Based on the simulations, critical design aspects of the landfill liner system and its effect on local groundwater flow regime were evaluated throughout the entire site. Details of the analyses are provided in a peer-reviewed journal article (Maslia et al.1992).

2.3 Agency for Toxic Substances and Disease Registry (ATSDR),1992–2017

Exposure-Dose Reconstruction Program
In 1980, Congress created the Agency for Toxic Substances and Disease Registry (ATSDR) to implement the health-related sections of laws that protect the public from hazardous wastes and environmental spills of hazardous substances. ATSDR was created under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)—also known as Superfund. A critical activity in achieving ATSDR's mission is characterizing past and current human exposures to, and doses received from, hazardous substances. Because direct measures of exposure and dose are often unavailable to agency health assessors and health scientists, sensitive, integrated, science-based methods for exposure-dose characterization needed to be developed. On December 23, 1992, Dr. Barry L. Johnson, Assistant Administrator, ATSDR, requested that a coordinated, comprehensive plan be developed that would serve as the agency's strategy for exposure-dose reconstruction activities. That plan, which I co-authored for ATSDR, is presented in **Appendix C**.

The overall goal of the Exposure-Dose Reconstruction Program (EDRP) was to enhance the agency's capacity to characterize exposure and dose to better support health assessments and consultations, health studies, and exposure registries. As agency and division needs and requirements were identified, specific projects under the auspices of the EDRP were proposed and developed. The EDRP workplan (**Appendix C**), therefore, sets forth ATSDR's program objectives and priorities for conducting exposure-dose reconstruction activities. Listed below are

examples of projects, analyses and methods development conducted under the auspices and funding of the EDRP (1993–2013) that are described in agency reports and peer-reviewed literature.

Two very high-profile sites where the EDRP was requested to provide scientific and technical expertise were: (1) the Dover Township (Toms River), New Jersey childhood cancer cluster investigation (1998–2001) and (2) exposure to volatile organic compound-contamination of drinking water supplies at U.S. Marine Corps Base (USMCB) Camp Lejeune, North Carolina (2003–2015). The Dover Township analysis, which applied a water-distribution system model and developed the novel concept of proportional contribution for an epidemiological study is described in detail in **Appendix D**. The Camp Lejeune analysis, which applied groundwater flow, contaminant fate and transport, and water-distribution system models (in addition to other specialized analysis methods) is described in detail in Section 7.0 of this report. Supporting documentation, including all materials referenced therein, for the Camp Lejeune analysis are provided in **Appendixes E–O** of this report. Listed below are selected sites where the EDRP applied analysis tools to reconstruct (or predict) contaminant concentrations.

- **The Analytical Contaminant Transport Analysis System (ACTS)—Multimedia Environmental Fate and Transport**
  The analytical contaminant transport analysis system (ACTS) is a computational platform designed to assist environmental engineers and health scientists with assessing and quantifying environmental multimedia fate and transport of contaminants within four environmental transport pathways—air, soil, surface water, and groundwater. ACTS was developed by the ATSDR Cooperative Agreement University partner, the Multimedia Environmental Simulations Laboratory (MESL) at the Georgia Institute of Technology (Ga. Tech, Atlanta, GA), and was applied by ATSDR engineers and health scientists to several sites ATSDR was investigating. ACTS contains more than 100 models and associated analytical solutions that are available in the public domain. Analyses can be conducted using a deterministic (single-point) and a probabilistic analysis (two-stage Monte Carlo simulation) to assess the fate and transport of contaminants in multi-pathway environmental assessments. ACTS is a user-friendly computational platform that was released publicly (Aral 1998), described in detail and applied to specific case studies in Maslia and Aral (2004), including: (1) deterministic fate and transport of tetrachloroethylene (PCE) at the North Railroad Avenue Plume site (Española, New Mexico), (2) probabilistic fate and transport of tetrachloroethylene (PCE) in groundwater using two-stage Monte Carlo simulation, and (3) probabilistic multi-pathway environmental fate and transport analysis of ethylene dibromide (EDB) using two-stage Monte Carlo simulation at the Massachusetts Military Reservation, Otis Air Force Base, near Hatchville, Massachusetts.

- **Use of Computational Models to Reconstruct and Predict Trichlorethylene (TCE) Exposure**
  ATSDR evaluates the public threat of hazardous waste sites using environmental and health outcome data and community concerns. For the Gratuity Road Site, located in the town of Groton, Massachusetts, the health assessment indicated onsite and off-site residential contamination of groundwater wells with TCE. Because direct measures of historical TCE were unavailable for the site, computational models were used to reconstruct and predict exposure to TCE. Groundwater flow and contaminant fate and transport models were applied to the site. Using output from these models, inhalation exposure to TCE during showering was estimated using empirical formulas developed from the results of laboratory studies, and these results

were compared with results of estimates of exposure by ingestion. The analyses are described in detail in a peer-reviewed article in the *Journal of Toxicology and Industrial Health* (Maslia et al. 1996).

- **Estimating Exposure to Volatile Organic Compounds (VOCs) using Water-Distribution System Modeling**
  In the 1970s, the groundwater aquifer supplying water to the town of Southington, Connecticut, was contaminated with VOCs thereby potentially exposing the town's residents to VOCs in their drinking water. The Southington water-supply system was characterized by a distribution network that contained more than 1,700 pipeline segments of varying diameters and construction materials, more than 186 miles of pipe, 9 groundwater extraction wells capable of pumping more than 4,700 gallons per minute and 3 municipal reservoirs. For this analysis, we applied a computational model (EPANET) to the water-distribution system to characterize and quantify the distribution of VOCs in the pipelines, from which we estimated the demographic distribution of potential exposure to the town's residents. Results were used to demonstrate that the use of a computational model, such as EPANET (Rossman 1994), allows for a more refined and rigorous methodology with which to estimate census-block-level contamination for exposure assessment and epidemiologic investigations. Details of the analyses are presented in the journal *Archives of Environmental Health* (Aral et al. 1996).

- **Exposure Assessment of Tetrachloroethylene (PCE) Groundwater Contamination Using Analytical and Numerical Models**
  At the Osborn Connecticut Correctional Institution (OCCI), near Somers, Connecticut, PCE from the OCCI dry-cleaning facility contaminated groundwater supplies under the prison and impacted domestic wells in the adjacent Rye Hill Circle neighborhood. Based on water-quality samples on the OCCI property, PCE concentrations ranged from 2,553 μg/L in the glacial till aquifer to 1,860 μg/L in the underlying bedrock aquifer. In residential wells tapping the same bedrock aquifer, PCE concentrations ranged from 545 μg/L to below detection limits (<1 μg/L). Analysis of the site by ATSDR included the use and application of simplified analytical and more complex numerical groundwater flow and contaminate fate and transport models, including parameter uncertainty analysis. The analysis indicated that the wells supplying drinking water to the Rye Hill Circle community were most likely contaminated since their installation, which occurred from 1978 through 1981. Thus, based on the ATSDR historical reconstruction, the citizens of the Rye Hill Circle community were most likely exposed to PCE-contaminated groundwater for 16 years—1978 through 1993, when carbon activated filters were installed on each well. The important lesson that was derived from this study was that the use of simplified one- and two-dimensional fate and transport models in an appropriately simplified hydrogeologic setting yielded meaningful and useful results for the community and state public health officials. Details of the analyses and results are available in the peer-reviewed *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management* (Maslia et al. 1997), published by the American Society of Civil Engineers.

- **Groundwater Modeling and GIS to Determine Exposure to TCE at Tucson, Arizona**
  ATSDR determined what portion of the city of Tucson, Arizona, received trichloroethylene (TCE)-contaminated drinking water from the Tucson International Airport Area National Priorities List (NPL) site. This study was accomplished by using analytical solutions for two-dimensional contaminant fate and transport in the underlying groundwater systems to

estimate the historical movement of groundwater contamination. The results of the groundwater analysis, the location of the municipal water-supply wells and distribution system, and the U.S. census tract locations were integrated using a geographic information system (GIS). By integrating these disparate databases and information sources using a GIS, ATSDR was able to estimate what portions of the Tucson population were exposed to site-related TCE, how long those people were exposed, and what the range of human exposure may have been. Details of this analysis are presented in American Society of Civil Engineers peer-reviewed *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management* (Rodenbeck and Maslia 1998).

- **Probabilistic Analysis of Pesticide Transport in Shallow Groundwater at the Oatland Island Education Center, Oatland Island, Georgia**
  The Oatland Island Education Center is located immediately east of Savannah, Georgia. The Center is owned and operated by the Savannah-Chatham County Public Schools as an environmental education facility. The 173-acre facility contains several buildings, wildlife enclosures, and trails. The Communicable Disease Center (now known as the Centers for Disease Control and Prevention [CDC]) and its predecessor agency, the Office of Malaria Control on War Areas, operated the Technical Development Laboratories (TDL) on the site during 1943–1973. In 1974, the U.S. Government deeded the property to the Savannah-Chatham Board of Public Education with the stipulation that the property be used for educational purposes for a period of 30 years. In 1998, school officials discovered a map from 1973 that indicated the location of two onsite disposal areas labeled "Insecticide Burial Area" and "Radioactive Burial Area". ATSDR became involved with the Oatland Island site at the request of the CDC Office of Health and Safety (OHS) to evaluate potential public health impacts associated with pesticide contamination at the site. The Insecticide Burial Area, designated as Area A, was the focus of the analysis by ATSDR's Exposure-Dose Reconstruction Program.

  ATSDR applied the analytical contaminant transport analysis system (ACTS, Maslia and Aral, 2004), to examine the fate and transport of organochlorine pesticides in shallow groundwater at the Oatland Island Education Center, Oatland Island, Georgia. Specific objectives included: (1) estimating the probability of affecting coastal wetlands located 800 feet (ft) downgradient of the pesticide source area, and (2) developing reference tools (probabilistic type curves) for evaluating future groundwater monitoring results at key site monitoring wells.

  Deterministic (single-point) modeling results were in good agreement with measured data from the Oatland Island site. Deterministic simulations using calibrated, single-value input parameters indicate the contaminant plume will not affect the wetlands. Probabilistic results derived by conducting a two-stage Monte Carlo analysis using 10,000 realizations for eight different input parameters indicated that the probability of exceeding the detection limit of 0.044 µg/L total benzene hexachloride (BHC, also known as HCH, hexachlorocyclohexane) in groundwater at the wetlands boundary increases from 1% during 2000 to a maximum of 13% during 2065. This represents an 87% confidence level that the wetlands will not be affected in the future by pesticide migration from Area A. Details of the ATSDR analysis are presented in a peer-reviewed ATSDR report available on the ATSDR websites (Anderson et al. 2007).

- **Modeling Indoor Air Quality from Formaldehyde Emissions of Chinese-Manufactured Laminate Flooring Products**
  In a letter dated March 4, 2015, Senator Bill Nelson (Florida) requested that the Consumer Product Safety Commission (CPSC) determine if Chinese-manufactured laminate flooring products— specifically products from Lumber Liquidators® as seen on the television program 60 Minutes—present an unreasonable risk to consumers. In response to Senator Nelson's letter, the CPSC requested ATSDR's assistance in estimating indoor air formaldehyde (HCOH) concentrations in homes containing the Chinese-manufactured laminate flooring products sold by Lumber Liquidators®. The EDRP conducted data analyses and modeled (simulated) indoor air HCOH. To accomplish this, the EDRP used an analytical model coupled with probabilistic analyses (Monte Carlo simulation) to estimate the range of possible indoor air HCOH concentrations in a residential setting. In this analysis, the mathematical model for a room is referred to as a "*well-mixed room model with a constant emission rate*" (IHMod 2015). Details of ATSDR's EDRP analyses are described in a Centers for Disease Control and Prevention (CDC)/National Centers for Environmental Health (NCEH)/ATSDR report (CDC/NECH/ATSDR 2016).

3.0 Awards

Throughout my career, I have been honored by my peers and professional organizations with awards recognizing the high level of research that I have conducted. A complete list of awards is provided in my CV (**Appendix A**). Listed below are the most notable.

- **American Academy of Environmental Engineers and Scientists (AAEES)**, 2015 Excellence in Environmental Engineering Award, Grand Prize, Research Category, April 2015: "*Using Environmental Engineering Tools, Scientific Analyses and Epidemiological Studies to quantify Human Exposure to Contaminated Drinking Water and to Benefit Public Health.*"
- **American Society of Civil Engineers (ASCE)**, 2011 James R. Croes Medal, for the paper, "*Optimal Design of Sensor Placement in Water Distribution Networks*," Journal of Water Resources Planning and Management, January-February 2010.
- **U.S. Public Health Service Engineering Literary Award (Publications Category)**, 2005, for the publication, "*Analytical Contaminant Transport Analysis System (ACTS)—Multimedia Environmental Fate and Transport"*.
- **American Academy of Environmental Engineers (AAEE),** 2003 Excellence in Environmental Engineering Award, Grand Prize, Research Category, April 2003: "*Enhancing Environmental Engineering Science to Benefit Public Health, Dover Township, Ocean County, New Jersey*"
- **Cumming Award, American Society of Military Engineers**, 2000, to the Dover Township Water-Distribution System Modeling Team.
- **American Society of Civil Engineers (ASCE)**, 2001, Best Practice-Oriented Paper of 2000 for the paper, *"Using Water-Distribution System Modeling to Assist Epidemiologic Investigations,"* ASCE Journal of Water Resources Planning and Management, Vol. 126, July/August 2000.

4.0 Professional Registration and Certifications

- Registered Professional Engineer (GA), #PE012689 (active)
- Certified Ground Water Professional, National Ground Water Association #115205
- Diplomate, American Academy of Water Resources Engineers, D.WRE #00066
- Diplomate, American Academy of Environmental Engineers & Scientists, DEE #00-20013

5.0 Scope of Work

I was retained by the Bell Legal Group in July 2022 on behalf of the *Camp Lejeune Water Litigation* Plaintiffs to consult and testify regarding the methodology and results of ATSDR's historical reconstruction study at USMCB Camp Lejeune and other associated facts, which estimated the locations and concentrations of contaminants in finished water[2] at the Base from 1953 to 1987. Specifically, I was tasked with the following:

1. Provide a high-level explanation of the ATSDR's historical reconstruction process for the Tarawa Terrace (TT), Hadnot Point (HP), and Holcomb Boulevard (HB) study sites, including my and other team members involvement in same for which I supervised.
2. Provide an explanation of measured and reconstructed (simulated) concentrations of contaminants in finished water at Camp Lejeune for the periods of 1951–1987 for TT, 1942–2008 for HP, and 1972–1985 for HB.
3. Provide an explanation of the calibration, sensitivity analysis, and probabilistic uncertainty analysis techniques for each of the models.
4. Summarize the conclusions and opinions included in the published ATSDR Reports for the study areas, as well as review, analysis and conclusions of the National Academy of Sciences 2009 NRC Report and its evolvement and committee activities for which I have knowledge and opinions.
5. Provide additional opinions beyond those already included in the ATSDR published works.

I am being compensated at an hourly rate of $400 for my work preparing this report. My rate for depositions and trial testimony is $2,000 per day.

6.0 Summary of Opinions

Based on the analysis presented in this report, my decades of expertise in environmental analysis and water modeling, and the 11 years I spent working on and overseeing ATSDR's historical reconstruction of contamination at Camp Lejeune, I have reached the following opinions within reasonable scientific and engineering certainty:

1. The models and techniques used by the ATSDR to determine the mean monthly concentrations of contaminants in finished water at Camp Lejeune were state of the art, consistent with standard practices in the field, and subject to peer review.

[2] For the ATSDR study and in this report, finished water is groundwater that has undergone treatment at a water treatment plant and subsequently is delivered to a family housing unit or other facility—also referred to as drinking water, finished drinking water, potable water, or tap water.

2. The model results show reconstructed finished water at Camp Lejeune was contaminated with varying levels of tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene. For TT, finished water was primarily contaminated with PCE and its degradation by-products TCE, 1,2-tDCE, and VC for the period 1953–1987. For HP, finished water was primarily contaminated with TCE, PCE and is by-degradation products, and benzene for the period 1953–1996. For HB, finished water was primarily contaminated with TCE from the HP water-distribution system for the period 1972–1985.

3. The reconstructed (simulated) monthly mean concentrations of PCE, TCE, 1,2-tDCE, VC, and benzene at TT, HP and HB are contained in ATSDR report appendices A2 for TT[3], A3 and A7 for HP[4], and A8 for HB[5]. These reconstructed monthly mean concentrations are also included in this report in **Appendixes H, I, J and K**, are reliable, and represent, within reasonable scientific and engineering certainty, the contaminant levels in selected water-supply wells and in finished water at Camp Lejeune from 1953 to 1996.

4. A water-modeling approach is a reliable and generally accepted method of reconstructing historical contamination in groundwater and water-distribution systems.

5. The analyses published in all ATSDR chapter reports, supplemental reports, supplemental information and scientific journal publications regarding Camp Lejeune, including the conclusions and monthly concentration data, were all done applying proper scientific methodologies that are generally accepted and remain to this day to be reliable, true and correct.

6. Any concerns or criticisms about whether the ATSDR Tarawa Terrace and Handot Point-Holcomb Boulevard models have been "validated" (e.g., August 6, 2024, deposition of D. Waddill; June 19, 2008, Department of the Navy (DON) letter to ATSDR on assessment of ATSDR water-modeling at Tarwa Terrace (**Appendix L**) are misplaced, inappropriate, and scientifically indefensible.

7. The opinions and conclusions expressed in the National Research Council's report on contaminated water-supplies at Camp Lejeune (NRC 2009) cannot be considered an authoritative interpretation or guidance document related to the historical exposure assessment of contaminated drinking water at Camp Lejeune because: (1) they are based on incomplete and missing information (even though ATSDR offered to provide such information to the NRC Committee Executive Secretary), (2) contains many errors and misrepresentations with respect to the findings of the ATSDR water-modeling analyses and (3) conclusions and recommendations contained in the NRC report are at such odds with recommendations rendered by several review panels consisting of national and international experts in water modeling and epidemiology (see **Appendix M** for ATSDR's response to NRC report).

[3] ATSDR's Tarawa Terrace Chapter A report, Appendix A2 (Maslia et al. 2007).
[4] ATSDR's Hadnot Point-Holcomb Boulevard Chapter A report, Appendixes A3 and A7 (Maslia et al. 2013).
[5] ATSDR's Hadnot Point-Holcomb Boulevard Chapter A report, Appendix A8 (Maslia et al. 2013).

8. The opinions discussed in issue number 5 (September-October) of the 2010 *Ground Water* journal published article, "*Complexities in Hindcasting Models-When Should We Say Enough is Enough?*" by author T. P. Clement (2010), are lacking in detail on several key issues with respect to ATSDR's modeling approaches and methods, the physics of contaminant transport in the subsurface, and ATSDR policies for the review and dissemination of data and reports. I submitted an editorial response to the article , which was published in issue number 1 (January-February) of the 2012 *Ground Water* journal. A copy of my editorial response (Maslia et al. 2012) is provided in **Appendix N** of this report.

9. I have read and reviewed the report, "Tarawa Terrace Flow and Transport Model Post-Audit," by N.L. Jones and R.J. Davis (2024, **Appendix O**). They applied acceptable scientific principles, groundwater-flow and contaminant fate and transport methods.

I have reviewed and relied on published literature, data and documents made available to me while consulting on this case and during my work on the Camp Lejeune studies as an employee of ATSDR. The materials I have considered include the literature identified in the references section of this report, as well as the documents listed in **Appendix P** of this report. Most of these materials, documents, and data are also listed in the publicly available ATSDR HP-HB Chapter A report, Appendix A2 (Maslia et al. 2013).

7.0 U.S. Marine Corps Base Camp Lejeune, North Carolina: Reconstructing Volatile Organic Compound Contamination of Drinking-Water Supplies[6]

The Agency for Toxic Substances and Disease Registry (ATSDR), a U.S. government health agency, conducted epidemiological studies to evaluate whether exposures to drinking water contaminated with volatile organic compounds (VOC) at USMCB Camp Lejeune, North Carolina, were associated with increased health risks to children and adults. These health studies required knowledge of contaminant concentrations in finished water—*at monthly intervals*—delivered to family housing, barracks, and other facilities within the study area. Because concentration data were limited or unavailable during much of the period of contamination (1950s–1987), the historical reconstruction process, which included substantial efforts in information gathering and data mining, water-modeling methods, and sensitivity and probabilistic uncertainty analyses, was used to estimate mean monthly contaminant-specific concentrations. These methods and analyses included *linking materials mass balance (mixing) and water-distribution system models to groundwater-flow and contaminant fate and transport models* to derive and quantify monthly mean concentrations and ranges of concentrations of contaminants of interest to the ATSDR epidemiological studies (PCE, TCE, *1,2*-tDCE, VC, and benzene).

[6] This section of the expert report refers to figures and tables contained within this report and figures and tables contained in ATSDR reports (e.g., Maslia et al. 2007, 2013, Faye 2008). Figures and tables in this report section begin with the number **7** and are numbered sequentially (e.g., Figure 7.1, Figure 7.2; Table 7.1, Table 7.2). Figures and tables that begin with the letter "**A**" (e.g., Figure A12, Table A4), refer to the ATSDR Chapter A reports (Maslia et al. 2007, 2013).

7.1 Introduction

As project manager I utilized both internal expertise at the ATSDR and brought in outside experts to create a multidisciplinary team with the required skill set to conduct the historical reconstruction analysis for the TT and HP-HB study areas. This team consisted of over 20 individuals that encompassed expertise in a variety of scientific and engineering disciplines, and spans every area and specialty involved in water modeling. Table 2.1 (previously discussed in Section 2.0 above) lists team members and organizations; **Appendix B** provides detailed information on each team member, including their organization and technical/scientific areas of expertise for the ATSDR Water Modeling Team.

Many years of effort have gone into ATSDR's drinking-water exposure and health studies at USMCB Camp Lejeune resulting in numerous agency reports and published papers. Owing to brevity, this section summarizes these efforts, reports, and papers into a synthesis of the overall approach to, and results from, the historical contaminant reconstruction study.

With respect to the three housing areas, barracks, and workplaces of interest to the ATSDR drinking-water exposure and health studies—Tarawa Terrace (TT), Hadnot Point (HP), and Holcomb Boulevard (HB) (Figure 7.1)—TT results are published as a series of externally peer-reviewed ATSDR reports that are summarized in the Tarawa Terrace Chapter A Report (Summary of Findings) by Maslia et al. (2007). TT results are also published in a peer-reviewed journal article (Maslia et al. 2009a). Approaches, methods, and results for the HP-HB areas are published as a series of externally peer reviewed ATSDR reports that are summarized in the HP-HB Chapter A Report (Summary of Findings) by Maslia et al. (2013). HP-HB results are also published in a peer-reviewed journal article (Maslia et al. 2016). The ATSDR reports contain very specific details for the TT, HP, and HB drinking-water analyses. Each summary report (Maslia et al. 2007, 2013) provides references to and descriptions of additional detailed ATSDR reports on the application of the historical reconstruction process to quantify historical drinking-water contamination from VOCs at USMCB Camp Lejeune, North Carolina.

Results show that at the TT water treatment plant (TTWTP) reconstructed (simulated) PCE concentrations reached a maximum monthly average value of 183 micrograms per liter (µg/L) compared to a one-time maximum measured value of 215 µg/L and exceeded USEPA's current maximum contaminant level (MCL) of 5 µg/L during the period November 1957–February 1987. At the HP water treatment plant (HPWTP), reconstructed TCE concentrations reached a maximum monthly average value of 783 µg/L compared to a one-time maximum measured value of 1,400 µg/L during the period August 1953–December 1984. The HPWTP also provided contaminated drinking water to the HB housing area continuously prior to June 1972, when the HB water treatment plant (HBWTP) came online (maximum reconstructed TCE concentration of 32 µg/L) and then intermittently during the period June 1972–February 1985 (maximum reconstructed TCE concentration of 66 µg/L). Drinking-water concentrations at the TTWTP and HPWTP for PCE, TCE, 1,2-tDCE, and VC and benzene were also reconstructed. **Appendixes H, J, and K** contain TT, HP, and HB, respectively, reconstructed mean monthly contaminant-specific concentration data in tabular form. **Appendix I** contains reconstructed monthly mean concentrations for selected HP-HB water-supply wells.

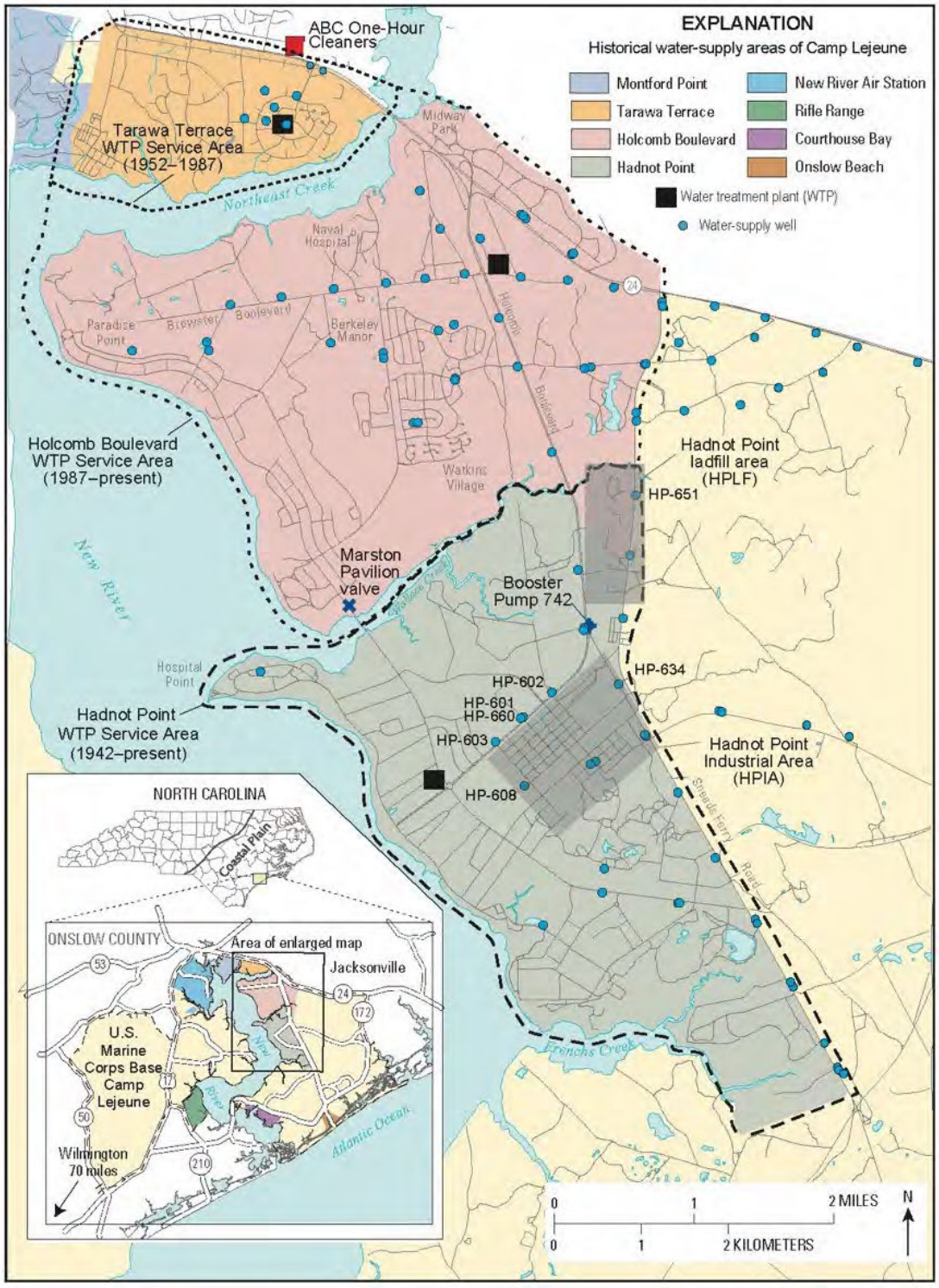


Figure 7.1. Water-supply areas with focus on housing areas, barracks, and workplaces included in the Agency for Toxic Substances and Disease Registry (ATSDR) drinking-water exposure and health studies, U.S. Marine Corps Base Camp Lejeune, North Carolina (Maslia et al. 2013, 2016).

7.2 Water Supply and Contamination at Camp Lejeune

USMCB Camp Lejeune is in the Coastal Plain of North Carolina, in Onslow County, southeast of the City of Jacksonville and about 70 miles northeast of the City of Wilmington, North Carolina. In general, the study area is bounded to the north by North Carolina Highway 24 (SR 24), to the west by New River, to the south by Frenchs Creek, and generally to the east by the drainage divides of upstream tributaries of Wallace and Frenchs Creeks. Northeast Creek separates the TT base housing area from the HP and HB base housing areas (Figure 7.1).

Groundwater is the sole source of water supply for USMCB Camp Lejeune. Eight water-distribution systems have supplied or currently (2024) supply drinking water to family housing, barracks, workplaces, and other facilities at USMCB Camp Lejeune. The three water-distribution systems of interest to the ATSDR health studies–TT, HP, and HB (Figure 7.1)–have historically supplied finished water to most family housing units, enlisted personnel barracks, and workplaces at the base. ATSDR documented information and aggregated data related to water-supply chronology within the study areas of Camp Lejeune. Details pertinent to water-supply well operations (e.g., construction, in-service, and out-of-service dates) and WTP operations are provided in Maslia et al. (2007, 2013).

HP was the original water-distribution system, serving the entire base with drinking water beginning in the early 1940s. The HPWTP was constructed and began operations likely during 1941–1942. The TTWTP began delivering drinking water during 1952–1953, and the HBWTP began delivering drinking water during June 1972 (Table 7.1). Currently (2024), the HPWTP services the HP area, and the HBWTP services the HB and TT base housing areas because the TTWTP was shut down during 1987 due to contamination of several supply wells (Table 7.1).

The HB water-distribution system is connected to the HP water-distribution system at the Marston Pavilion valve and at booster pump 742 (Figure 7.1). Booster pump 742 was removed during 2007, but the two systems can still be interconnected by opening a valve at the same location. For operational reasons, the two water-distribution systems are rarely connected—exceptions being some documented (and undocumented) intermittent connections that occurred during late spring and summer months of 1972–1986 and a continuous 8-day period of 28 January–4 February 1985 (Maslia et al. 2013, 2016) (refer to Camp Lejeune Water documents [CLW] 6774–8761, 8109, and 8117 [CLW, 2007]).

Operational chronologies for water-supply wells in the TT, HP, and HB study areas during the period 1942–2008 are provided in Figures 7.2 and 7.3. These graphs show dates of operation for each well that supplied raw water to the TTWTP, HPWTP, and HBWTP, the dates when some of the wells were permanently taken out of service, and wells with documented contamination. The water-supply well historical operations graph and chronology table for TT are shown below as Figure 7.2. For HP-HB, Figure 7.3 shows water-supply well operations and chronologies graphically. Note, TT had a total of 16 water-supply wells whereas HP-HB had nearly 100 water-supply wells.

Table 7.1. Chronology of selected events related to water supply and environmental contamination at U.S. Marine Corps Base Camp Lejeune, North Carolina, and vicinity. [#,*]

Event	Date or approximate date
Hadnot Point water treatment plant (WTP) comes online	1941–42
Tarawa Terrace WTP comes online	1952–53
Holcomb Boulevard WTP comes online	June 1972
Several Tarawa Terrace and Hadnot Point water-supply wells shut down due to documented volatile organic compound (VOC) contamination	November 1984–February 1985
Marston Pavilion interconnection valve opened and booster pump 742 continuously operated for eight days (because of shut down of Holcomb Boulevard WTP) to augment Holcomb Boulevard drinking-water supply with contaminated Hadnot Point drinking water	January 27–February 4, 1985
Holcomb Boulevard WTP expanded to provide water to Tarawa Terrace and Camp Johnson water-distribution system areas	1987
Tarawa Terrace WTP and remaining operating supply wells shut down and taken out of service	March 1987
ABC One-Hour Cleaners placed on the USEPA's National Priorities List (NPL) of contaminated sites	March 1989
USMCB Camp Lejeune placed on the USEPA's NPL of contaminated sites	October 1989

[#]Refer to Maslia et al. (2007, 2009a, 2013, and 2016) for details
[*]See Figure 7.1 for location of water-supply areas.

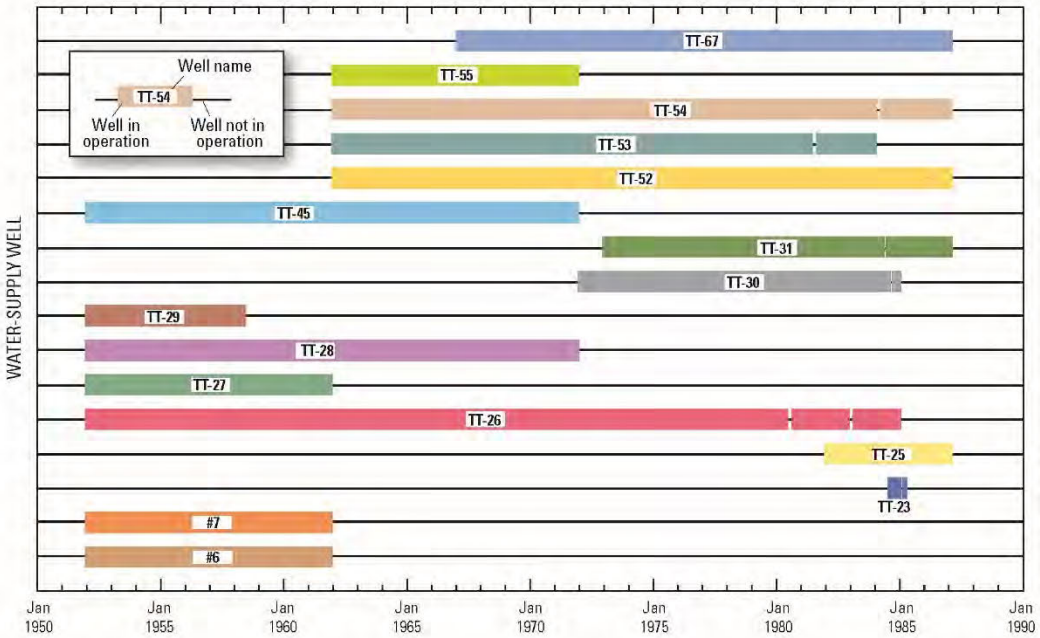


Figure A5. Historical operations of water-supply wells, 1952–87, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Table A6. Historical operations for water-supply wells, 1952–1987, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.[1]

[—, not applicable]

Well identification	In service	Off-line	Service terminated
#6	January 1952	—	January 1962
#7	January 1952	—	January 1962
TT-23	August 1984	February 1985	May 1985
TT-25	January 1982	—	March 1987
TT-26	January 1952	July–August 1980; January–February 1983	February 1985
TT-27	January 1952	—	January 1962
TT-28	January 1952	—	January 1972
TT-29	January 1952	—	July 1958
TT-30	January 1972	September 1984	February 1985
TT-31	January 1973	June 1984	March 1987
TT-45	January 1952	—	January 1972
TT-52	January 1962	March 1986	March 1987
TT-53	January 1962	July–August 1981	February 1984
TT-54	January 1962	February–March 1984	March 1987
TT-55	January 1962	—	January 1972
TT-67	January 1967	—	March 1987

[1]Refer to the Chapter C report (Faye and Valenzuela In press 2007) for additional details

Figure 7.2. Operational chronologies of Tarawa Terrace water-supply wells, Tarawa Terrace study area, 1952–1987 (Maslia et al. 2007).

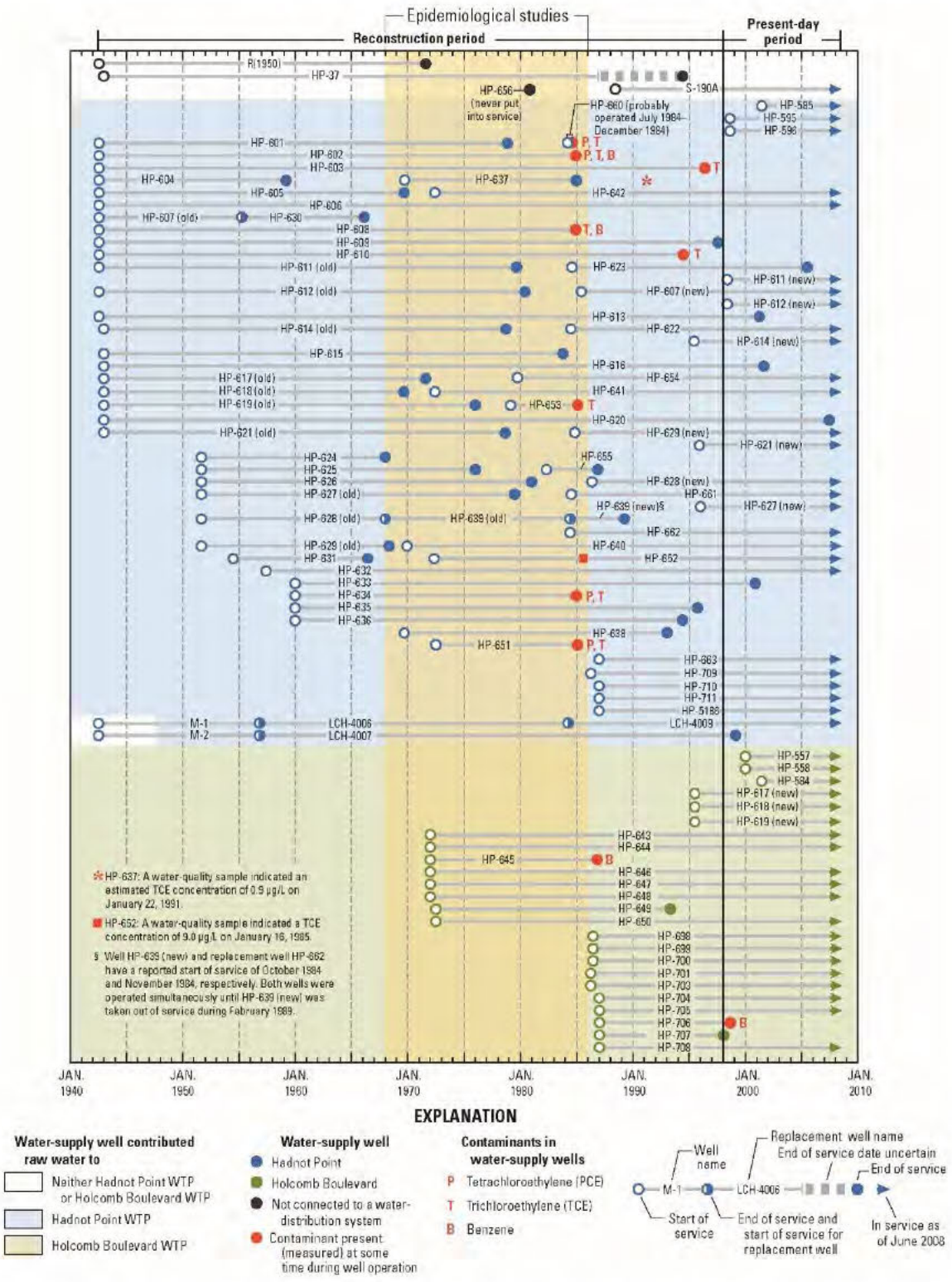


Figure 7.3. Operational chronology of Hadnot Point and Holcomb Boulevard water-supply wells, Hadnot Point-Holcomb Boulevard study area (Maslia et al. 2013).

During the early 1980s, high concentrations of VOCs were discovered in groundwater and drinking water serving some areas at Camp Lejeune. Within the TTWTP service area, groundwater was contaminated mostly with PCE and its degradation products. An off-base dry-cleaning facility (ABC One-Hour Dry Cleaners—Figure 7.1) was identified as being responsible for contaminating several on-base water-supply wells at Tarawa Terrace (Maslia et al. 2007, 2009a). Within the HPWTP service area, groundwater was contaminated mostly with TCE, as well as PCE and refined petroleum products, such as BTEX compounds. Historical base operations and lack of environmentally protective disposal practices at Camp Lejeune have been identified as being responsible for contamination of groundwater and drinking-water supplies within the HPWTP service area (Faye et al. 2010, 2012). Within the HBWTP service area, drinking water remained predominantly uncontaminated except for intermittent supply during spring and summer months of contaminated HP water during years 1972–1985. Maximum measured concentrations of selected contaminants within the study areas have been documented as follows (CLW 2007, Maslia et al. 2007, 2013, Faye et al. 2010, 2012):

- 18,900 µg/L of TCE in an HPWTP supply well (May 1985),
- 1,400 µg/L of TCE in finished water at the HPWTP (May 1982),
- 380 µg/L and 720 µg/L of benzene in a HPWTP supply well (July and December 1984, respectively),
- 215 µg/L of PCE in finished water at the TTWTP (February 1985), and
- 1,580 µg/L of PCE in a TTWTP supply well (January 1985).

In 1989, USMCB Camp Lejeune and ABC One-Hour Cleaners (an offsite dry-cleaning facility, Figure 7.1) were placed on the USEPA's National Priorities List (NPL) of hazardous waste sites. ATSDR is required to gather information and data to assess human health impacts from exposures at NPL sites. Because of the potential exposures to high VOC concentrations, ATSDR began health studies in 1995 to evaluate effects of exposure to contaminated drinking water.

7.3 Water-Modeling and Study Objectives

When ATSDR health study epidemiologists requested scientific and technical support from the Exposure-Dose Reconstruction Program, they presented a list of five objectives and questions that they wanted to achieve and to answer. These five objectives and questions were originally presented at a meeting held on October 8, 2003, at ATSDR Headquarters in Chamblee, Georgia, with attendance by ATSDR (staff, Management, and Leadership), U.S. Marine Corps (Camp Lejeune and Headquarters staff), DON, Naval Facilities Engineering Command (NAVFAC) staff, the ATSDR University Partner, and contractors. The five study objectives and questions are listed below.

- **Objective 1:** What chemical compounds contaminated the drinking water and where did they come from (*determine sources of contaminants*)?
- **Objective 2:** When did contaminated groundwater reach water-supply wells and what was the duration of the contamination (*determine arrival dates*)?
- **Objective 3:** What were the *mean monthly* drinking-water *concentrations*?

- **Objective 4:** How was contaminated water distributed to housing areas (*quantify and identify water transfers*)?
- **Objective 5:** What were the ranges of concentration values (based on modeling results) for a specific month (*conduct sensitivity and uncertainty analysis*)?

These objectives and questions were successfully achieved and answered for the TT, HP, and HB study areas based on applying the historical reconstruction process for water-modeling analyses. They are described in detail in externally peer-reviewed ATSDR reports (Maslia et al. 2007, 2013) and peer-reviewed scientific journals (Maslia et al. 2009a, 2016).

The ATSDR water-modeling analyses and epidemiological studies were guided by recommendations contained in the 1990 ABC One-Hour Dry Cleaner and 1997 USMCB Camp Lejeune Public Health Assessments. Therefore, only VOCs (PCE, TCE, 1,2-tDCE, VC, and BTEX compounds) and VOC contamination of finished water supplies at the three housing areas (TT, HP, and HB), barracks, and workplaces of interest to the ATSDR drinking-water exposure and health studies at Camp Lejeune were studied.

7.4 Historical Reconstruction Methods

When direct, past knowledge of contaminant concentrations in drinking water is limited or data are unavailable, historical reconstruction methods can be used to provide estimates of contaminant concentrations. The process of historical reconstruction is an accepted methodology. Sahmel et al. (2010) provide a review of more than 400 papers in exposure reconstruction for substances of interest to human health. Water modeling (e.g., contaminant fate and transport and water-distribution systems analysis) is an accepted method to reconstruct (or predict) contaminants delivered through water systems. Examples of historical reconstruction applied to different sites are found in Grayman et al. (2004, Chapter 10). They provide summaries of successful and accepted historical reconstruction applied to Gideon, Missouri; Walkerton, Ontario; Dover Township (Toms River), New Jersey; and Redlands, California. Historical reconstruction includes information gathering and data mining activities and the application of simulation tools, such as models, to re-create or represent past conditions There are numerous examples demonstrating this including Costas et al. (2002), Grayman et al. (2004), Kopecky et al. (2004), McLaren/Hart-ChemRisk (2000), Maslia et al. (2000b, 2001, 2005, 2007, 2009a, 2013, 2016), Reif et al. (2003), Rodenbeck and Maslia (1998), and Samhel et al. (2010). For ATSDR's drinking-water exposure analyses at Camp Lejeune, methods included linking materials mass balance (mixing) and water-distribution system models to groundwater-flow and contaminant fate and transport models.

7.4.1 Overview

The generalized five-step process used to identify information sources, extract usable model-specific data, and develop, apply, and calibrate models to reconstruct historical contaminant-specific concentrations in drinking water at USMCB Camp Lejeune is shown in Figure 7.4. By its very nature, historical reconstruction is an *iterative* process. The five-steps of the process are:

(1) review information sources,

(2) extract information and data and develop databases,

(3) develop, simulate, and calibrate models,

(4) determine if model conceptualization or calibration issues exist, and if they do, use subject matter experts to iteratively refine model databases and search for additional information sources, and

(5) assess when sufficient agreement exists between water-level, groundwater contaminant concentration, and water treatment plant concentration data (historical and present-day) and model results.

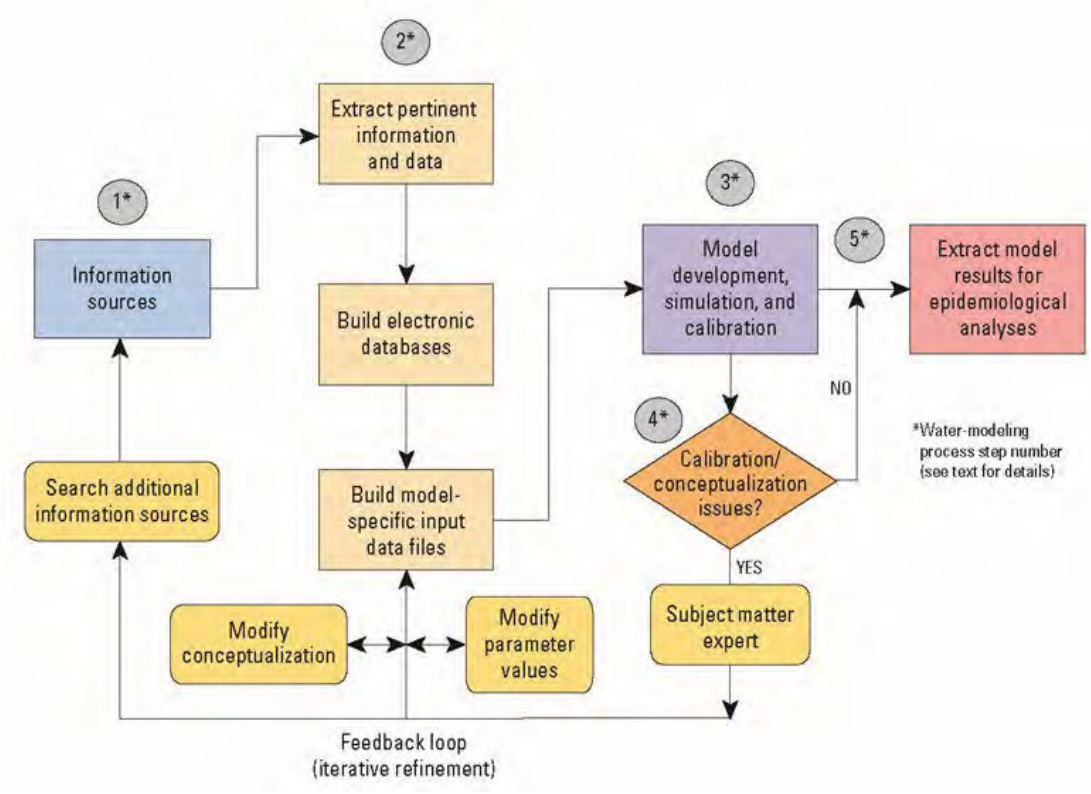


Figure 7.4. A generalized process of identifying information, extracting usable model-specific data, and applying models to reconstruct historical drinking-water contaminant-specific concentrations (Maslia et al. 2013, 2016).

After satisfactory completion of these five steps, historical contaminant concentration simulation results were extracted from model-output databases and provided to ATSDR epidemiologists for use in the Camp Lejeune epidemiological analyses (Bove et al. 2014a, b; Ruckart et al. 2013, 2014, 2015). It is important to note that throughout the historical reconstruction process, **data analysts and water modelers were blinded to the health outcome status** of individuals included in the epidemiological studies.

7.4.2 Information and Data Discovery

Substantial effort and resources were dedicated to the task of identifying information sources and extracting data because of the voluminous and disparate sources of information and data pertinent to the study area (**Appendix E** of this report and in Maslia et al. 2013, Appendix A2). The purpose was to obtain information and data that could be extracted and transformed into digital databases to conduct historical reconstruction analyses using a modeling approach. By its very nature, information discovery and data mining are not an exact process that can be used or relied upon to identify a single, specific piece of information or data point. Numerous information sources were identified, located, and assessed prior to extracting usable model-specific data. Once pertinent model-specific data were identified and extracted, they had to be entered into digital databases. Computer model-specific input databases were then developed from these digital databases. A list of information and data sources used to develop model-input databases for the TT, HP, and HB study areas is provided in **Appendix E**.

Information and data discovery is an iterative process with ATSDR requesting information and data from Camp Lejeune and DON. At times, this process became a contentious issue but was eventually resolved. However, the consequences and impacts on project timelines and completion dates were delays and needs for increased resources for data extraction and processing required for model calibration and completing the water-modeling analyses. Three examples are noteworthy:

1. Based on discussions of the 2005 ATSDR Expert Peer Review Panel evaluating ATSDR's water-modeling activities at Camp Lejeune (Maslia 2005), panel members recommended that ATSDR put additional effort and resources into conducting more rigorous data discovery activities. DON brought in a contractor, Booz-Allen-Hamilton (BAH), to search for information and documents in buildings throughout Camp Lejeune. This activity began with a "kick-off" meeting during November 2005. The results of the BAH effort provided the USMC and DON with a document referred to as the "Marine Corps Base Camp Lejeune Consolidated Repository Index (4-27-2009)," which was approximately 514 pages long, that ATSDR staff, contractors, and subject matter experts searched in April 2009 and thereafter.

2. During March 2009, an ATSDR subcontractor discovered through a series of email exchanges with Camp Lejeune staff, a password protected portal containing more than 1,530 folders and files pertinent to underground storage tank (UST) information (**Appendix E**). Identifying the existence of this portal (containing pertinent information needed by ATSDR), although known to Camp Lejeune beginning July 2003, was not communicated to ATSDR until March 2009. The consequences of finding out about the UST portal resulted in ATSDR devoting additional time and resources to developing an additional chapter report for the HP-HB study area on above ground and underground storage tank information and data (Chapter D of the HP-HB report series [Faye et al. 2012];).

3. As a result of ongoing information and data needs for ATSDR's water-modeling activities, Camp Lejeune leadership (civilian and military) recognized the need to document and provide ATSDR with a comprehensive catalogue of all information and data sources known

or unknown to USMC, NAVFAC, DON and DON contractors. Therefore, on June 30, 2010, an initial meeting of the "DON-ATSDR Camp Lejeune Data Mining Technical Workgroup" was held in Washington, DC. The charge of the workgroup was:

a. Develop a plan to ensure that ATSDR possesses all relevant data and information needed for their health activities. This includes information and data possessed by current DON contractors. All reasonable efforts will be made to ensure that ATSDR possesses all relevant data and information possessed by former contractors and other federal and state agencies.

b. Implement the plan to ensure ATSDR possesses all relevant data and information needed for their health activities.

c. Complete the data mining phase that must be done prior to the historical dose reconstruction modeling and epidemiological phases of the health activities.

The DON-ATSDR Camp Lejeune Data Mining Technical Workgroup completed its task and issued a final report on November 27, 2012. Much of the information and information sources listed in **Appendix E** of this report is a result of the effort of the DON-ATSDR Camp Lejeune Data Mining Technical Workgroup.

Most of the information sources listed in **Appendix E** were not in readily usable digital format that could be directly used for developing input databases for modeling. Rather, a time-consuming process was required to extract pertinent and usable information. This process consisted of determining potentially pertinent documents and information, reviewing pertinent documents, manually extracting data (in most cases), and then entering these data into digital databases. A generalized three-stage process was developed for reviewing, assessing, and extracting information and data. This process is shown in Figure 7.5 and is described below.

- *Stage 1*: A cursory review was conducted to determine if a particular source of information or data referred to the TT, HP, or HB study areas; if not, the information source or data was noted and not reviewed,
- *Stage 2*: Information sources and data pertinent to the study areas were filtered by content and subject matter (e.g., remedial investigation, lab analysis). Depending on the content and subject matter, certain files were not reviewed in detail (e.g., meeting notes), whereas other files were promoted to a stage 3 review (e.g., site characterization data, laboratory analyses, groundwater-level data), and
- *Stage 3*: If a file contained certain key words or dates (e.g., water supply, VOC, benzene, underground storage tank, TT-26, HP-651, WTP), it was reviewed in detail by subject matter experts. Pertinent information and data were identified, and contract staff extracted the information and data and entered it into digital databases. Then, data were extracted from the digital databases and appropriate model-input databases were prepared. It is important to note, however, that even with the three-stage review process, because of the volume of information, not every document was reviewed, nor was every page of every document

reviewed unless such a review was determined to be critical to extracting information and data pertinent to the historical reconstruction process and specifically to computer model-specific input database development. For example, daily water-supply well operational data available during 1999–2008 consisted of 10,000 pages of pertinent information, all of which were reviewed, evaluated, and transcribed to digital data (**Appendix E**).

7.4.3 Water-Modeling Approach and Simulation Tools

The water-modeling approach used to reconstruct historical drinking-water concentrations at the TTWTP and HPWTP and within the HB water-distribution system is shown as a flowchart (Figure 7.6). The modeling required four steps: characterizing (1) the subsurface contamination sources, (2) the groundwater flow under natural (pre-development) and pumping conditions, (3) contaminant migration influenced by the groundwater flow as well as other transformation processes (e.g., adsorption, degradation), and (4) the mixing of contaminants from pumping wells at the WTP and within the distribution system and delivery to the housing areas, barracks, and other buildings. The analyses and simulation tools used as part of the historical reconstruction process for TT, HP and HB included: (1) geohydrologic analyses; (2) water-distribution system field testing; (3) water-level data to characterize groundwater flow; (4) groundwater-flow and contaminant fate and transport models (for dissolved and light nonaqueous-phase liquid [LNAPL] constituents); (5) parameter sensitivity and uncertainty analyses; (6) probabilistic Markov analyses; and (7) water-distribution system modeling. Detailed descriptions of each analysis and simulation tool, the type of analysis (e.g., data, interpretation, or simulation) and supporting references are provided in Maslia et al. (2007, 2013). Details of the groundwater-flow and contaminant fate and transport models are provided in Maslia et al. (2007, 2009a, 2013, 2016) and associated reports.

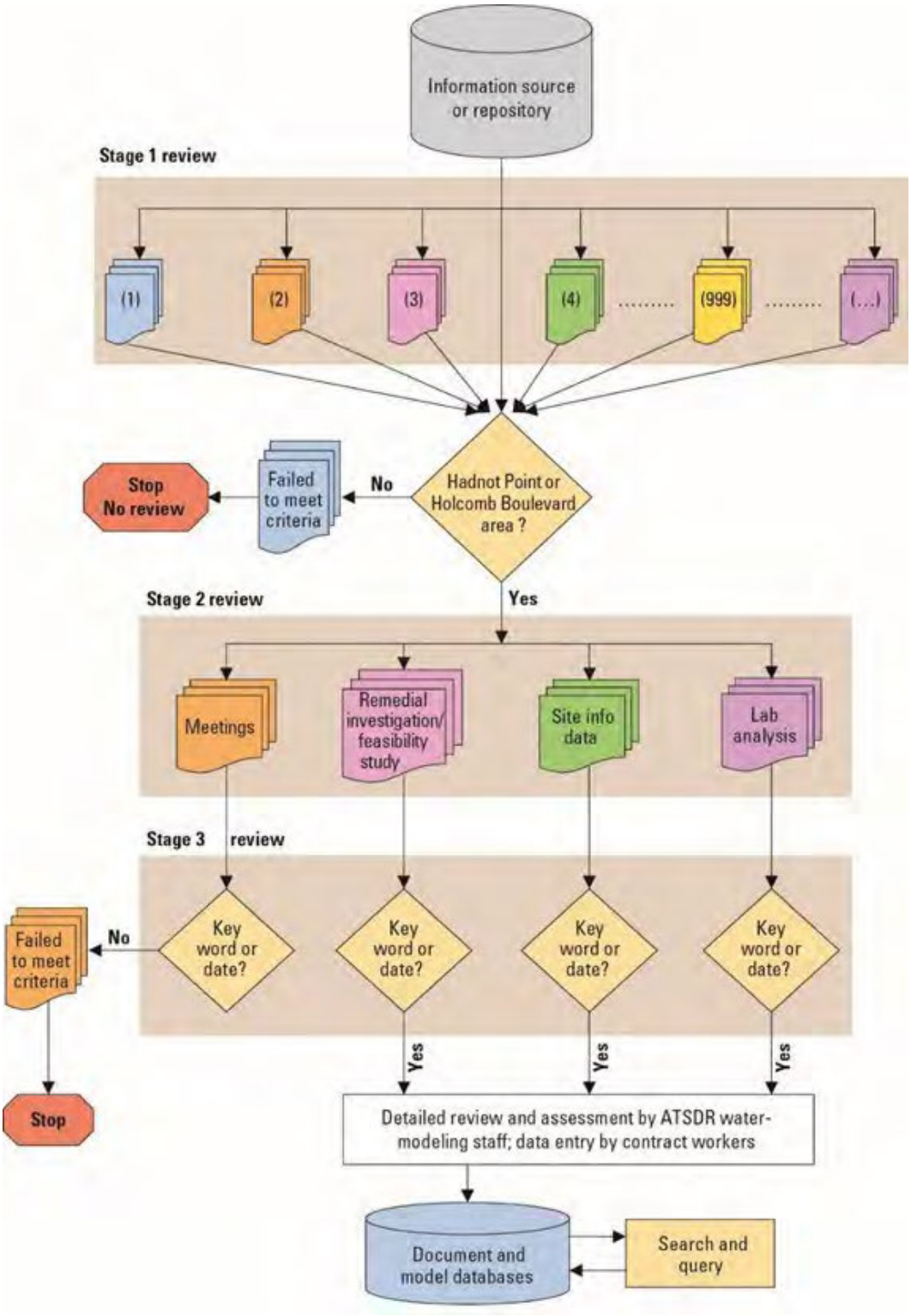


Figure 7.5. Three-stage process used for identifying relevant information and extracting data for databases and model development, Tarawa Terrace, Hadnot Point, and Holcomb Boulevard study areas (Maslia et al. 2013).

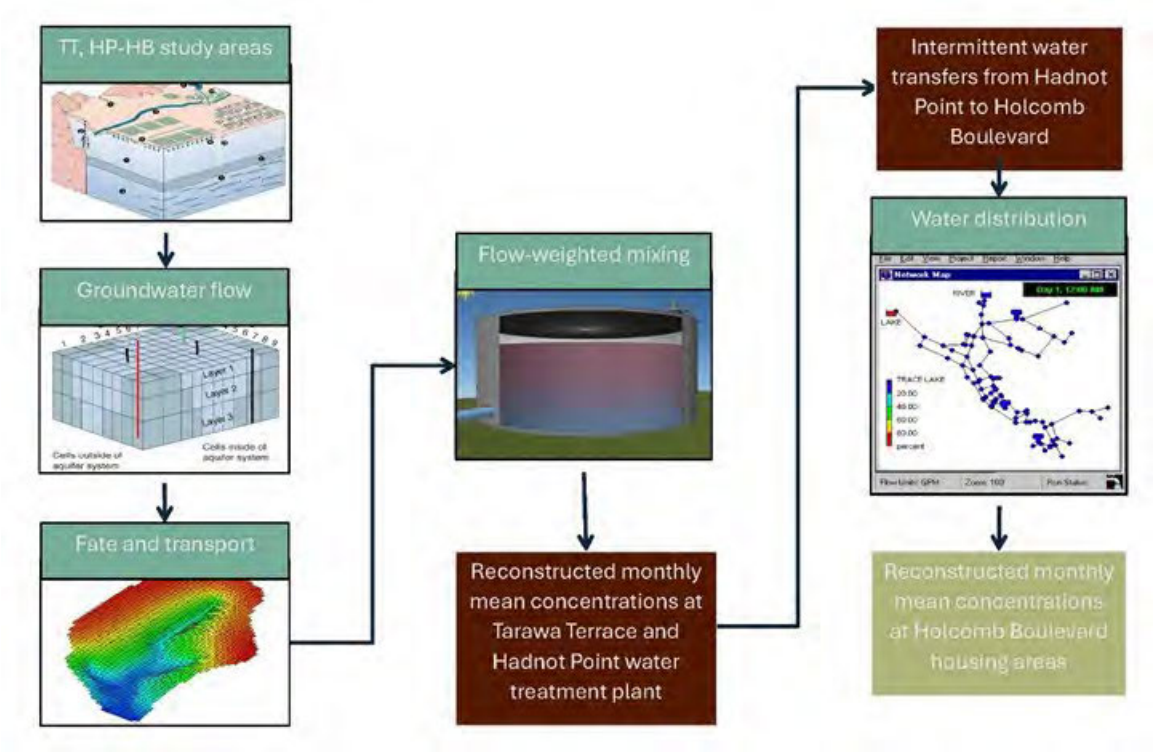


Figure 7.6. Water-modeling approach used for reconstructing historical drinking-water contaminant concentrations at Tarawa Terrace (TT), Hadnot Point (HP), and Holcomb Boulevard (HB). (Details of the groundwater-flow and contaminant fate and transport models are provided in Maslia et al. [2007, 2009a, 2013, 2016] and associated reports.)

To reconstruct groundwater levels, three-dimensional steady-state (pre-development, i.e., before pumping began) and transient groundwater-flow models were used and were calibrated using available geohydrologic field data, hydrogeologic and aquifer property data, and water-supply well monthly pumping and on-off cycling. Upon achieving an acceptable calibration for predevelopment (steady state) conditions and transient conditions (water-supply well pumping), the calibrated groundwater-flow velocity field and required fate and transport parameters (e.g., dispersity, retardation, source concentration variation) were input to a three-dimensional contaminant fate and transport model to simulate and calibrate the fate and transport of contaminants such as PCE.

Several custom methods and models were developed as part of the historical reconstruction process owing to the complex character of the study area, the complex historical water-supply well operations, and the need to reconstruct mean monthly contaminant-specific concentrations. Summarized below are some of these methods:

- Effective and efficient (with respect to published methods) fire-flow test method for water-distribution system model calibration (Grayman et al. 2006),
- Historical monthly operations and pumped groundwater volumes reconstructed for nearly 100 supply wells (Telci et al. 2013),

- Linear state-space representation of a contaminated aquifer developed to reconstruct historical concentrations in supply wells without the need to use traditional numerical fate and transport modeling (Guan et al. 2013),
- Volume estimates of lost benzene and LNAPL fate and transport in groundwater (Jang et al. 2013), and
- Probabilistic Markov process to estimate the number of intermittent transfers of drinking water between a contaminated and uncontaminated drinking-water system (Sautner et al. 2013b).

Specific details and descriptions for each type of analysis and each type of model or computational tool used are provided in Maslia et al. (2007, 2013) and set out below. Use of custom methods such as proprietary models is consistent with EPA guidance to produce the most reliable results for specific sites. (USEPA 2009). Further details regarding the proprietary models used by ATSDR are set forth in the expert report of Dr. Mustafa M. Aral.

Tarawa Terrace

Table 7.2 lists the analyses and simulation tools (models) used to reconstruct historical contamination events at Tarawa Terrace and vicinity. The primary focus for the investigation of the Tarawa Terrace historical reconstruction analyses was the fate and transport of, and concentration levels of a single constituent—PCE.

For Tarawa Terrace the information and data in Table 7.2 were applied to the models in the following sequence:

1. Geohydrologic framework information, aquifer and confining unit hydraulic data, and climatic data were used to determine predevelopment (prior to 1951) groundwater-flow characteristics. To simulate predevelopment groundwater-flow conditions, the public-domain code **MODFLOW-96** (Harbaugh and McDonald 1996)—a three-dimensional groundwater-flow model code—was used.
2. Transient groundwater conditions occurring primarily because of the initiation and continued operation of water-supply wells at Tarawa Terrace also were simulated using the three-dimensional model code **MODFLOW-96**; well operations were accounted for and could vary on a monthly basis.
3. Groundwater velocities or specific discharges derived from the transient groundwater-flow model were used in conjunction with PCE source, fate, and transport data to develop a fate and transport model. To simulate the fate and transport of PCE as a single species from its source at ABC One-Hour Cleaners to Tarawa Terrace water-supply wells, the public domain code **MT3DMS** (Zheng and Wang 1999) was used. **MT3DMS** is a model capable of simulating three-dimensional fate and transport. Simulations describe PCE concentrations on a monthly basis during January 1951–December 1994.[7]

[7] The contaminant fate and transport model, MT3DMS, has several options for solving the transport equation. These solvers include Finite-Difference (F-D), Method of Characteristics (MOC), and Total Variation Diminishing (TVD). The F-D solver produces more numerical dispersion whereas the TVD solver minimizes numerical dispersion at the expense of

4. The monthly concentrations of PCE assigned to finished water at the Tarawa Terrace WTP were determined using a materials mass balance model (simple mixing) to compute the flow-weighted average concentration of PCE. The model is based on the principles of continuity and conservation of mass (Masters 1998).
5. To analyze the degradation of PCE into degradation by-products (TCE, 1,2-tDCE, and VC) and to simulate the fate and transport of these contaminants in the unsaturated zone (zone above the water table), a three-dimensional, multispecies, and multiphase mass transport model (**TechFlowMP**) was developed by the Multimedia Simulations Laboratory (MESL) at the Georgia Institute of Technology (Jang and Aral 2005, 2007).
6. To analyze and understand the impacts of unknown and uncertain historical pumping schedule variations of water-supply wells on arrival of PCE at the Tarawa Terrace water-supply wells and WTP, a pumping and schedule optimization system tool (**PSOpS**) was used. This model was also developed by the MESL (Wang and Aral 2007).
7. To assess parameter sensitivity, uncertainty, and variability associated with model simulations of flow, fate and transport, and computed PCE concentrations in finished water at the Tarawa Terrace WTP, sensitivity and probabilistic analyses were conducted. Sensitivity analyses were conducted using a one-at-a-time approach; the probabilistic analyses applied Monte Carlo simulation (MCS) and sequential Gaussian simulation (SGS) methods to results previously obtained using **MODFLOW-96, MT3DMS**, and the drinking-water mixing model.
8. The initial approach for estimating the concentration of PCE delivered to residences of Tarawa Terrace used the public domain model, **EPANET 2** (Rossman 2000)—a water-distribution system model used to simulate street-by-street PCE concentrations (Sautner et al. 2005, 2013b).

introducing oscillations. For both the TT and HP models, the F-D solver was used. A sensitivity analysis was conducted to assess the different solution methods for the HP models (Jones et al. 2013, Figure S6.21, p. S6.41).

Table 7.2. Analyses and simulation tools (models) used to reconstruct historical contamination events at Tarawa Terrace and vicinity (Maslia et al. 2007)

[VOC, volatile organic compound; PCE, tetrachloroethylene; GIS, geographic information system; WTP, water treatment plant; TCE, trichloroethylene; 1,2-tDCE, *trans*-1,2-dichloroethylene; VC, vinyl chloride]

Analysis	Description	Analysis or simulation tool and type	Reference
Geohydrologic framework	Detailed analyses of well and geohydrologic data used to develop framework of the Castle Hayne aquifer system at Tarawa Terrace and vicinity	Data analysis	Faye (In press 2007a)
Predevelopment groundwater flow	Steady-state groundwater flow, occurring prior to initiation of water-supply well activities (1951) or after recovery of water levels from cessation of pumping activities (1994)	MODFLOW-96—numerical model	Harbaugh and McDonald (1996); Faye and Valenzuela (In press 2007)
Transient groundwater flow	Unsteady-state groundwater flow occurring primarily because of the initiation and continued operation of water-supply wells (January 1951–December 1994)	MODFLOW-96—numerical model	Harbaugh and McDonald (1996); Faye and Valenzuela (In press 2007)
Properties of VOCs in groundwater	Properties of degradation pathways of common organic compounds in groundwater	Literature survey	Lawrence (2006, In press 2007)
Computation of PCE mass	Estimates of mass (volume) of PCE; (a) unsaturated zone (above water table) in vicinity of ABC One-Hour Cleaners based on 1987–1993 data; (b) within Tarawa Terrace and Upper Castle Hayne aquifers based on 1991–1993 data	Site investigation data, GIS, and spatial analyses	Roy F. Weston, Inc. (1992, 1994); Pankow and Cherry (1996); Faye and Green (In press 2007)
Fate and transport of PCE	Simulation of the fate and migration of PCE from its source (ABC One-Hour Cleaners) to Tarawa Terrace water-supply wells (January 1951–December 1994)	MT3DMS—numerical model	Zheng and Wang (1999); Faye (In press 2007b)
PCE concentration in WTP finished water	Computation of concentration of PCE in drinking water from the Tarawa Terrace WTP using results from fate and transport modeling	Materials mass balance model using principles of conservation of mass and continuity—algebraic	Masters (1998); Faye (In press 2007b)
Fate and transport of PCE and degradation by-products in groundwater and vapor phase	Three-dimensional, multiphase simulation of the fate, degradation, and transport of PCE degradation by-products: TCE, 1,2-tDCE, and VC	TechFlowMP—numerical	Jang and Aral (2005, 2007, In press 2007)
Early and late arrival of PCE at WTP	Analysis to assess impact of schedule variation of water-supply well operations on arrival of PCE at wells and the Tarawa Terrace WTP	PSOpS—numerical; optimization	Wang and Aral (2007, In press 2007)
Parameter uncertainty and variability	Assessment of parameter sensitivity, uncertainty, and variability associated with model simulations of ground-water flow, fate and transport, and water distribution	PEST; Monte Carlo simulation—probabilistic	Doherty (2005); Maslia et al. (In press 2007b)
Distribution of PCE in drinking water	Simulation of hydraulics and water quality in water-distribution system serving Tarawa Terrace based on present-day (2004) conditions	EPANET 2—numerical	Rossman (2000); Sautner et al. (In press 2007)

Hadnot Point – Holcomb Boulevard

Table 7.3 lists the analyses and simulation tools (models) used to reconstruct historical contamination events at Hadnot Point and Holcomb Boulevard.

For the Hadnot Point-Holcomb Boulevard (HP-HB) study area the information and data in Table 7.3 were applied to the models in the following sequence:

1. Geohydrologic framework information, aquifer and confining unit hydraulic data, and climatic data were used to determine predevelopment (prior to 1942) groundwater-flow characteristics. Detailed analyses of well and geohydrologic data used to develop the framework of the Brewster Boulevard and Castle Hayne aquifer systems and Tarawa Terrace aquifer are described in Faye (2012).

2. Water-level data were used to characterize groundwater flow in the study area. Detailed water-level data and analyses are presented in Faye et al. (2013).

3. To simulate predevelopment groundwater-flow conditions, the code MODFLOW-2005 (Harbaugh 2005)—a three-dimensional groundwater-flow model code—was used. Estimates of model parameter values also were obtained using the objective parameter estimation code PEST-12 (Doherty 2003, 2010).

4. To simulate the transient (unsteady) effects caused primarily by the onset and continued operation of water-supply wells in the study area, historical water-supply well operating schedules were developed. This was accomplished by documenting water-supply well capacities and histories (Sautner et al. 2013a) and reconstructing operating schedules on a monthly basis for the period 1942–2008 (Telci et al. 2013); operational chronologies for all water-supply wells in the study area are shown in Figure 7.3.

5. Transient groundwater conditions primarily caused by the onset and continued operation of water-supply wells within the HP-HB study area (and the onset of remediation pumping during the late 1990s and 2000s) also were simulated using the MODFLOW three-dimensional groundwater-flow model code; water-supply well operations were accounted for. To address historical water-supply well operations and the absence of nearby hydrologic boundaries, the active model domain (Figure 7.7) was further discretized into two individual variably spaced grid models, one for the Hadnot Point Industrial Area (HPIA) and one for the Hadnot Point Landfill (HPLF). Descriptions and characterizations of the groundwater-flow model discretization properties used to simulate three-dimensional groundwater flow and contaminant fate and transport in the HP-HB study area and comparison with the model used in the TT study area are listed in Table 7.4. A map of the active model domain for groundwater flow and the HPIA and HPLF area subdomain model areas selected for transient groundwater flow and contaminant fate and transport is shown in Figure 7.7.

6. Groundwater velocities or specific discharges derived from the calibrated transient groundwater-flow model were used in conjunction with contaminant source, fate, and property data in the HPIA to simulate the fate and transport of TCE and benzene (as single species) dissolved in groundwater using the model code MT3DMS-5.3 (Zheng and Wang 1999; Zheng 2010). In addition, the fate and transport of PCE and TCE from source areas in the HPLF area to water-supply well HP-651 was simulated using the MT3DMS code. Details pertaining to the fate and transport model calibration and reconstruction of PCE, TCE, and

benzene dissolved in groundwater are provided in Jones et al. (2013). The HPIA and HPLF contaminant fate and transport model subdomain areas, contaminant sources, and nearby historically operated water-supply wells are shown in Figure 7.7 Larger scale maps are shown in Maslia et al. (2013, Figures A13 and A14).

7. The occurrence of benzene as an LNAPL in the subsurface in the vicinity of the HPFF and HPIA is described in Faye et al. (2010 and 2012). Estimates of subsurface LNAPL volume were developed using historical measurements of LNAPL thickness over time—monitor well data—in the HPIA combined with the TechNAPLVol code that uses semi-analytical and numerical methods in a three-dimensional domain (Jang et al. 2013). The resulting saturation profile from the LNAPL volume analysis was used within the TechFlowMP model code (Jang and Aral 2007 2013) to simulate the dissolution of LNAPL constituents and the fate and transport of dissolved-phase benzene. Details pertinent to the application of TechFlowMP to the HPIA subdomain area and historical reconstruction results for the fate and transport of benzene are described in detail by Jang et al. (2013). The historical area of free product (fuel) and location of former fuel lines from the HPFF to other sites within the HPIA are shown in Figure A13 of Maslia et al. (2013).

8. An alternative method, a linear state-space representation of a contaminated aquifer system designated as the linear control model (LCM) methodology, was developed to reconstruct contaminant concentrations in water-supply wells (Guan et al. 2013). Using the model code TechControl, this simplified approach was used to reconstruct historical contaminant concentrations, including PCE, TCE, 1,2-tDCE, and VC, in water-supply well HP-651 in the HPLF area (Figure 7.7). Details pertinent to the development, testing, and application of the LCM methodology are presented in Guan et al. (2013). Results from the LCM application at water-supply well HP-651 are compared to simulated PCE and TCE concentrations obtained using the MT3DMS numerical fate and transport code (item 6, above) later in this report.

9. Reconstructed (simulated) monthly mean concentrations of PCE, TCE, 1,2-tDCE, VC, and benzene for finished water at the HPWTP were determined by using a materials mass balance model (simple mixing) to compute the flow-weighted average concentration of the aforementioned contaminants. This computational method is based on the principles of continuity and conservation of mass (Masters 1998). The use of the materials mass-balance method is justified because all raw water from water-supply wells within the HPWTP service area was mixed at the HPWTP prior to treatment and distribution. Details of this method are described in a subsequent section of this report.

10. Intermittent operations of booster pump 742 and the opening of the Marston Pavilion valve transferred contaminated Hadnot Point finished water to Holcomb Boulevard family housing areas and other facilities (Figure 7.1). Owing to missing data related to pump and valve operations, probabilistic analyses of the intermittent water transfers during the period 1972–1985 were conducted using a Markov analysis (Ross 1977) and the code TechMarkovChain. Results provided probabilistic estimates of the intermittent transfer of contaminated Hadnot Point finished water to the Holcomb Boulevard family housing areas. Details of the application of the TechMarkovChain code to the Hadnot Point-Holcomb Boulevard study area are described in Sautner et al. (2013b).

Table 7.3. Analyses and simulation tools (models) used to reconstruct historical contamination events at Handot Point-Holcomb Boulevard and vicinity (Maslia et al. 2013).

[ft, foot; HPIA, Hadnot Point Industrial Area; HPLF, Hadnot Point landfill; VOC, volatile organic compound; BTEX, benzene, toluene, ethylbenzene, and xylenes; IRP, Installation Restoration Program; AST/UST, above-ground storage tank/underground storage tank; TCE, trichloroethylene; PCE, tetrachloroethylene; GIS, geographic information system; LNAPL, light nonaqueous phase liquid; 1,2-tDCE, *trans*-1,2-dichloroethylene; VC, vinyl chloride; WTP, water treatment plant]

Analysis	Description	Analysis type and simulation tool	[1]Reference
Geohydrologic framework	Detailed analyses of well and geohydrologic data used to develop framework of the Brewster Boulevard and Castle Hayne aquifer systems and Tarawa Terrace aquifer	Data analysis and interpretation	Faye (2012)
Water-level analyses and groundwater flow	Characterizations of water-level data and groundwater flow	Data analysis and interpretation	Faye et al. (2013)
Predevelopment groundwater flow	Steady-state, three-dimensional groundwater flow, occurring prior to initiation of water-supply well activities (1942) using a grid of uniform cells of 300 ft × 300 ft	Simulation using MODFLOW-2005	Harbaugh (2005); Suárez-Soto et al. (2013)
Historical water-supply well operations	Documenting water-supply well capacities, histories, and reconstructing operating schedules on a monthly basis for the period 1942–2008	Data analysis, interpretation, and simulation using TechWellOp	Sautner et al. (2013a); Telei et al. (2013)
Transient groundwater flow	Unsteady-state, three-dimensional groundwater flow occurring primarily because of the initiation and continued operation of water-supply wells (July 1942–June 2008), using a variably spaced grid ranging in area from 300 ft × 300 ft to 50 ft × 50 ft in the HPIA and HPLF model subdomain areas	Simulation using MODFLOW-2005	Harbaugh (2005); Suárez-Soto et al. (2013)
Properties of VOCs in groundwater	Properties of degradation pathways of common organic compounds in groundwater	Literature survey	Lawrence (2007)
Occurrence of selected contaminants in groundwater	Description and summaries of groundwater contaminants of selected VOCs and BTEX components at IRP and AST/UST sites; listing of water-supply and monitor well location and construction data	Data analysis	Faye et al. (2010, 2012)
Computation of mass for PCE, TCE, and benzene	Estimates of mass (volume) of TCE, PCE, and benzene in groundwater using field data and a variety of analytical and numerical techniques (Tables A6, A15, and A16)	Site investigation data, GIS spatial analyses, LNAPL volume analyses (TechNAPLVol)	Ricker (2008); Faye et al. (2010, 2012); Jones et al. (2013); Jang et al. (2013)
Fate and transport of TCE, PCE, and benzene	Simulation of the fate and migration of TCE and benzene from sources in the HPIA; simulation of the fate and migration of PCE from the HPLF	Simulation using MT3DMS-5.3	Zheng and Wang (1999); Zheng (2010); Jones et al. (2013)
Fate and transport of benzene (LNAPL)	Simulation of the fate and migration of benzene as an LNAPL from sources at the Hadnot Point fuel farm in the HPIA	Simulation using TechFlowMP	Jang and Aral (2007, 2008a, b); Jang et al. (2013)
Concentrations of PCE, TCE, 1,2-tDCE, and VC in a water-supply well	Reconstructing concentrations of PCE, TCE, 1,2-tDCE, and VC in water-supply well HP-651 (HPLF) using a linear control model (LCM) methodology	Simulation using TechControl	Guan et al. (2009, 2010, 2013)
TCE, PCE, 1,2-tDCE, VC, and benzene in WTP finished water	Computations of concentrations of TCE, PCE, 1,2-tDCE, VC, and benzene in drinking water from the Hadnot Point WTP using results from fate and transport and linear control model simulations	Materials mass balance model using principles of conservation of mass and continuity—algebraic	Masters (1998); Jones et al. (2013)
Parameter sensitivity and uncertainty	Assessment of parameter sensitivity and uncertainty associated with model simulations of groundwater flow, fate and transport, and water distribution	One-at-a-time sensitivity analysis (OAT), Monte Carlo (MC) simulation using Latin hypercube sampling (LHS), and MC simulation	Saltelli et al. (2000); Suárez-Soto et al. (2013); Jones et al. (2013); Sautner et al. (2013b)
Intermittent pump operation for transfer of finished water	Probabilistic analysis of the occurrence of pumping operations during the period 1972–1985 for transferring Hadnot Point finished water to Holcomb Boulevard housing areas	Probabilistic Markov analysis using TechMarkovChain	Ross (1977); Sautner et al. (2013b)
Distribution of TCE, PCE, 1,2-tDCE, VC, and benzene throughout the Holcomb Boulevard housing areas	Simulation of hydraulics and water quality in the water-distribution system serving the Holcomb Boulevard housing areas, 1972–1985; intermittent pumping operations estimated by using data and Markov analysis	Simulation using EPANET 2	Rossman (2000); Sautner et al. (2013b)

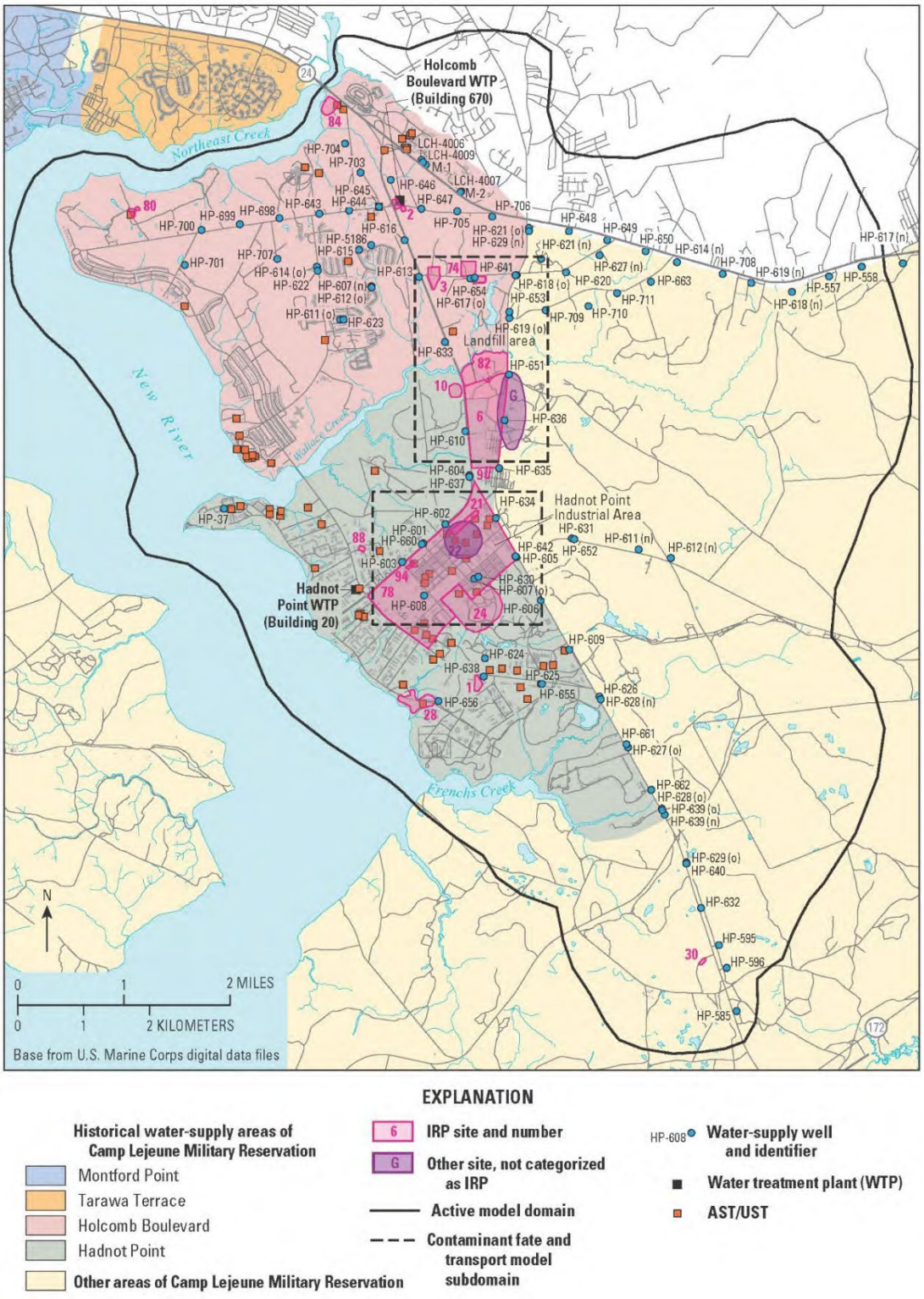


Figure 7.7. Groundwater-flow model domain and contaminate fate and transport model subdomains for the Hadnot Point Industrial Area (HPIA) and Hadnot Point landfill (HPLF). (Maslia et al. 2013).

Table 7.4. Description and characteristics of model properties used to simulate three-dimensional groundwater flow and contaminant fate and transport, Hadnot Point- Holcomb Boulevard and Tarawa Terrace study areas (Maslia et al. 2013).

[ft, foot; mi², square mile; TCE, trichloroethylene; PCE, tetrachloroethylene; —, not applicable]

Model feature	[1]Hadnot Point–Holcomb Boulevard study area					[4]Tarawa Terrace study area
	[2]Uniform grid	[3]Variably spaced grid		Fate and transport model subdomain		
		Hadnot Point Industrial Area	Hadnot Point landfill area	Hadnot Point Industrial Area	Hadnot Point landfill area	
Number of rows	152	288	348	132	204	200
Number of columns	172	298	268	168	132	270
Number of layers	7	7	7	7	7	7
Total number of finite-difference cells	183,008	600,768	652,848	155,232	188,496	378,000
Number of active domain or subdomain cells	108,695	453,654	532,287	155,232	188,496	191,927
Finite-difference cell size (ft×ft)	300×300	300×300–50×50	300×300–50×50	50×50	50×50	50×50
Total model or subdomain area (mi²)	84	84	84	2.0	2.4	4.8
Active domain area (mi²)	50	50	50	2.0	2.4	2.5
Contaminant-source areas (contaminants)	—	—	—	Building 900 (TCE); Building 1115 (TCE); Building 1401 (TCE); Building 1601 (TCE, benzene)[5]	Hadnot Point landfill (PCE, TCE)	ABC One-Hour Cleaners (PCE)

[1] Groundwater-flow simulation using MODFLOW-2005 (Harbaugh 2005); fate and transport simulation using MT3DMS (Zheng and Wang 1999); see Figure A12 for locations of active model boundaries and contaminant fate and transport model subdomains

[2] Uniform grid of 300-ft×300-ft cells used for simulating and calibrating predevelopment (steady-state) groundwater flow

[3] Variably spaced grid used for simulating and calibrating transient groundwater flow and contaminant fate and transport

[4] Groundwater-flow simulation using MODFLOW-96 (Harbaugh and McDonald 1996); fate and transport simulation using MT3DMS (Zheng and Wang 1999); uniform and coincident grids used for groundwater-flow and fate and transport simulations, refer to Maslia et al. (2007), Faye and Valenzuela (2007), and Faye (2008)

[5] Benzene occurs as a light nonaqueous phase liquid (LNAPL) at Building 1115 and at the Hadnot Point fuel farm (HPFF); see Jang et al. (2013) for modeling details.

11. Using the reconstructed monthly mean concentrations of PCE, TCE, 1,2-tDCE, VC, and benzene in finished water from the HPWTP and the Markov analysis to estimate the occurrence of intermittent water transfers, extended period simulations (EPS) of hydraulics and water quality for the water-distribution system serving the HB housing areas and other facilities during the period 1972–1985 were conducted using the model code EPANET 2 (Rossman 2000). Details pertaining to these analyses are presented in Sautner et al. (2013b) and are summarized in a subsequent section of this report.

Assessment of parameter sensitivity, variability, and uncertainty associated with model simulations of groundwater flow, contaminant fate and transport, and water-distribution system analyses were conducted using (1) one-at-a-time (and a variation of the one-at-a-time) sensitivity analysis (Saltelli et al. 2000),(2) Monte Carlo simulation (Tung and Yen 2005), and (3) the parameter estimation code PEST (Doherty 2003, 2010). Details relevant to the application of parameter estimation and sensitivity and uncertainty analyses for the HP-HB study area models are provided in Guan et al.

(2013), Jang et al. (2013), Jones et al. (2013), Sautner et al. (2013b), and Suárez-Soto et al. (2013), and are summarized in subsequent sections of this report.

Because all water-supply wells for TT mixed at the TTWTP before finished water was distributed throughout the water-distribution system network and all water-supply wells for HP were mixed at the HPWTP before finished water was distributed throughout the water-distribution system network, ATSDR determined that a simple-mixing model approach using flow-weighted mixing consisting of equations for continuity and conservation of mass (Masters 1998; Maslia et al. 2007) could be used to reconstruct contaminant concentrations within the water-distribution systems. Using the simple mixing-model approach, for any given month during the historical reconstruction period, PCE and TCE concentrations of finished water at the TTWTP and HPWTP, respectively, were computed using the following equations:

$$Q_T = \sum_{i=1}^{NWP} Q_i \qquad (7.1)$$

and

$$C_{WTP} = \frac{\sum_{i=1}^{NWP} C_i Q_i}{Q_T} \qquad (7.2)$$

where:

NWP is the number of water-supply wells simulated as operating (pumping) during the month of interest,

Q_i is the simulated groundwater pumping rate of water-supply well *i*,

Q_T is the total simulated groundwater pumping rate from all operating water-supply wells during the month of interest,

C_i is the simulated concentration for water-supply well *i*, and

C_{WTP} is the concentration of finished water delivered from the TTWTP or HPWTP to the respective distribution systems for the month of interest.

Equation (7.1) is known as the continuity equation and Equation (7.2) describes the conservation of mass (Masters 1998). The assumptions for using the simple mixing model approach are: (1) mixing is instantaneous and uniform, (2) average steady-state conditions during each particular month, and (3) contaminants are conservative (no degradation or decay within the WTP and water-distribution system). A schematic representation comparing the simple-mixing model approach with the more complex network representation used by EPANET is shown in Figure 7.8A and 7.8B, respectively.

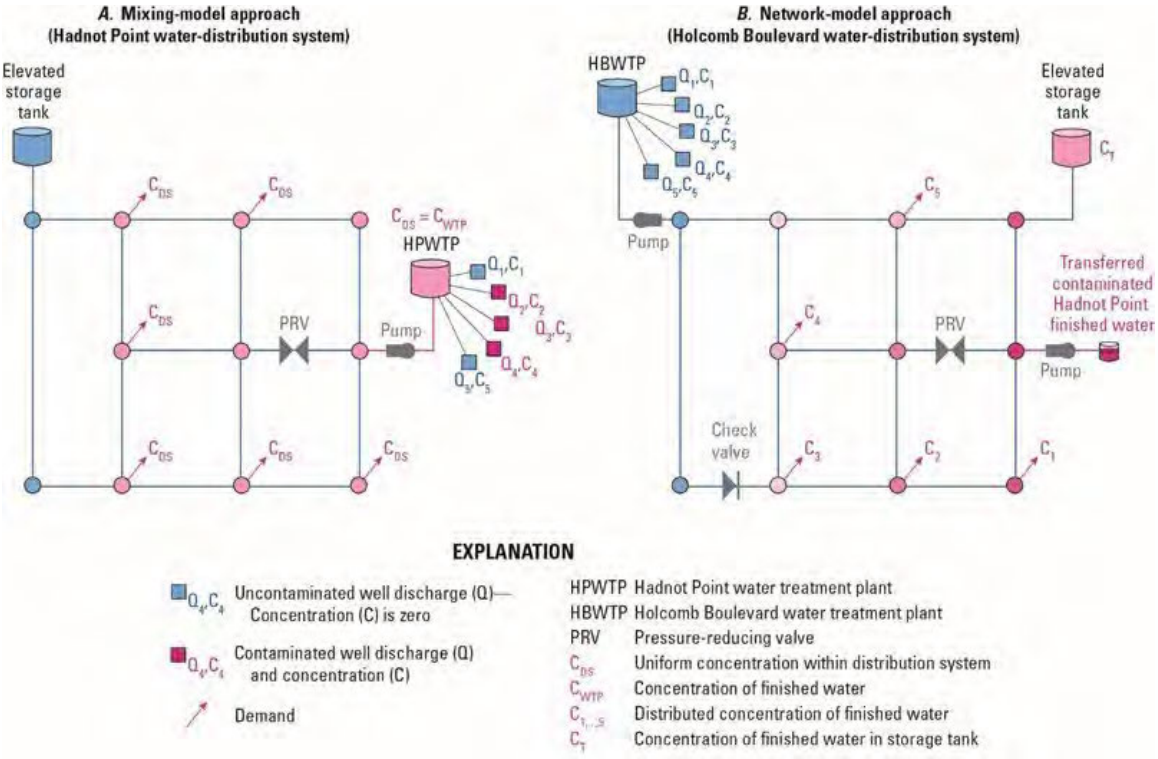


Figure 7.8. Schematic node-link representations for water-distribution systems: *(A)* mixing-model approach used for the Tarawa Terrace and Hadnot Point water treatment plant analyses and *(B)* network-model approach used for the Hadnot Point and Holcomb Boulevard interconnection analyses (Maslia et al. 2013).

To test the appropriateness of this assumption (simple mixing at the WTPs), results of a simulation for December 1984 conditions based on using the mixing model and the water-distribution system model approaches are described in Maslia et al (2009b, Table I4). These results demonstrated that after 7 days, the mixing model and the spatially derived EPANET (Rossman 1994) concentrations of PCE for TT were equivalent—even at the furthest extent of the water-distribution system (Montford Point area, Maslia et al. 2009b, Figure I3). These results confirmed the appropriateness of the decision to use the simple mixing model approach for estimating (reconstructing) PCE and TCE concentrations in finished water delivered to the Tarawa Terrace and Hadnot Point areas from the TTWTP and HPWTP, respectively.

Because of the interconnection of the HP and HB water-distribution systems, a more complex analysis was necessary compared to the simple mixing-model approach (Figure 7.8) described by Equations (7.1) and (7.2). This more complex numerical analysis was used to determine the concentration of finished water in the HB water-distribution system during periods of interconnection. This required the application of the EPANET (version 2 or EPANET 2) water-distribution system model (Rossman 2000) and extended period simulation (EPS). The EPANET water-distribution system model was calibrated for the HB water-distribution system using field data collected by the ATSDR water-modeling team; field data represented operational conditions

during 2004 (Sautner et al. 2013b). EPSs were used to reconstruct water-distribution system flow and mass transport patterns during discrete interconnection events (Maslia et al. 2013, Figure A28) when booster pump 742 (Figure 7.1) was intermittently operated, resulting in the transfer of contaminated finished water from the HP water-distribution system to the "uncontaminated" HB water-distribution system. Pipelines represented in the water-distribution system network model coincide with locations of streets within the HP-HB study area (Maslia et al. 2009b, Figure I3; Sautner et al. 2013b).

7.4.4 Model Calibration, Sensitivity, and Uncertainty

ATSDR utilized a stepwise or hierarchical, four-level calibration process (Maslia et al. 2007, Faye and Valenzuela, 2007; Faye, 2008; Maslia et al. 2013) whereby groundwater-flow and contaminant fate and transport models of TT and HP-HB were calibrated to available historical field data. Level 1 of the calibration was for a steady-state (pre-development) groundwater-flow model. Level 2 calibration was for the transient (pumping conditions), and Level 3 of the calibration was for the fate and transport of PCE and/or TCE from contaminant sources (ABC One-Hour Cleaners, HPIA, and HPLF) to water-supply wells at USMCB Camp Lejeune supplying water to the TTWTP and the HPTWP. The Level 4 calibration was essentially a confirmation of or testing a "goodness of fit" of the previous three levels of calibration because in Level 4, measured PCE and TCE concentrations at the WTPs were compared to the flow-weighted mixing model used to compute the monthly mean concentrations at the TTWTP and the HPWTP (refer to section 7.4.3 of this report and Equations 7.1 and 7.2). That is, the measured WTP water-quality samples of PCE and TCE were **never used** to adjust **any model parameters**, but rather, to **test the adequacy** of the groundwater-flow, contaminant fate and transport, and flow-weight mixing models. Discussion of the results of the calibration process is contained in section 7.5 below.

Best modeling practice requires that evaluations be conducted to ascertain confidence in models and model results by assessing parameter sensitivity, variability, and uncertainty associated with the modeling process and with the outcomes attributed to models (ASTM International 1994; Saltelli et al. 2000). There are numerous methods for characterizing a model's sensitivity and uncertainty based on variations of calibrated parameter values (ASTM International 1994, Cullen and Frey 1999, Saltelli et al. 200, Tung and Yen 2005, Hill and Tiedeman 2007). These methods are generally classified into two groups: (1) sensitivity analysis, wherein calibrated model parameter values are varied either manually or through some automated method and (2) probabilistic uncertainty analysis, wherein probabilistic methods are used to characterize and quantify the input and output parameter variation and uncertainty. Substantial numbers of sensitivity analyses (using a one-at-a-time method) and uncertainty analyses (using Monte Carlo simulation (MCS)) were conducted as part of the Camp Lejeune historical reconstruction analysis. These analyses and results are presented below; readers are referred to Maslia et al. (2007; 2013) for additional specific details and results. An example of a probabilistic uncertainty analysis for the finished-water concentrations at the TTWTP is shown in Figure A26 (Maslia et al. 2007, p. A60). Based on these analyses, for the TT study area, reconstructed drinking-water concentrations of PCE varied within a range of about 3 or less for all the MCS relative to the calibrated single values (Figure A26). For the HP-HB study areas, reconstructed drinking-water concentrations of TCE ranged by a factor of about 10 or less (Maslia et al. 2013, Figure A41).

7.5 Historical Reconstruction Analyses and Results

Details of historical reconstruction analyses and results are described in substantial detail in peer-reviewed ATSDR reports for the TT, HP, and HB areas. Reports describing geohydrologic data, hydrogeologic data, water supply data, analyses and results are presented Tables 7.5 and 7.6 for the TT and HP-HB study areas, respectively.

- **Tarawa Terrace and Vicinity**

Table 7.5. Reports describing geohydrologic data, hydrogeologic data, water-supply data, analyses and results for the Tarawa Terrace study area.

Year of Publication	ATSDR Report (Publication)	Reference Citation
2007	Chapter A: Summary of Findings	Maslia et al. (2007)
2007	Chapter B: Geohydrologic Framework of the Castle Hayne Aquifer System	Faye (2007)
2007	Chapter C: Simulation of Three-Dimensional Groundwater Flow	Faye and Valenzuela (2007)
2007	Chapter D: Properties of Degradation Pathways of Common Organic Compounds in Groundwater	Lawrence (2007)
2007	Chapter E: Occurrence of Contaminants in Groundwater	Faye and Green, Jr. 2007)
2008	Chapter F: Simulation of the Fate and Transport of Tetrachloroethylene (PCE)	Faye (2008)
2008	Chapter G: Simulation of Three-Dimensional, Multispecies Mass Transport of Tetrachloroethylene (PCE) and Associated Degradation By-Products	Jang and Aral (2008)
2008	Chapter H: Effect of Groundwater Pumping Schedule Variation on Arrival of Tetrachloroethylene (PCE) at Water-Supply Wells and the Water Treatment Plant	Wang and Aral (2008)
2009	Parameter Sensitivity, Uncertainty, and Variability Associated with Model Simulations of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water	Maslia et al. (2009b)

- **Hadnot Point, Holcomb Boulevard and Vicinity**

Table 7.6. Reports describing geohydrologic data, hydrogeologic data, water-supply data, analyses and results for the Hadnot Point-Holcomb Boulevard study area.

Year of Publication	ATSDR Report (Publication)	Reference Citation
2013	Chapter A: Summary of Findings	Maslia et al. (2013)
2013	Chapter A–Supplement 1: Descriptions and Characterizations of Data Pertinent to Water Supply, Well Capacities, Histories, and Operations	Sautner et al. (2013a)
2013	Chapter A–Supplement 2: Development and Application of a Methodology to Characterize Present-Day and Historical Water-Supply Well Operations	Telci et al. (2013)
2013	Chapter A–Supplement 3: Descriptions and Characterization of Water-Level Data and Groundwater Flow for the Brewster Boulevard and Castle Haye Aquifer Systems and the Tarawa Terrace Aquifer	Faye et al. (2013)
2013	Chapter A–Supplement 4: Simulation of Three-Dimensional Groundwater Flow	Suárez-Soto et al. (2013)
2013	Chapter A–Supplement 5: Linear Control Methodology to Reconstruct Contaminant Concentrations at Selected Water-Supply Wells	Guan et al. (2013)
2013	Chapter A–Supplement 6: Simulation of Fate and Transport of Selected Volatile Organic Compounds in the Vicinities of the Handot Point Industrial Area and Landfill	Jones et al. (2013)
2013	Chapter A–Supplement 7: Source Characterization and Simulation of the Migration of Light Nonaqueous Phase Liquids (LNAPLs) in the Vicinity of eh Hadnot Point Industrial Area	Jang et al. (2013)
2013	Chapter A–Supplement 8: Field Tests, Data Analyses, and Simulation of the Distribution of Drinking Water with Emphasis on intermittent Transfers of Drinking Water between the Handot Point and Holcomb Boulevard Water-Distribution Systems	Sautner et al. (2013b)
2012	Chapter B: Geohydrologic Framework of the Brewster Boulevard and Castle Hayne Aquifer System and Tarawa Terrace Aquifer	Faye (2012)[8]
2010	Chapter C: Occurrence of Selected Contaminants in Groundwater at Installation Restoration Sites	Faye et al. (2010)
2012	Chapter D: Occurrence of Selected Contaminants in Groundwater at Above Ground and Underground Storage Tank Sites	Faye et al. (2012)

Historical reconstruction results for TT, HP, and HB are summarized below. Specific details can be found in the peer-reviewed ATSDR reports listed above and available online at the ATSDR website: https://www.atsdr.cdc.gov/sites/lejeune/Water-Modeling.html.

[8] In December 2011, ATSDR released the HP-HB Chapter B report (Geohydrologic Framework of the Brewster Boulevard and Castle Hayne Aquifer Systems and the Tarwa Terrace Aquifer). On January 5, 2012, ATSDR received a letter from the USMC (written communication from Major General J. A. Kessler, USMC to Dr. Thomas Sinks, Deputy Director, ATSDR) requesting ATSDR to address security concerns related to identification of coordinate locations of active drinking water-supply wells (based on 18 U.S.C. 795(a)). In January 2012, ATSDR publicly released a **redacted** version of the HP-HB Chapter B report (Faye 2012). The unredacted version of the Chapter B report was externally peer reviewed like all ATSDR Camp Lejeune reports. References in this expert report to Faye (2012) are to the **redacted** HP-HB Chapter B report.

7.5.1 Tarawa Terrace (TT)

As discussed in Section 7.4.4 (Calibration, Sensitivity, and Uncertainty) above, ATSDR utilized a four-level calibration process (Maslia et al. 2007, Faye and Valenzuela, 2007; Faye, 2008) whereby groundwater-flow and contaminant fate and transport models for Tarawa Terrace were calibrated in a hierarchical, stepwise approach to available historical field data (Maslia et al. 2007, Figure A9). At each hierarchical level, an initial calibration target or "goodness of fit" criterion was selected based on the availability, method of measurement or observation, and overall reliability of field data and related information. Once model-specific parameters were calibrated, statistical and graphical analyses were conducted to determine if selected parameters met calibration criteria targets. Summaries of calibration targets and resulting calibration statistics for each of the four hierarchical levels are listed in Table 7.7.

Table 7.7. Summary of calibration targets and resulting calibration statistics for models used to reconstruct historical contamination events at Tarawa Terrace and vicinity (Maslia et al. 2007).

Calibration level[1, 2]	Analysis type	Calibration target[3]	Resulting calibration statistics[4]	[5]Number of paired data points (N)
1	Predevelopment (no pumping) groundwater flow	Magnitude of head difference: 3 feet	$\lvert\overline{\Delta h}\rvert$ = 1.9 ft σ = 1.5 ft *RMS* = 2.1 ft	59
2	Transient groundwater flow—monitor wells	Magnitude of head difference: 3 feet	$\lvert\overline{\Delta h}\rvert$ = 1.4 ft σ = 0.9 ft *RMS* = 1.7 ft	263
	Transient groundwater flow—supply wells	Magnitude of head difference: 12 feet	$\lvert\overline{\Delta h}\rvert$ = 7.1 ft σ = 4.6 ft *RMS* = 8.5 ft	526
3	Contaminant fate and transport—supply wells	Concentration difference: ± one-half order of magnitude or model bias (B_m) ranging from 0.3 to 3	Geometric bias [6]B_g = 5.8/3.9	[7]36
4	Mixing model—treated water at water treatment plant	Concentration difference: ± one-half order of magnitude or model bias (B_m) ranging from 0.3 to 3	Geometric bias B_g = 1.5	[8]25

[1]Refer to the Chapter C report (Faye and Valenzuela In press 2007) for calibration procedures and details on levels 1 and 2

[2]Refer to the Chapter F report (Faye In press 2007b) for calibration procedures and details on levels 3 and 4

[3]Head difference is defined as observed water level (h_{obs}) minus simulated water level (h_{sim}); Magnitude of head difference is defined as: $|\Delta h| = |h_{obs} - h_{sim}|$; a concentration difference of ± one-half order of magnitude equates to a model bias of 0.3 to 3, where, B_m = model bias and is defined as: $B_m = C_{sim}/C_{obs}$, where C_{sim} is the simulated concentration and C_{obs} is the observed concentration; when $B_m = 1$, the model exactly predicts the observed concentration, when $B_m > 1$, the model overpredicts the concentration, and when $B_m < 1$, the model underpredicts the concentration

[4]Average magnitude of head difference is defined as: $\overline{|\Delta h|} = \frac{1}{N}\sum_{i=1}^{N}|\Delta h_i|$; standard deviation of head difference is defined as: $\sigma = \sqrt{\frac{\sum_{i=1}^{N}\left(\Delta h_i - \overline{\Delta h}\right)^2}{N-1}}$, where $\overline{\Delta h}$ is the mean or average of head difference; root-mean-square of head difference is defined as: $RMS = \left[\frac{1}{N}\sum_{i=1}^{N}\Delta h_i^2\right]^{\frac{1}{2}}$; geometric bias, B_g, is defined as: $B_g = \exp\left[\frac{\sum_{i=1}^{N}\ln\left(B_{m,i}\right)}{N}\right]$, where ln ( ) is the Naperian logarithm

[5]A paired data point is defined as any location with observed data that is associated with a model location for the purpose of comparing observed data with model results for water level or concentration

[6]B_g = 5.8 computed using all water-supply wells listed in table A9; B_g = 3.9 computed without considering water-supply well TT-23—See text for explanation

[7]Observed concentration of 17 samples recorded as nondetect (see Table A9) and are not used in computation of geometric bias

[8]Observed concentration of 15 samples recorded as nondetect (see Table A10) and are not used in computation of geometric bias

Level 1 Calibration (Predevelopment Conditions)

Level 1 calibration of the Tarawa Terrace groundwater-flow model (details provided in Maslia et al. 2007, p.A24–A31) was accomplished by successfully simulating estimated predevelopment conditions; that is, flow and water-level conditions prior to development of the underlying aquifers by wells. Predevelopment conditions are considered representative of long-term, average annual flow and water-level conditions within the Tarawa Terrace aquifer and the Upper Castle Hayne aquifer system at Tarawa Terrace and vicinity. Criteria used to determine a satisfactory predevelopment calibration were: (1) conformance of simulated conditions to the conceptual groundwater-flow model and (2) a satisfactory comparison of simulated and observed (measured) water levels within the active model domain. A scatter diagram showing the agreement between simulated and observed water levels for simulated predevelopment conditions is shown in Figure 7.9. The flow model (MODFLOW-96) spatially interpolates simulated results from cell centers to the location coordinates assigned to various observation points, such as well locations, to facilitate direct comparisons of simulated and observed conditions. All Tarawa Terrace water-supply wells and several monitor wells are open to multiple aquifers. At these sites, simulated water levels were processed post-calibration by proportioning simulated water levels in several aquifers at multiaquifer wells to compute a composite water level. This composite water level was then compared to the observed water level to evaluate calibration "goodness of fit."

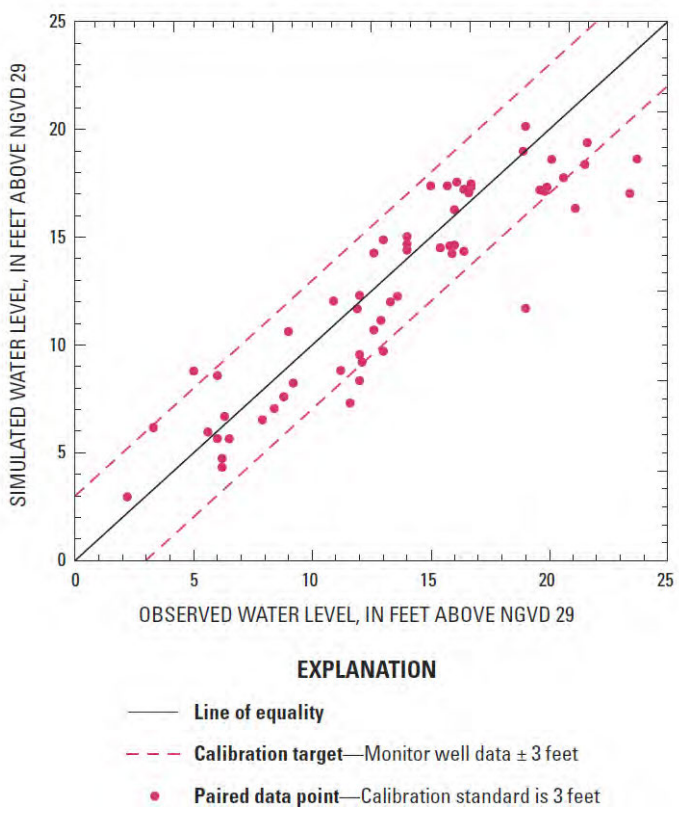


Figure 7.9. Simulated and observed predevelopment water levels, Tarawa Terrace and vicinity (Faye and Valenzuela 2007).

When the data points plot near or on the solid diagonal "line of equality," the simulated and measured water levels are the same. When the data points plot above the solid line, the simulated values are higher than the measured values, and when the data points plot below the solid line, the simulated values are lower than the measured values. The dashed lines correspond to the desired range (calibration goal) of values about the equality line. The input parameter values are systematically varied to minimize the deviation about the line of equality while maximizing the data points within the target range about the line of equality.

Level 2 Calibration (Transient Conditions)

Details of the Level 2 calibration are described in the ATSDR TT Chapter C report by Faye and Valenzuela (2007). Calibration of the transient flow model was achieved using pumpage (Tables C8 and C9), water-level (Appendix C1, Tables C1.1– C1.11), and well capacity (Appendix C3, Tables C3.1– C3.10) data collected at Tarawa Terrace and vicinity (Faye and Valenzuela 2007). An indication of gross model calibration is shown in the scatter diagram of Figure 7.10. Paired data shown within the bottom half of the diagram generally correspond to water-supply well data. Paired data within the upper part of the diagram generally correspond to data listed. The average absolute difference between simulated and observed water levels for 789 paired water levels shown in Figure 7.10 is 5.2 ft. The root-mean-square error of the absolute differences is 7.0 ft.

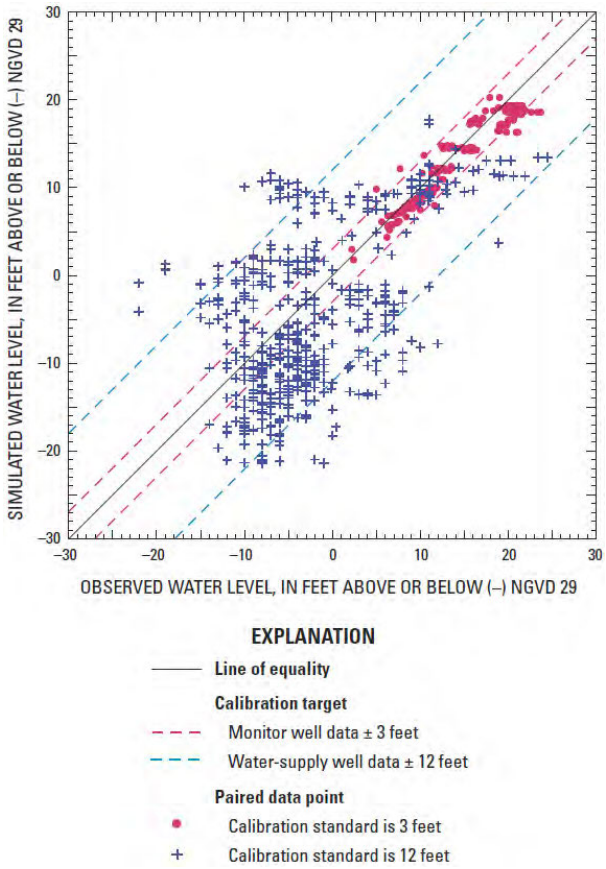


Figure 7.10. Simulated and observed transient water levels, Tarawa Terrace and vicinity (Faye and Valenzuela 2007).

Input parameters are calibrated to minimize deviations between simulated and observed elevations. It should be noted that four decades of data were available for this calibration (1951-1994). Figure 7.10 demonstrates that the groundwater flow model (calibration Levels 1 and 2) has been successfully calibrated to produce reconstructed values in close agreement with measured values. Table 7.8 lists the calibrated model parameter values used for simulating groundwater flow at TYT and vicinity.

Table **7.8**. Calibrated model parameter values used for simulating groundwater flow and contaminant fate and transport, Tarawa Terrace and vicinity (Faye 2008).

[ft/d, foot per day; ft^3/d, cubic foot per day; ft^3/g, cubic foot per gram; g/ft^3, gram per cubic foot; d^{-1}, 1/day; g/d, gram per day; ft, foot; ft^2/d, square foot per day; —, not applicable]

Model parameter[1]	Model layer number[2]						
	1	2	3	4	5	6	7
Predevelopment groundwater-flow model (conditions prior to 1951)							
Horizontal hydraulic conductivity, K_H (ft/d)	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[3]	1:7.3	1:10	1:8.3	1:10	1:10	1:10	1:10
Infiltration (recharge), I_R (inches per 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 (inches per year)	6.6–19.3	—	—	—	—	—	—
Pumpage, Q_k (ft^3/d)	See footnote[4]	—	See footnote[4]	—	0	—	0
Fate and transport of tetrachloroethylene (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_E	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[5], q_sC_s (g/d)	1,200	—	—	—	—	—	—
Longitudinal dispersivity, α_L (ft)	25	25	25	25	25	25	25
Transverse 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/d)	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}

[1] Symbolic notation used to describe model parameters obtained from Chiang and Kinzelbach (2001)

[2] 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

[3] For model cells simulating water-supply wells, vertical hydraulic conductivity (K_V) equals 100 feet per day to approximate the gravel pack around the well

[4] Pumpage varies by month, year, and model layer; refer to Chapter K report (Maslia et al. In press 2008) for specific pumpage data

[5] Introduction of contaminant mass began January 1953 and terminated December 1984

Level 3 Calibration (Contaminant Fate and Transport)

The hydraulic characteristic and recharge arrays of the MODFLOW-96 flow model assigned following the Level 2 calibration were not adjusted during Level 3 calibration. Initial values of several transport parameters were modified during trial-and-error calibration and are described in the TT Chapter F report (Faye 2008). Final calibrated parameter values are listed in Table 7.8. Level 3 model calibration was achieved by comparing simulated PCE concentrations at TT water-supply wells to corresponding observed concentrations. Simulated PCE concentrations were computed at the end of each stress period and were considered representative of an average (mean) concentration for the respective month. Field data (observed PCE concentrations) were compared to the simulated concentration closest in time (days) to the simulated day.

Figure 7.11 shows a plot for simulated and observed PCE concentrations in TT water-supply wells (Level 3 calibration), demonstrating the ability of the contaminant migration (fate and transport) modeling to reproduce contaminant concentrations in the individual water-supply wells. In this graph, points plotting above the line of equality correspond to simulated values higher than measured values. In contrast, values plotting below the line represent simulated values lower than measured values. It is observed that the simulated concentrations tended to overestimate lower measured concentrations while underestimating the highest observed concentrations. Although model calibration could have resulted in a line of equality with more data points closer to equality, doing so would have meant that the highest simulated concentrations would have been underestimated even more. Thus, the Level 3 calibration minimized the overall deviations between measured and observed values.

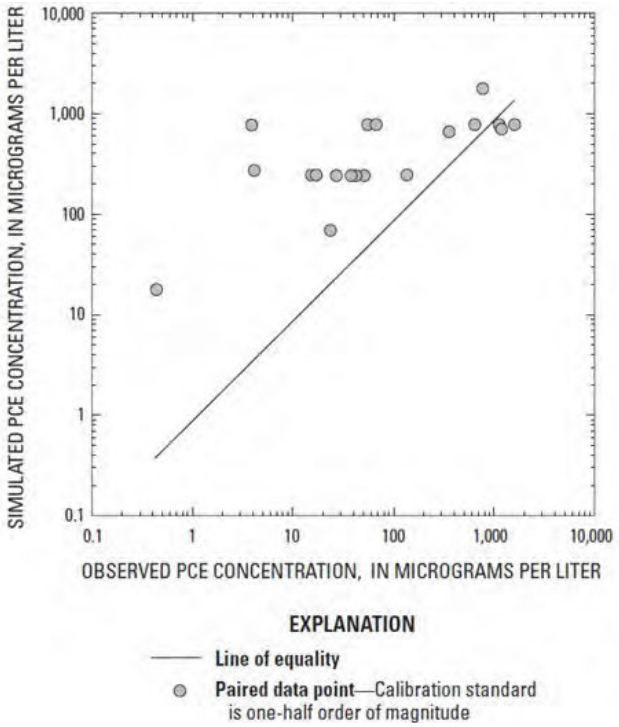


Figure 7.11. Simulated and observed tetrachloroethylene (PCE) concentrations at selected water-supply wells, Tarawa Terrace and vicinity (Faye 2008).

Table 7.9. Summary of reconstructed (simulated) values and observed data of tetrachloroethylene (PCE) at water-supply wells, Tarawa Terrace (Maslia et al. 2007).

[PCE, tetrachloroethylene; µg/L, microgram per liter; J, estimated; ND, nondetect]

Model-derived value		Observed data				
Month and year	PCE concentration, in µg/L	Sample date	PCE concentration, in µg/L	Detection limit, in µg/L	Calibration targets[2], in µg/L	Sample number[3]
Supply well TT-23						
January 1985	254	1/16/1985	132	10	41.7–417	1
February 1985	253	2/12/1985	37	10	11.7–117	2
February 1985	253	2/19/1985	26.2	2	8.3–82.9	3
February 1985	253	2/19/1985	ND	10	1–10	4
March 1985	265	3/11/1985	14.9	10	4.7–47.1	5
March 1985	265	3/11/1985	16.6	2	5.2–52.5	6
March 1985	265	3/12/1985	40.6	10	12.8–128	7
March 1985	265	3/12/1985	48.8	10	15.4–154	8
April 1985	274	4/9/1985	ND	10	1–10	9
September 1985	279	9/25/1985	4J	2	1.3–12.6	10
July 1991	191	7/11/1991	ND	10	1–10	11
Supply well TT-25						
February 1985	7.3	2/5/1985	ND	10	1–10	12
April 1985	9.6	4/9/1985	ND	10	1–10	13
September 1985	18.1	9/25/1985	0.43J	10	0.14–1.4	14
October 1985	20.4	10/29/1985	ND	10	1–10	15
November 1985	22.8	11/4/1985	ND	10	1–10	16
November 1985	22.8	11/12/1985	ND	10	1–10	17
December 1985	25.5	12/3/1985	ND	10	1–10	18
July 1991	72.7	7/11/1991	23	10	7.3–72.7	19
Supply well TT-26						
January 1985	804	1/16/1985	1,580.0	10	500–4,996	20
January 1985	804	2/12/1985	3.8	10	1.2–12	21
February 1985	798	2/19/1985	64.0	10	20.2–202	22
February 1985	798	2/19/1985	55.2	10	17.5–175	23
April 1985	801	4/9/1985	630.0	10	199–1,992	24
June 1985	799	6/24/1985	1,160.0	10	367–3,668	25
September 1985	788	9/25/1985	1,100.0	10	348–3,478	26
July 1991	670	7/11/1991	350.0	10	111–1,107	27
Supply well TT-30						
February 1985	0.0	2/6/1985	ND	10	1–10	28
Supply well TT-31						
February 1985	0.17	2/6/1985	ND	10	1–10	29
Supply well TT-52						
February 1985	0.0	2/6/1985	ND	10	1–10	30
Supply well TT-54						
February 1985	6.0	2/6/1985	ND	10	1–10	31
July 1991	30.4	7/11/1991	ND	5	1–5	32
Supply well TT-67						
February 1985	4.1	2/6/1985	ND	10	1–10	33
Supply well RW1						
July 1991	0.0	7/12/1991	ND	2	1–2	34
Supply well RW2						
July 1991	879	7/12/1991	760	2	240–2,403	35
Supply well RW3						
July 1991	0.0	7/12/1991	ND	2	1–2	36

Selected Simulation Results: Tarawa Terrace

Examples of simulated results (reconstructed PCE concentrations) in groundwater for model layer 1 are shown as a series of maps (Figure 7.12 A–D) for January 1958, January 1968, December 1984, and December 1994, respectively. These maps show the areal spread of PCE within model layer 1 under the influence of pumping wells (Figure 7.12 A–C) and under no-pumping conditions (Figure 7.12D) once all water-supply wells were removed from service by March 1987. Table 7.9 lists a summary of reconstructed (simulated) values and observed data of PCE at TT water-supply wells.

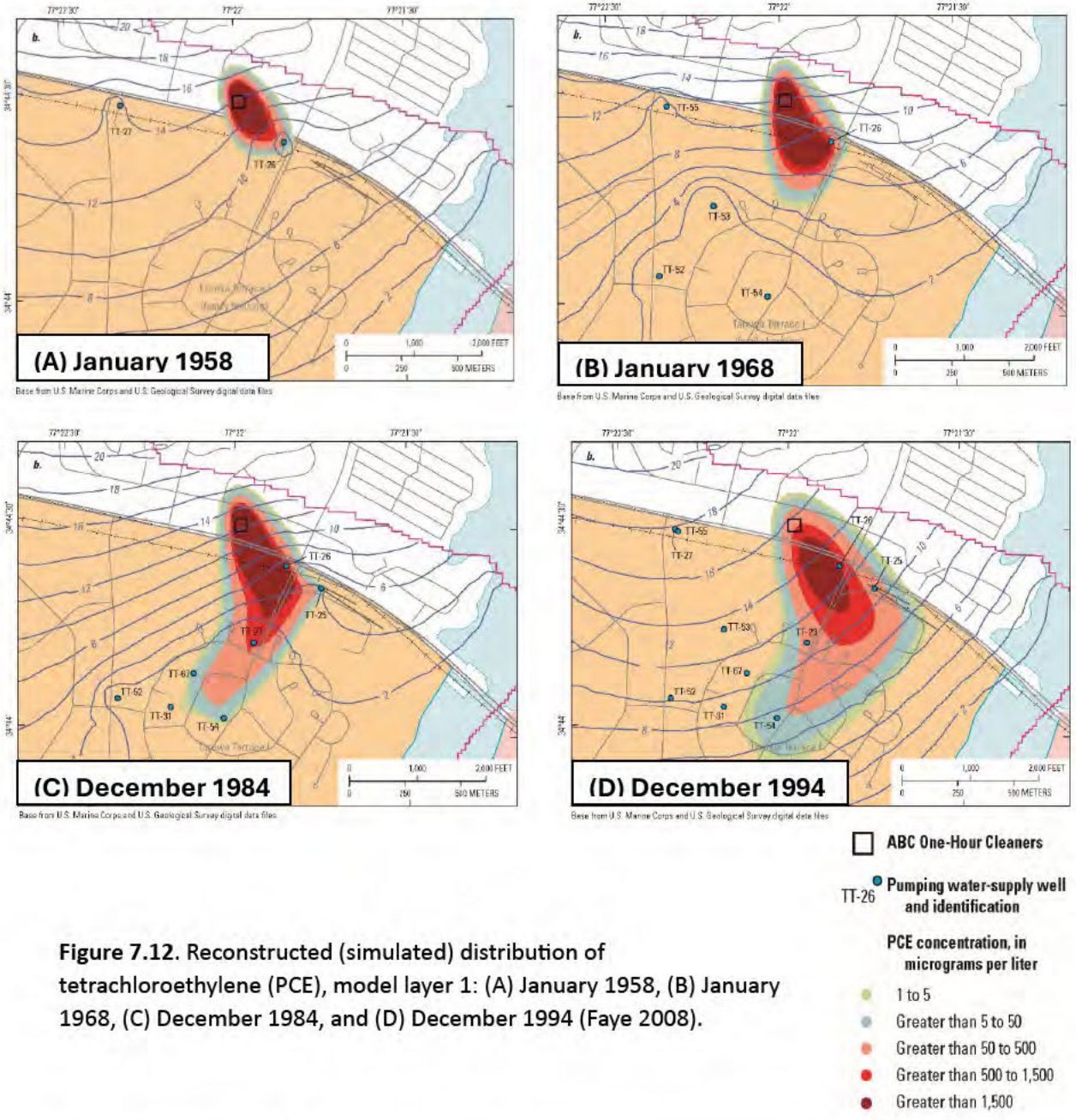


Figure 7.12. Reconstructed (simulated) distribution of tetrachloroethylene (PCE), model layer 1: (A) January 1958, (B) January 1968, (C) December 1984, and (D) December 1994 (Faye 2008).

January 1958

With the onset of simulated pumping at water-supply well TT-26 during January 1952, local cones of depression developed around all active supply wells (Figure 7.12A). In general, however, the flow is toward Northeast Creek and Frenchmans Creek. Under these flow conditions, PCE migrated southeast from its source at the site of ABC One-Hour Cleaners in the direction of water-supply well TT-26 (Figure 7.12A). The simulated PCE concentration at water-supply well TT-26 during January 1958 was about 29 µg/L.

January 1968

During January 1968 (Figure 7.12B), the designated start date of the epidemiological case-control study, groundwater flow in the northern half of the model domain was little changed from January 1958 conditions. In the immediate vicinity of the Tarawa Terrace I housing area, groundwater flow and water levels are affected by pumpage from water-supply wells TT-52, TT-53 and TT-54. Groundwater flow from the vicinity of TT-26 toward well TT-54 is particularly evident (Maslia et al. 2007, Figure A14). Under these flow conditions, PCE has migrated in a more southwardly direction from its source at the site of ABC One-Hour Cleaners toward water-supply well TT-54 (Figure 7.12B) and covers a greater spatial extent than during January 1958. By January 1968, the simulated concentration of PCE in water-supply well TT-26 was 402 µg/L.

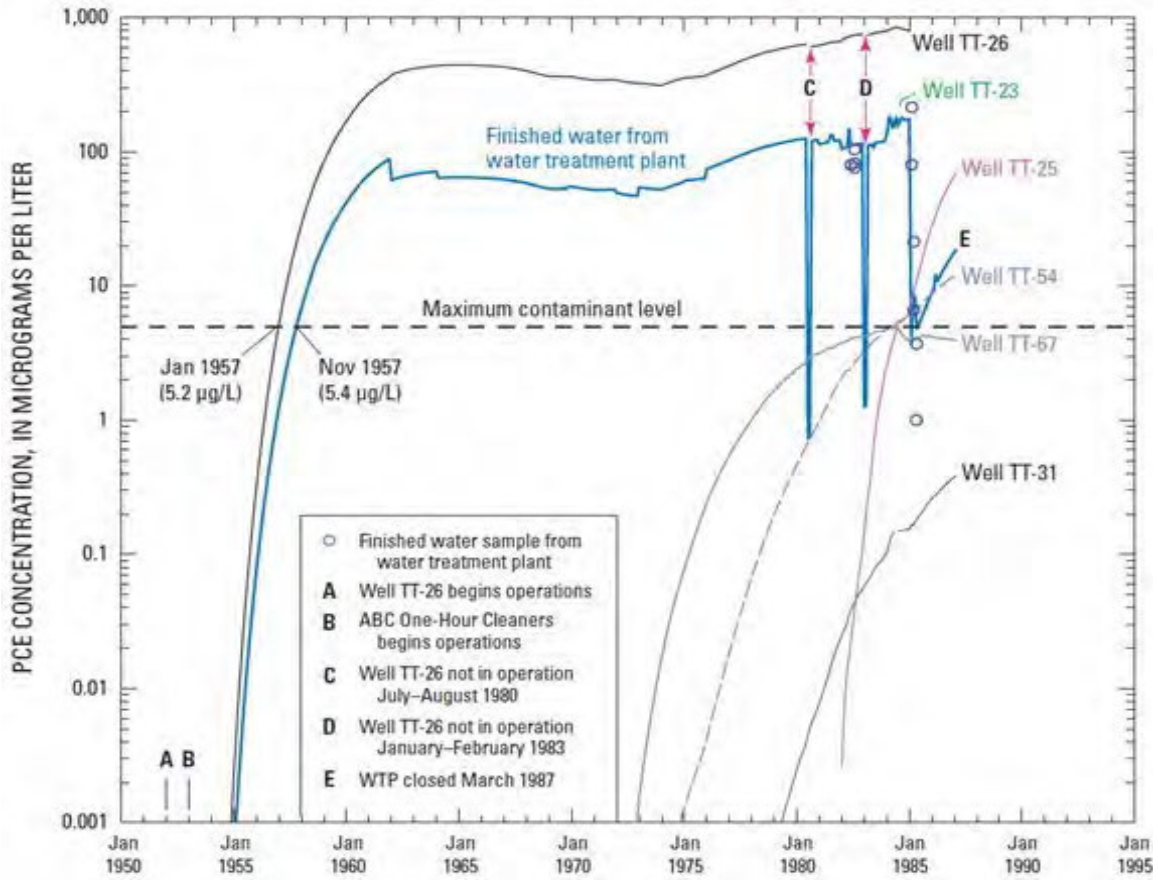
December 1984

Groundwater pumpage increased water-level declines during December 1984 (Figure 7.12C) in the vicinity of the Tarawa Terrace I housing area and probably accelerated the migration of PCE toward the vicinity of well TT-54. Between January 1968 and December 1984, the center of mass of PCE migrated generally southeastward from its source at the site of ABC One-Hour Cleaners, and the arm of the PCE plume migrated southwestward toward water-supply wells TT-23, TT-67, and TT-54 (Figure 7.12C). The areal extent of simulated PCE contamination has increased significantly from the areal extent of January 1958 and January 1968 (Figures 7.13A and 7.13B, respectively). By December 1984, the simulated concentration of PCE in water-supply wells TT-23, TT-25, and TT-26 was 255 µg/L, 6 µg/L, and 805 µg/L, respectively.

December 1994

Owing to documented PCE contamination in water samples obtained from the TT water-supply wells and the TTWTP (Tables 7.9 and 7.10), wells TT-23 and TT-26 were taken off-line during February 1985. The TTWTP was closed and pumping at all Tarawa Terrace water-supply wells was discontinued during March 1987 (Table 7.1 and Figure 7.2). As a result, potentiometric levels began to recover. By December 1994 (Figure 7.12D), the simulated potentiometric levels were nearly identical to predevelopment conditions of 1951 (Faye and Valenzuela 2007). Groundwater flow was from the north and northwest to the south and east, discharging to Northeast Creek. Groundwater discharge also occurs to Frenchmans Creek in the westernmost area of the model domain. TT water-supply wells shown in Figure 7.12D were not operating during December 1994 but are shown on this illustration for reference purposes.

A graph showing simulated concentrations of PCE at TT water-supply wells from the beginning of operations at ABC One-Hour Cleaners through the closure of the wells and the TTWTP is shown in Figure 7.13. Simulated PCE concentrations in water-supply well TT-26 exceeded the current MCL of 5 µg/L for PCE during January 1957 (simulated value is 5.2 µg/L) and reached a maximum simulated value of 851 µg/L during July 1984. The mean simulated PCE concentration in water-supply well TT-26 for its entire period of operation was 351 µg/L. The mean simulated PCE concentration for the period exceeding the current MCL of 5 µg/L—January 1957 to January 1985—was 414 µg/L (Table 7.11). This represents a duration of 333 months (27.7 years). These results are summarized in Table 7.11 along with simulated results for water-supply wells TT-23 and TT-25. It should be noted that although simulation results indicate several water-supply wells were contaminated with PCE (wells TT-23, TT-25, TT-31, TT-54, and TT-67–Table 7.9), by far, the highest concentration of PCE and the longest duration of contamination occurred in water-supply well TT-26 (Figure 7.13).



7.13. Concentration of tetrachloroethylene (PCE): (1) simulated at selected water-supply wells and in finished water at the water treatment plant and (2) measured in finished water at the water treatment plant, Tarawa Terrace (Maslia et al. 2007).

Table 7.10. Summary of reconstructed (simulated) values and observed data of tetrachloroethylene (PCE) at the water treatment plant, Tarawa Terrace (Maslia et al. 2007).

[PCE, tetrachloroethylene; µg/L, microgram per liter; J, estimated; ND, nondetect]

Model-derived value		Observed data				
Month and year	PCE concentration, in µg/L	Sample date	PCE concentration, in µg/L	Detection limit, in µg/L	Calibration targets, in µg/L[2]	Sample number[3]
May 1982	148	5/27/1982	80	10	25–253	1
July 1982	112	7/28/1982	104	10	33–329	2
July 1982	112	7/28/1982	76	10	24–240	3
July 1982	112	7/28/1982	82	10	26–259	4
January 1985	176	2/5/1985	80	10	25–253	5
January 1985	176	2/11/1985	215	10	68–680	6
February 1985	3.6	2/13/1985	ND	10	1–10	7
February 1985	3.6	2/19/1985	ND	2	1–2	8
February 1985	3.6	2/22/1985	ND	10	1–10	9
March 1985	8.7	3/11/1985	ND	2	1–2	10
March 1985	8.7	3/12/1985	6.6	10	2.1–21	11
March 1985	8.7	3/12/1985	21.3	10	6.7–67	12
April 1985	8.1	4/22/1985	1	10	0.3–3.2	13
April 1985	8.1	4/23/1985	ND	10	1–10	14
April 1985	8.1	4/29/1985	3.7	10	1.2–11.7	15
May 1985	4.8	5/15/1985	ND	10	1–10	16
July 1985	5.5	7/1/1985	ND	10	1–10	17
July 1985	5.5	7/8/1985	ND	10	1–10	18
July1985	5.5	7/23/1985	ND	10	1–10	19
July 1985	5.5	7/31/1985	ND	10	1–10	20
August 1985	6.0	8/19/1985	ND	10	1–10	21
September 1985	6.5	9/11/1985	ND	10	1–10	22
September 1985	6.5	9/17/1985	ND	10	1–10	23
September 1985	6.5	9/24/1985	ND	10	1–10	24
October 1985	7.1	10/29/1985	ND	10	1–10	25

Table 7.11. Summary statistics for reconstructed (simulated) tetrachloroethylene (PCE) contamination of selected water-supply wells and the water treatment plant based on calibrated

[MCL, maximum contaminant level; µg/L, microgram per liter; WTP, water treatment plant; PCE, tetrachloroethylene]

Water supply	Month and year and duration exceeding MCL [1]	Month and year of maximum value and maximum concentration, in µg/L	Average concentration,[2] in µg/L
TT-23	August 1984–April 1985 8 months[3]	April 1985 274	252
TT-25	July 1984–February 1987 32 months	February 1987 69	27
TT-26	January 1957–January 1985 333 months[4]	July 1984 851	414
WTP	November 1957–February 1987 346 months	March 1984 183	70

[1] Current MCL for PCE is 5 µg/L, effective date July 6, 1992 (40 CFR, Section 141.60, Effective Dates, July 1, 2002, ed.)

[2] For periods exceeding 5 µg/L when water-supply well was operating

[3] Water-supply well TT-23 was not operating during February 1985

[4] Water-supply well TT-26 was not operating July–August 1980 and January–February 1983

It is clear from the graph in Figure 7.13 that the Tarawa Terrace finished water (blue trace) mimicked the concentration of PCE at well TT-26 but at a lower level. The finished water trace indicated the concentration of PCE after all supply wells have been mixed at the TTWTP. TT-26's mixing with the uncontaminated wells in the supply field resulted in a reduction in concentration. See Tables 7.9 and 7.10 for comparisons of model-derived values and observed data of PCE at selected water-supply wells and the TTWTP, respectively.

Well TT-26

Based on calibrated model simulations, water- supply well TT-26 had the highest concentration of PCE- contaminated groundwater and the longest duration of PCE-contaminated groundwater with respect to any other Tarawa Terrace water-supply well (Figure 7.13). This is due to two reasons (1) its proximity to ABC One-Hour Cleaners source and (2) its total run time over the 1953 to 1987 time period.

Assessing Level 3 calibration results using MT3DMS discussed above, water-modeling staff relied on the measured water-quality sample data to compare with reconstructed (simulated) concentrations (Figure 7.14, Table 7.9). An additional assessment of the Level 3 calibration is to compare PCE mass remaining in the Tarawa Terrace and Upper Castle Haye aquifers calculated from field observations (Fay 2008, Table F11, p. F30) with MT3DMS calibrated mass computations, which represents PCE mass in all model layers for each pumping period. Most of the data used to calculate the quantity of PCE mass in solution summarized in Faye (2008, Table F11, p. F30), were collected between December 1991-April 1992 (Roy F. Weston, Inc. 1992, 1994). Algebraic manipulation of mass balance data computed for February 1992 indicates the remaining PCE mass in solution at that time equals 1.0 X 10^6 g. This simulated quantity of remaining PCE mass compares very favorably to the calculated

quantity of PCE mass remaining in the Tarawa Terrace and Upper Castle Hayne aquifers of 1.5×10^6 g tabulated in Faye (2008, Table F11, p,. F30) using observed PCE concentrations (Roy F. Weston, Inc. 1992, 1994). It is quite remarkable that both numbers compare so favorably and is a confirmation of the concordance of model results (MT3DMS) with observed data. This is another indicator that reconstructed PCE concentrations (using the Level 3 calibration of MT3DMS) at Tarawa Terrace represent real-world conditions.

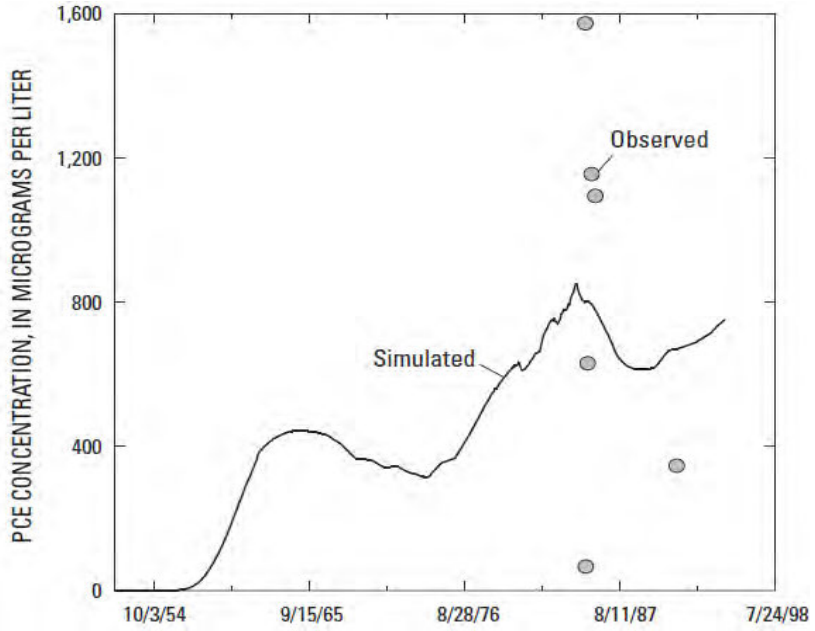


Figure 7.14. Reconstructed (simulated) and observed tetrachloroethylene (PCE) concentrations at water-supply well TT-26, Tarawa Terrace (Faye 2008).

Level 4 Calibration (Mixing Model)

The final level of model calibration employed a simple mixing (flow-weighted average) model to compute PCE concentrations delivered to the TTWTP from all operating water-supply wells and subsequently to the Tarawa Terrace water-supply distribution network. The model is based on the principles of continuity and conservation of mass (Masters 1998) and is used to compute the flow-weighted average concentration of PCE. For each stress period (month) of the simulation period (from January 1951 to December 1994), the PCE concentration simulated at each operating water-supply well is weighted by the respective well discharge to compute a weighted-mean PCE concentration. This weighted-mean concentration was considered the monthly mean PCE concentration delivered to the TTWTP. The results of these computations compared to an analysis of a water sample collected at a point in time, either at the TTWTP or at a location within the TT water-distribution system such as an outdoor or indoor faucet, are summarized in Table 7.12. The computed PCE concentration is compared to the

observed PCE concentration on a same-month basis; that is, if a sample date was reported as May 1, 1982, then the corresponding computed PCE concentration was the weighted-mean concentration for the month of May 1982. Results of the reconstructed mean monthly PCE concentrations at the TTWTP are listed in **Appendix H1** (Column 3) for each stress period, January 1951–March 1987. Data listed in **Appendix H1** are from Maslia et a. (2007, Appendix A2).

Computations were accomplished for simulated pumpage and PCE concentrations for all 528 stress periods and are plotted in Figure 7.13 (the blue line representing the reconstructed mean monthly PCE concentrations at the TTWTP). Computed breakthrough of PCE at the MCL concentration of 5 µg/L occurs at the TTWTP about October or November 1957 and, except when water-supply well TT-26 was temporarily removed from service, continues above 40 µg/L from about December 1959 until the termination of operations at well TT-26 during February 1985. The precipitous declines in PCE concentration noted in Figure 7.13 represent periods when well TT-26 was temporarily removed from service during July and August 1980 and January and February 1983. The last decline in PCE concentration corresponds to the final removal of well TT-26 from service. The points indicating "observed" PCE concentrations on Figure 7.13 correspond to the numerical concentrations listed in Table 7.10.

Table 7.12 summarizes simulated and observed PCE water treatment plant concentrations at the TTWTP. In Table 7.12, the measured PCE concentrations ranged from 215 µg/L to non-detect (detection limits of 2-10 µg/L). For the same period, model predictions of PCE concentrations at the TTWTP ranged from 176 µg/L to 3.6 µg/L (Table 7.12). This close agreement between simulated and measured values supports the collective ability of the four-stage modeling and calibration process to capture the Tarawa Terrace water-distribution system behavior accurately.

The results shown in Figure 7.13 and Table 7.12 represent the calibrated model being compared to a separate dataset than that used for the calibration of the model (Figure 7.14). The observed data used for calibration included all available geologic data, supply well characteristics and observed well contaminate values. The observed values in Figure 7.13 represent the measured concentrations taken at both the TTWTP and at other locations in the TT water-distribution system. It is important to note these **observed values were not used in the calibration process** and therefore represent an additional set of observed (field) data by which to assess the "goodness of fit" of the four-level, hierarchical calibration process.

Table 7.12. Computed and observed tetrachloroethylene (PCE) concentrations in water samples collected at the Tarawa Terrace water treatment plant and calibration target range, Tarawa Terrace (from Fay 2008).

[µg/L, microgram per liter; TTWTP, Tarawa Terrace water treatment plant; ND, not detected]

Date	PCE concentration, in µg/L		Calibration target range, in µg/L
	Computed[1]	Observed	
[2]TTWTP Building TT-38			
5/27/1982	148	180	25–253
7/28/1982	112	[3]104	33–329
7/28/1982	112	[3]76	24–240
7/28/1982	112	[3]82	26–259
2/5/1985	176	[3,4]80	25–253
2/13/1985	3.6	[5]ND	0–10
2/19/1985	3.6	[6]ND	0–2
2/22/1985	3.6	[5]ND	0–10
3/11/1985	8.7	[6]ND	0–2
3/12/1985	8.7	[6,7]6.6	2.1–21
3/12/1985	8.7	[6,8]21.3	6.7–67
4/22/1985	8.1	[5]1	0.3–3.2
4/23/1985	8.1	[5]ND	0–10
4/29/1985	8.1	[5]3.7	1.2–11.7
5/15/1985	4.8	[5]ND	0–10
7/1/1985	5.5	[5]ND	0–10
7/8/1985	5.5	[5]ND	0–10
7/23/1985	5.5	[5]ND	0–10
7/31/1985	5.5	[5]ND	0–10
8/19/1985	6.0	[5]ND	0–10
9/11/1985	6.0	[5]ND	0–10
9/17/1985	6.0	[5]ND	0–10
9/24/1985	6.0	[5]ND	0–10
10/29/1985	6.0	[5]ND	0–10
[2]TTWTP Tank STT-39			
2/11/1985	176	[5]215	0–10

[1]Weighted-average computation
[2]See Plate 1, Chapter A report, for location (Maslia et al. 2007)
[3]Detection limit is unknown
[4]Analysis of tap water sample for Tarawa Terrace, address unknown
[5]Detection limit = 10 µg/L
[6]Detection limit = 2 µg/L
[7]Sample collected downstream of TTWTP reservoir after operating well TT-23 for 24 hours
[8]Sample collected upstream of TTWTP reservoir after operating well TT-23 for 22 hours

To build further confidence in the four-level calibration for TT and to assess model uncertainty, a multiphase, multispecies finite-element model, TechFlowMP (Jang and Aral 2005, 2008), developed by ATSDR's University Partner, MESL, was run using the calibrated parameter values from MODFLOW-96 and MT3DMS (Table 7.8). Unlike MT3DMS that simulated contaminant fate and transport in the saturated zone

for a single contaminant that does not undergo degradation, TechFlowMP can simulate flow in the unsaturated zone (above the water table), in the saturated zone (below the water table), the degradation of PCE (into TCE, 1,2-tDCE, and VC), and the loss of PCE by accounting for volatilization. Reconstructed (simulated) concentrations of PCE and its degradation products (TCE, 1,2-tDCE, and VC) for each stress period (month), January 1951–March 1987 are listed **Appendix H1** (Columns 4–7) alongside the reconstructed PCE concentrations simulated by MT3DMS for PCE that is not degraded or volatilized (**Appendix H1**, Column 3). Results of the two modeling approaches are also compared in graphs in Maslia et al. (2007, Figure A19, p. A43). As would be expected, the reconstructed PCE concentrations simulated using TechFlowMP are slightly lower than those simulated by MT3DMS because PCE mass is degraded to TCE, 1,2-tDCE, and VC by TechflowMP. In addition, PCE mass is lost (destroyed) in TechflowMP because it simulates volatilization within the unsaturated zone. If one sums the concentrations of PCE, TCE, 1,2-tDCE, and VC for a given month from TechFlowMP (**Appendix H1**, Columns 4–7), they should be approximately near the PCE concentrations reconstructed using MT3DMS (**Appendix H1**, Column3). This very close agreement between two different contaminant fate and transport models, solving two different transport equations (to assess model uncertainty) provides additional evidence and confidence that the reconstructed concentrations at the TTWTP represent "real world" conditions.

Post-Audit of the Tarawa Terrace Models

Additional confidence in groundwater-flow and contaminant fate and transport models can be assessed by conducting a "**post-audit**." A post-audit uses calibrated model parameter values (e.g., Table 7.8) and extends the model out to another time wherein additional and sufficient observation data are available. Jones and Davis (2024) conducted a post-audit with the TT groundwater-flow and contaminant fate and transport models by extending the TT simulations for the time 1995–2008, where ample PCE remediation data for ABC One-Hour Cleaners was available. Their conclusions were, "*In summary, the extended model demonstrates that the original model was developed using sound methods, and the model remains a reliable tool for understanding the general trends of contaminant migration in the Tarawa Terrace region. Based on this post-audit, we can find no significant evidence that would invalidate the analyses performed by ATSDR with the original model.*" Details and results of the post-audit (Jones and Davis 2024) are provided **in Appendix O**.

Uncertainty

Models and associated calibrated parameters described previously are inherently uncertain because they are based on limited data. Under such circumstances, good modeling practice requires that evaluations be conducted to ascertain the confidence in models by assessing uncertainties associated with the modeling process and with the outcomes attributed to models (Saltelli et al. 2000). With respect to model simulations at TT, the availability of data to thoroughly characterize and describe model parameters and operations of water-supply wells was considerably limited, which gave rise to the following questions:

1. Could alternative water-supply well operating schedules or combinations of model parameter values provide acceptable simulation results when compared to observed data and previously established calibration targets?

2. What is the reliability of the historically reconstructed estimates of PCE concentration determined using the calibrated models (for example, results shown in Figure 7.13 and Table 7.10)?

To answer these questions and address the over-arching issues of model and parameter variability and uncertainty, three analyses were conducted using the calibrated groundwater-flow and contaminant fate and transport models described in Faye and Valenzuela (2007) and Faye (2008), respectively. These analyses were: (1) an assessment of pumping schedule variation at TT water-supply wells with respect to contaminant arrival times and concentrations, (2) sensitivity analysis, and (3) probabilistic analysis.

Water-Supply Well Scheduling Analysis

The scheduling and operation histories of TT water-supply wells directly affected times and concentrations of PCE in groundwater at wells and at the WTP during 1952–1987. Thus, simulated water-supply well operations could be a major cause and contributor to uncertainty and variability with respect to PCE arrival and PCE concentrations at water-supply wells and in finished water at the TTWTP. To assess the impact of pumping schedule variability and uncertainty on groundwater-flow, contaminant fate and transport, and WTP mixing models, a procedure was developed that combined groundwater simulation models and optimization methods.

The simulation tool developed for this analysis—PSOpS (Table 7.2)—combines the MODFLOW-96 and MT3DMS groundwater simulators with a rank-and-assign optimization method developed specifically for the TT analysis. This tool optimizes pumping (operational) schedules to minimize or maximize the arrival time of contaminants at water-supply wells. Based on the optimized operational schedules, the concentration of a contaminant is recalculated, and the effect of pumping schedule variation on contaminant concentration and the arrival time of groundwater exceeding the current MCL of PCE (5 µg/L) are evaluated. Details of the water-supply well analysis are provided in Wang and Aral (2008) and are summarized in Maslia et al. (2007, p. A47). PSOpS simulations demonstrated that the current MCL for PCE (5 µg/L) would have been exceeded in finished drinking water from the Tarawa Terrace WTP as early as December 1956 and no later than June 1960 (Maslia et al. 2007, Figure A21, p. A48)

Sensitivity Analysis

Sensitivity analysis is a method used to ascertain the dependency of a given model output (for example, water level or concentration) upon model input parameters (for example, hydraulic conductivity, pumping rate, and mass loading rate). Sensitivity analysis is important for checking the quality of the calibration of a given model, as well as a powerful tool for checking the robustness and reliability of model simulations. Thus, sensitivity analysis provides a method for assessing relations between information provided as input to a model—in the form of model input parameters—and information produced as output from the model. Maslia et al. (2007, p. A50) describe and discuss details of varying 7 groundwater-flow model parameter values and 7 contaminant fate and transport model parameter values and list the results in Table A14 (Maslia et al. 2007, p. A51).

Probabilistic Analysis

A probabilistic analysis is used to generate uncertainties in model inputs (e.g., hydraulic conductivity or contaminant source mass loading rate) so that estimates of uncertainties in model outputs (e.g., water level

or PCE concentration in groundwater) can be made. Although the sensitivity analysis provided some insight into the relative importance of selected model parameters, a probabilistic analysis provides quantitative insight about the range and likelihood (probability) of model outputs. Thus, one purpose of a probabilistic analysis is to assist with understanding and characterizing variability and uncertainty of model output (Cullen and Frey 1999). Several methods are available for conducting a probabilistic analysis. These methods can be grouped as follows: (1) analytical solutions for moments, (2) analytical solutions for distributions, (3) approximation methods for moments, and (4) numerical methods. The probabilistic analysis conducted on the TT models used numerical methods—Monte Carlo simulation (MCS) and sequential Gaussian simulation (SGS)—to assess model uncertainty and parameter variability.

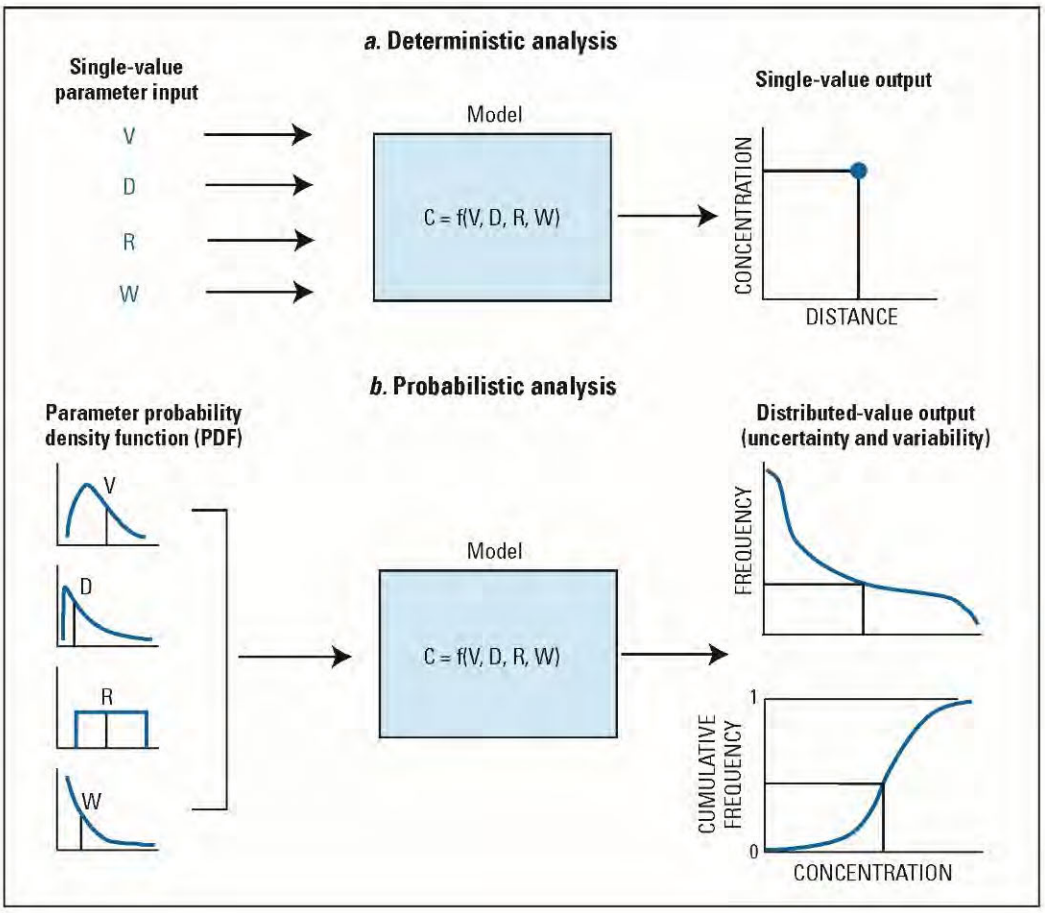


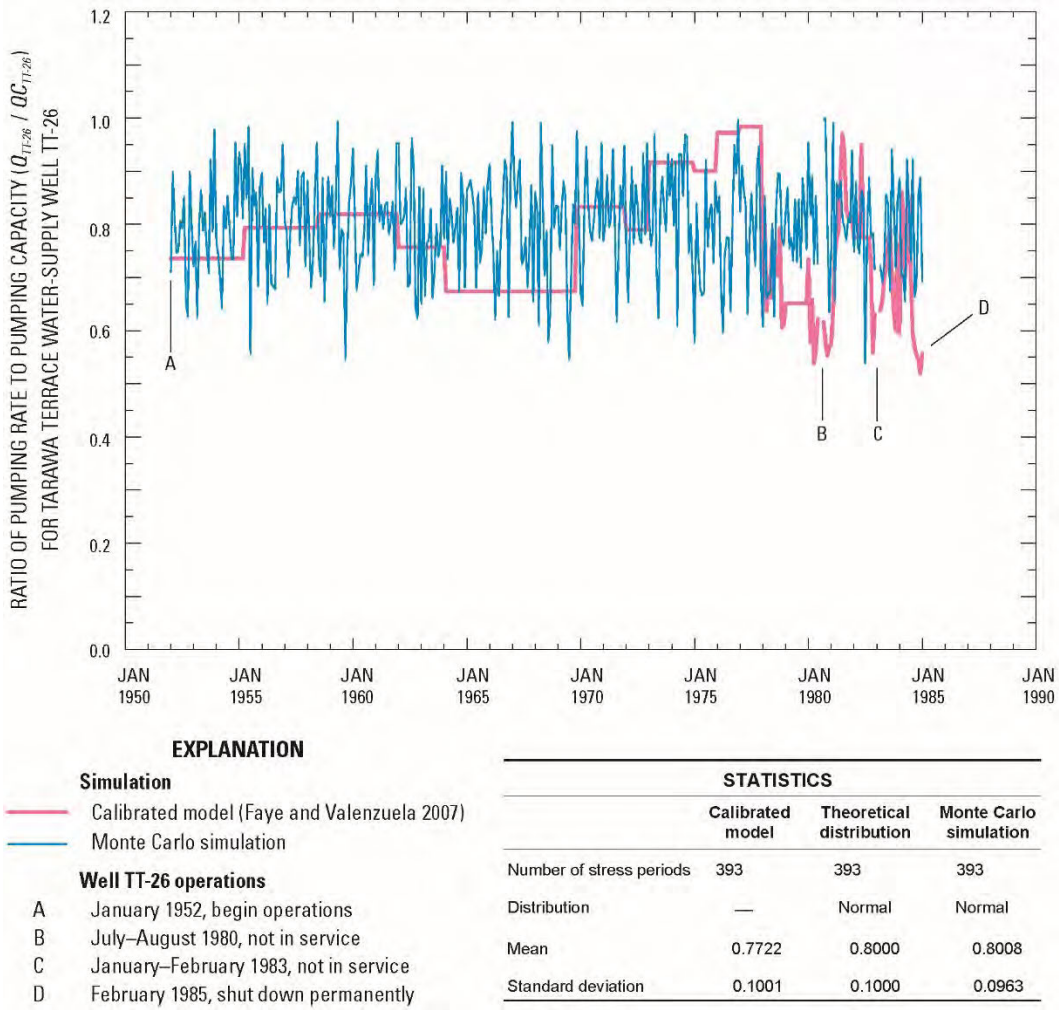
Figure 7.15. Conceptual framework for (a) a deterministic analysis and (b) a probabilistic analysis (from Maslia and Aral 2004).

Before proceeding with the probabilistic analysis applied to the TT models, it is important to understand the conceptual difference between the deterministic modeling analysis approach used to calibrate groundwater-flow (Faye and Valenzuela 2007) and fate and transport (Faye 2008) model parameter values and a probabilistic analysis. As described in Maslia and Aral (2004), with respect to the approach referred to as a deterministic modeling analysis, **single-point values** are specified for model input parameters and results are obtained in terms of **single-valued output**, for example, the concentration of PCE. This approach is shown conceptually in Figure 7.15*a*. In a probabilistic analysis, input parameters (all or a selected subset) of a particular model (for example, contaminant fate and transport) may be characterized in terms of **statistical distributions** that can be generated using the MCS method (USEPA 1997, Tung and Yen 2005) or the SGS method (Deutsch and Journel 1998, Doherty 2005). Results are obtained in terms of **distributed-value output** that can be used to assess model uncertainty and parameter variability as part of the probabilistic analysis (Figure 7.15*b*). MCS is a computer-based (numerical) method of analysis that uses statistical sampling techniques to obtain a probabilistic approximation to the solution of a mathematical equation or model (USEPA 1997). The MCS method is used to simulate probability density functions (PDFs). PDFs are mathematical functions that express the probability of a random variable (or model input) falling within some interval. SGS is a process in which a field of values (such as horizontal hydraulic conductivity) is obtained multiple times assuming the spatially interpolated values follow a Gaussian (normal) distribution. Additional details pertaining to the SGS methodology are provided in Deutsch and Journel (1998) and Doherty (2005).

The probabilistic analysis conducted using MCS was applied to the entire period of operation of the TTWTP (January 1953–February 1987). The PCE concentration in finished water determined using the deterministic analysis (single-value parameter input and output; Figure 7.13, **Appendix H2**-Column 3) also can be expressed and presented in terms of a range of probabilities for the entire duration of WTP operations. Water-supply well pumping variation and uncertainty could have a significant impact on contaminated groundwater delivered to the TTWTP. For example, Figure 7.16a shows a comparison of the calibrated pumping schedule for well TT-26 (Faye and Valenzuela 2007) with a pumping schedule generated using a Gaussian pseudo-random number generator (PRNG) and MCS.[9] (See Maslia et al. 2009b for specific details).

To assess pumping schedule uncertainty (like that shown in Figure 7.16a for well TT-26), two MCSs were conducted. In scenario 1, pumping uncertainty was excluded (i.e., the calibrated pumping schedules were used [red line in Figure 7.16a]); in scenario 2, pumping uncertainty was included (a randomly generated pumping schedule for well TT-26 shown by the blue lines in Figure 7.16a).

[9] A pseudo-random number generator (PRNG) is an algorithm for generating a sequence of numbers that approximates the properties of random numbers. These approximate random numbers can be used in MCS to generate a probability density function, such as a normal or log-normal distribution.



STATISTICS

	Calibrated model	Theoretical distribution	Monte Carlo simulation
Number of stress periods	393	393	393
Distribution	—	Normal	Normal
Mean	0.7722	0.8000	0.8008
Standard deviation	0.1001	0.1000	0.0963

Figure 7.16a. Ratio of pumping rate to pumping capacity (Q_{TT-26} / QC_{TT-26}) for water-supply well TT-26 for calibrated model and Monte Carlo simulation, Tarawa Terrace (Maslia et al. 2009b).

The concentration of PCE in finished water at the TTWTP is shown in Figure 7.16b, considering the following conditions:

(a) calibrated (reconstructed) PCE concentrations simulated using MT3DMS (blue line in Figure F.16b; **Appendix H2**–Column 3),
(b) pumping uncertainty excluded (scenario 1, yellow band in Figure 7.16b (**Appendix H2**-Scenario 1, Columns 4–6), and
(c) pumping uncertainty included (scenario 2, red lines in Figure 7.16b (**Appendix H2**-Scenario 2, Columns 7–9).

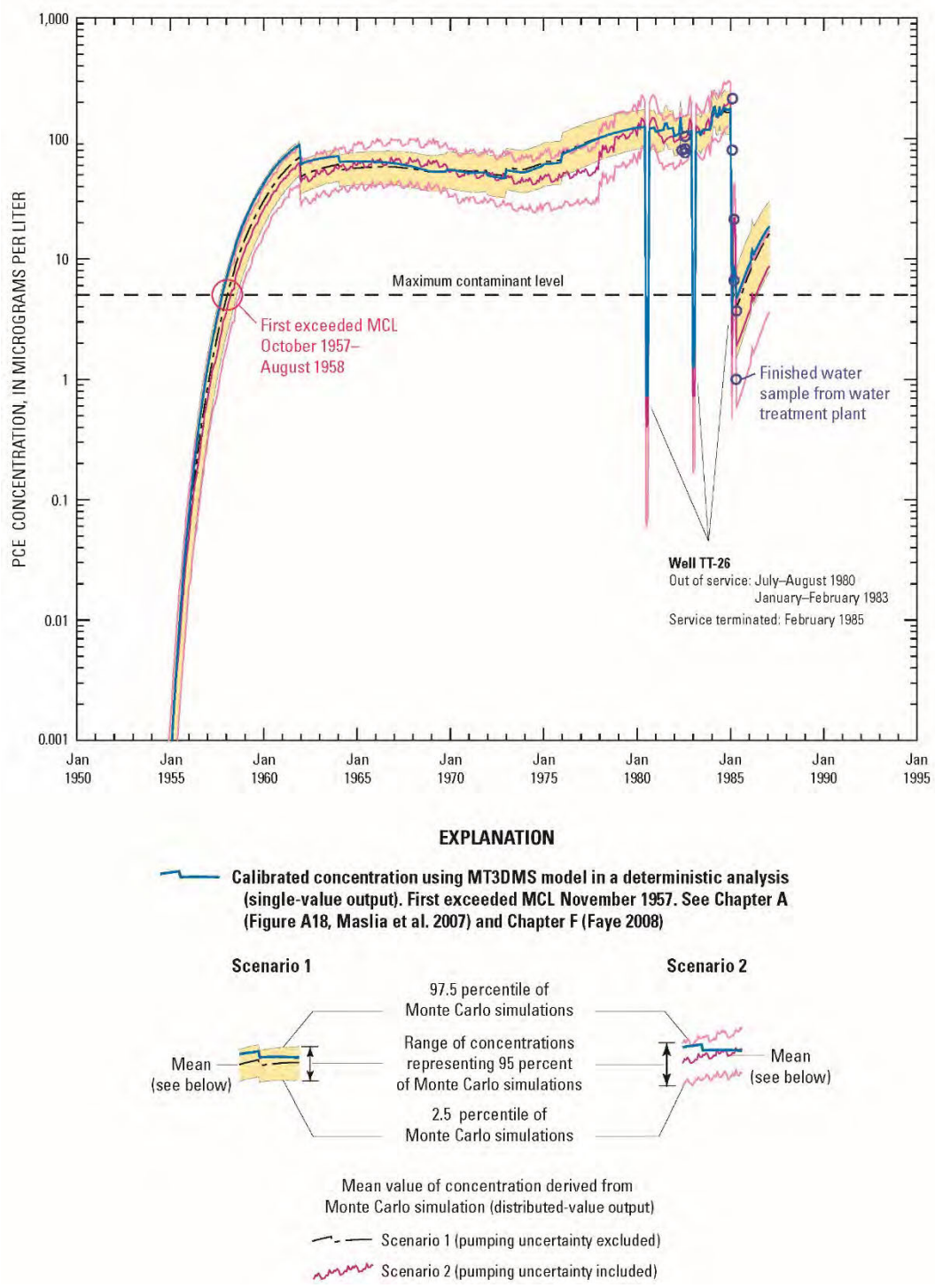


Figure 7.16b. Concentrations of tetrachloroethylene (PCE) in finished water at the water treatment plant derived from the calibrated MT3DMS model, probabilistic analysis using Monte Carlo simulation for scenario 1 (pumping uncertainty excluded) and scenario 2 (pumping uncertainty included), Tarwa Terrace study area (Maslia et al. 2009b).

The probabilistic results shown in Figure 7.16b (derived from MCS and MT3DMS) represent a range of concentrations representing 95% percent of Monte Carlo simulations. Therefore, we now have established a lower confidence level (LCL) and an upper confidence level (UCL), which are represented by the 2.5 percentile and 97.5 percentile, respectively, of Monte Carlo simulations. Two examples, in reference to **Appendix H2** (digital output used to construct Figure 7.16b) are now looked at in detail.

- **January 1968 (stress period 205)**: the calibrated (reconstructed) PCE concentration in finished water at the TTWTP is 58 μg/L (**Appendix H2**-Column 3). Under scenario 1 (pumping uncertainty excluded, the LCL ($P_{2.5}$) concentration is 39 μg/L and the UCL ($P_{97.5}$) is 76 μg/L. Under scenario 2 (pumping uncertainty included), the LCL ($P_{2.5}$) concentration is 41 μg/L and the UCL ($P_{97.5}$) is 98 μg/L. The range of concentrations between the LCL ($P_{2.5}$) and UCL ($P_{97.5}$) represent 95% of the MCSs, or a 95% confidence that for January 1968, PCE concentration in finished water at the TTWTP would lie between the LCL and UCL range.

- **December 1984 (stress period 408)**: the calibrated (reconstructed) PCE concentration in finished water at the TTWTP is 173 μg/L (**Appendix H2**-Column 3). Under scenario 1 (pumping uncertainty excluded, the LCL ($P_{2.5}$) concentration is 108 μg/L and the UCL ($P_{97.5}$) is 246 μg/L. Under scenario 2 (pumping uncertainty included), the LCL ($P_{2.5}$) concentration is 128 μg/L and the UCL ($P_{97.5}$) is 301 μg/L. The range of concentrations between the LCL ($P_{2.5}$) and UCL ($P_{97.5}$) represent 95% of the MCSs, or a 95% confidence that for December 1984, PCE concentration in finished water at the TTWTP would lie between the LCL and UCL range.

Four points are worth noting about the probabilistic uncertainty analysis results:

1. In a world without any uncertainty, the calibrated mean monthly finished water PCE concentrations (**Appendix H2**-Column 3) would equal the P_{50} values, or 50 percentile MCSs (**Appendix H2**-Columns 5 and 8). Because there is uncertainty, the calibrated mean monthly PCE concentrations values at the TTWTP are close to the P_{50} values obtained from MCS, but not necessarily equal in value.
2. The bands in Figure 7.16b (and tabular values in **Appendix H2**), demonstrate that uncertainty ranges within a factor of about 3 for any given month, providing additional confidence in the reconstructed mean monthly PCE concentrations at the TTWTP.
3. In Figure 7.16b, every observed data point falls within the banded regions of the MCSs. This is quite remarkable that calibrated and MCS-derived monthly PCE values compare so favorably with observed (measured) PCE values at the TTWTP and is a confirmation of the concordance of model results with observed data (even under uncertainty). This is another indicator that reconstructed PCE concentrations represent real-world conditions at Tarawa Terrace.
4. The PCE concentration in TTWTP finished water during January 1985, simulated using the probabilistic analysis, ranges from 110–251 μg/L (pumping uncertainty excluded, 95 percent of Monte Carlo simulations) and 123–293 μg/L (pumping uncertainty included) . These ranges include the maximum calibrated value of 183 μg/L (derived without considering uncertainty and variability using MT3DMS [Faye 2008]) and the maximum measured value of 215 μg/L (Table 7.8).

Therefore, these probabilistic analysis results—obtained by using MCS—instill confidence in the historically reconstructed PCE concentrations that were delivered to residents of Tarawa Terrace in finished water from the TTWTP.

In summary, effects of parameter uncertainty and variability were analyzed using three approaches—water-supply well scheduling analysis, sensitivity analysis, and probabilistic analysis. Individually and combined, these analyses demonstrate the high reliability of and confidence in results determined using the calibrated MODFLOW-96 and MT3DMS models. The probabilistic analysis conducted using the combination of MODFLOW-2K, MT3DMS, MCS, SGS and PRNG, provides a tool to address issues of parameter uncertainty and variability with respect to the concentration of PCE in finished water delivered from the TTWTP to residents of family housing at Tarawa Terrace and vicinity.

Conclusions Regarding Tarawa Terrace

Based on field data, modeling results, and the historical reconstruction process, the following conclusions are made with respect to drinking-water contamination at Tarawa Terrace:

- Simulated PCE concentrations exceeded the current MCL of 5 µg/L at water-supply well TT-26 for 333 months—January 1957–January 1985; the maximum simulated PCE concentration was 851 µg/L; the maximum measured PCE concentration was 1,580 µg/L during January 1985.
- Simulated PCE concentrations exceeded the current MCL of 5 µg/L in finished water at the TTWTP for 346 months—November 1957–February 1987; the maximum simulated PCE concentration in finished water was 183 µg/L; the maximum measured PCE concentration in finished water was 215 µg/L during February 1985.
- Simulation of PCE degradation by-products—TCE, 1,2-tDCE, and VC—indicated that maximum concentrations of the degradation by-products generally were in the range of 10 –100 µg/L at water-supply well TT-26; measured concentrations of TCE and 1,2-tDCE on January 16, 1985, were 57 and 92 µg/L, respectively.
- Maximum concentrations of the degradation by-products in finished water at the TTWTP generally were in the range of 2–15 µg/L; measured concentrations of TCE and 1,2-tDCE on February 11, 1985, were 8 and 12 µg/L, respectively.
- Monthly mean reconstructed concentrations at the TTWTP for the entire historical period included with this report as **Appendix H1** (single-specie and multi-species PCE) and **Appendix H2** (probabilistic analysis using MCS) represent, within reasonable scientific and engineering certainty, the contaminant levels in finished water from 1953 to 1987.
- In addition to assurances in model reliability afforded by ATSDR's probabilistic and uncertainty analysis, the results of a post-audit using remediation data for ABC One-Hour Cleaners (1995–2008) instill further confidence in the TT models. (See report of Dr. Norman Jones and Jeff Davis in **Appendix O)**.

PCE concentrations in finished water at the TTWTP exceeding the current MCL of 5 µg/L could have been delivered as early as December 1956 and no later than December 1960. Concentrations of PCE in finished water at the TTWTP were also reconstructed under a probabilistic uncertainty analysis using a two-stage Monte Carlo simulation. Details pertinent to the two-stage MCS are provided in Maslia and Aral (2004, p. 185-186), Maslia et al. (2007, 2009b). Typically, 500, 1,000, or 10,000 MCS

runs are conducted to get a sense of the variation and uncertainty of model parameters and output. These results are shown graphically in Figure 7.16. Based on probabilistic analyses, the most likely dates that finished water first exceeded the current MCL ranged from October 1957 to August 1958 (95 percent probability), with an average (most likely) first exceedance date of November 1957. Exposure to PCE and PCE degradation by-products from contaminated drinking water ceased after February 1987; the TTWTP was closed March 1987 (Table 7.1).

7.5.2 Hadnot Point (HP)

The Hadnot Point area represented a far more complex analysis than for Tarawa Terrace. HP had multiple locations and multiple contaminant sources compared to the single source at TT (ABC One-Hour Cleaners). Contaminants for HP were PCE (PCE degradation products), TCE, and benzene (BTEX). These contaminants were found in multiple locations such as the Hadnot Point landfill (HPLF; PCE and TCE), the Hadnot Point Industrial Area (HPIA; PCE, TCE, and benzene), and the Hadnot Pont fuel farm (HPFF; benzene), which is located within the HPIA. Tables A4 and A5 in Maslia et al. (2013, p. A21–A22) lists contaminant data with detections of PCE, TCE, 1,1-DCE, 1,2-tDCE, 1,2-cDcE, VC, and benzene in water-supply wells for the HP-HB study area. An extensive effort was put into the identification and documentation of source areas, timelines, primary contaminants, and location of major dissolved sources for the HP area, and these data are listed in Table 7.13. There are substantially more sources in the HP area than at TT (one source), making data analysis and historical reconstruction substantially more complex. The areal distribution of contaminant sources and impacted water-supply wells in the HP area are shown in Figure 7.17.

Calibration of models for the HP-HB area used a similar hierarchical, 4-level approach, previously described for the TT models, namely: (1) predevelopment (steady or nonpumping) groundwater-flow conditions, (2) transient (time varying or pumping) groundwater-flow conditions, (3) the fate and transport (migration) of VOCs (PCE, TCE, and benzene) from their sources at the HPIA, HPLF , and HPFF areas to HP water-supply wells, and (4) comparing measured concentrations of VOCs in finished water at the HPWTP with the flow-weighted mixing model concentrations. Because of multiple sources, additional analysis methods and modeling approaches were used for the HP area. The following ATSDR reports contain specific details pertinent to the different modeling approaches and calibration results:

- Three-dimensional groundwater flow (predevelopment and transient)—described in Suárez-Soto et al. (2013),
- Three-dimensional contaminant fate and transport of PCE, TCE, and benzene in the vicinities of the HPIA and HPLF area—described in Jones et al. (2013),
- Linear control theory methodology to reconstruct contaminant concentrations of PCE, TCE, 1,2-tDCE, and VC in water-supply well HP-651—described in Guan et al. (2013),
- Dissolution of benzene from an LNAPL source area and subsequent three-dimensional fate and transport of dissolved-phase benzene in the HP Industrial Area—described in Jang et al. (2013), and
- Distribution of finished water from the HPWTP to the HB water-distribution system—described in Sautner et al. (2013b).

Table 7.13. Identification of documented source areas, primary contaminants, and location of major dissolved-phase sources, Hadnot Point area (Figure references are to the Chapter A report [Maslia et al. 2013]).

[HPFF, Hadnot Point fuel farm; UST, underground storage tank; AS/SVE; air sparging/soil vapor extraction; MW, monitor well; µg/L, microgram per liter; gal, gallon; LUST, leaking underground storage tank; CERCLA, Comprehensive Environmental Response, Compensation, and Liability Act of 1980; TCE, trichloroethylene; PCE, tetrachloroethylene]

[1]Source-area timeline [reference documents]	Primary contaminant; number of major sources	Location of major dissolved-phase sources
Hadnot Point Industrial Area (see Figure A13)		
Hadnot Point fuel farm events **1941**, HPFF USTs installed [UST #669, UST #670] **1942**, Building 1115 USTs installed [UST #670] **1993 January**, HPFF and Building 1115 USTs removed [UST #1186, UST #670] **2000 December**, Piping removal (extensive) at HPFF/Building 1115 [UST #417] **Building 1613 events** **1950s**, USTs installed [UST #548, UST #546] **1995 January**, USTs and contaminated soil removed [UST #535, UST #548] **1998–2004**, AS/SVE remediation system operated **Building 1601 events** **1940s**, Building 1601 built [UST #172, UST #195] UST removal date unknown	Benzene; three sources	HPFF/Building 1115/Building 1101 free product footprint Building 1613 free product footprint Building 1601 locations of maximum measured benzene in groundwater (78-GW75-1 and 78-GW74) and former location of USTs and dispenser island at southeast corner of building; MW 78-GW75-1 (5,500 µg/L in 2003; 3,200 µg/L in 2004); MW 78-GW74 (3,200 µg/L in 2004) (See Figure A9 for building and monitor well [MW] locations)
Building 1601 events **1940s**, Building 1601 built [UST #172, UST #195] **1942**, 1,500-gal UST install date listed in LUST study completed in 1990 by Geraghty and Miller [UST #504, UST #507] **1993 June 29**, UST excavated/removed [UST #624] **Building 901/902/903 events** **1948**, Buildings 900, 901, 902, 903 constructed [CERCLA #258, p. 149] TCE UST installation date unknown; removal/abandonment date unknown, but probably occurred prior to onset of remediation efforts around January 1995 [Sovereign Consulting, Inc. 2007]	TCE; two sources	Building 1601 locations of maximum measured TCE in groundwater (MW 78-GW09-1 (old) and (new)) and former location of 1,500-gal waste UST on north side of building; MW 78-GW09-1 (old) (5,000–14,000 µg/L during 1987–1991); MW 78-GW09-1 (new) (at/above 1,000 µg/L during 1993–1996) Building 901/902/903 locations of max measured TCE in groundwater (MW 78-GW23; 13,000 µg/L in 1987), maximum measured vinyl chloride in groundwater (MW 78-GW44; 1,600–6,700 µg/L during 2000–2004), and former locations of USTs containing TCE/solvent waste at Building 901 and between Buildings 902/903. (See Figure A9 for building and monitor well [MW] locations)
Hadnot Point landfill area (see Figure A14)		
Landfill **1940s**, reportedly used as a waste disposal area (Site 6 and Site 82; Figure A8) beginning in the 1940s	PCE and TCE; one source	Location of maximum measured concentration of TCE and PCE in groundwater (MW 06-GW01D) TCE ranged from 6,400 to 180,000 µg/L during 1992–2004; PCE ranged from 210 to 6,500 µg/L during 1992–2004 (See Figure A10 for monitor well [MW] locations)

[1] UST # refers to UST Web Management Portal file number (see References section of this report for complete details); CERCLA # refers to CERCLA Administrative Record file number (provided on digital video disc [DVD] in Maslia et al. 2007)

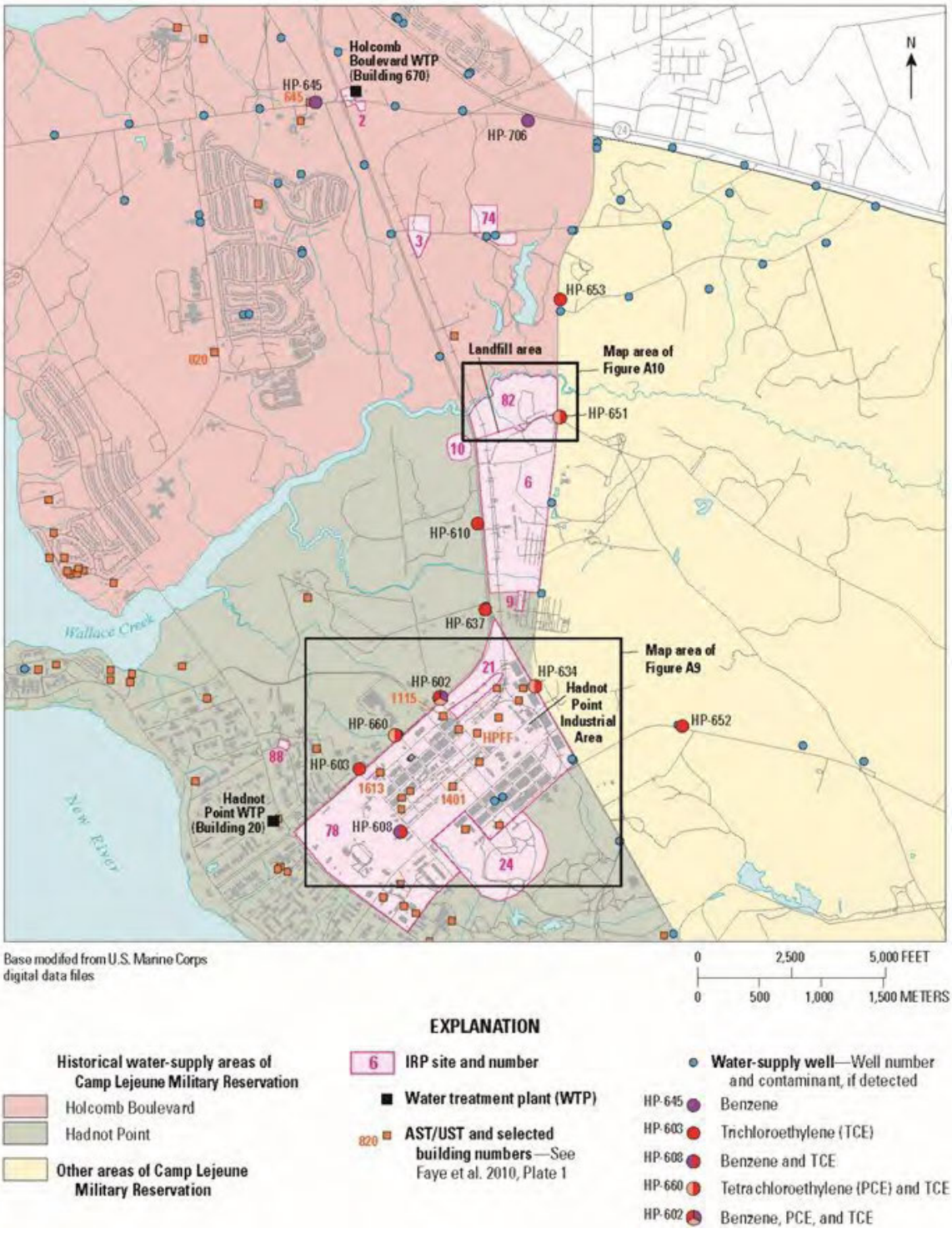


Figure 7.17. Locations of historically contaminated water-supply wells, Installation Restoration Program (IRP) sites, and above-ground and underground storage tank (AST/UST) sites, Hadnot Point–Holcomb Boulevard study areas (map area figures refer to the Chapter A report [Maslia et al. 2013]).

Level 1 Calibration (Predevelopment Conditions)

In Level 1 calibration, more than 700 water-level measurements were used to calibrate the steady-state model by using an automated parameter-estimation approach. A highly parameterized model—with more than 3,800 parameters—was calibrated using regularization and singular value decomposition. PEST 12 (Doherty 2010) was used to conduct simulations and optimization. The parameters included 970 pilot points for each of four parameter groups—horizontal hydraulic conductivity for layers 1, 3, and 5 and recharge. A graph of simulated versus observed potentiometric levels (heads or water-level measurements, Figure 7.18, top graph) shows a generally good agreement about the line of equality (diagonal line on Figure 7.18). A residual analysis (lower graph on Figure 7.18) was used to evaluate the goodness of the fit of the solution. Residual analysis includes a plot of observed potentiometric levels versus residuals and a spatial analysis of the residuals.

Level 2 Calibration (Transient Conditions)

Level 2 calibration included a trial-and-error approach in which hydrographs for multiple wells were compared against simulated water levels. In this Level 2 calibration, vertical anisotropy and temporal variation in recharge were adjusted to improve the match between observed and simulated water levels. Level 1 and 2 calibrations for the HP-HB study area are shown in Figures 7.18 and 7.19, respectively. Figure 7.18 demonstrates close agreement between simulated and measured values for the predevelopment (non-pumping) condition (Level 1) and Figure 7.19 shows good agreement between simulated and measured values for pumping conditions (Level 2). Thus, Levels 1 and 2 calibrations were successful for the HP-HB study area.

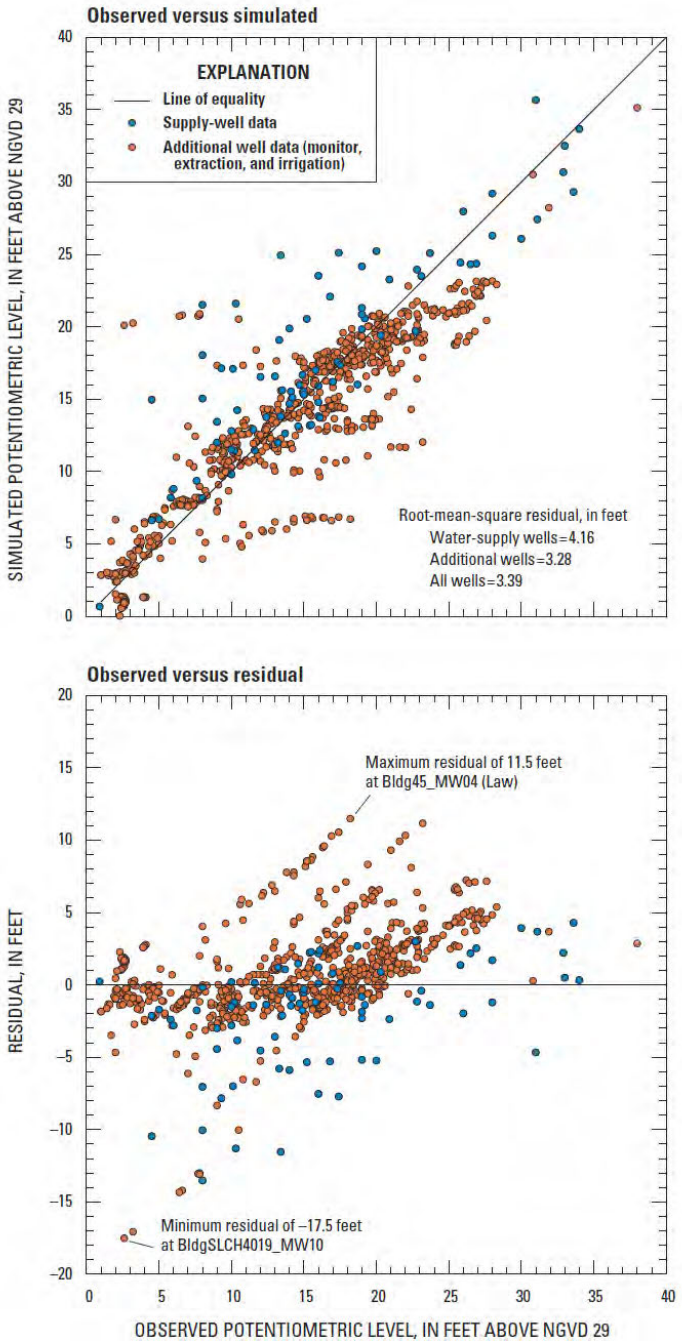


Figure 7.18. Steady-state groundwater-flow model results shown as observed and simulated potentiometric levels, and observed potentiometric levels and corresponding residuals, steady-state groundwater-flow model calibration, Hadnot Point–Holcomb Boulevard study area (from Suárez-Soto et al. 2013).

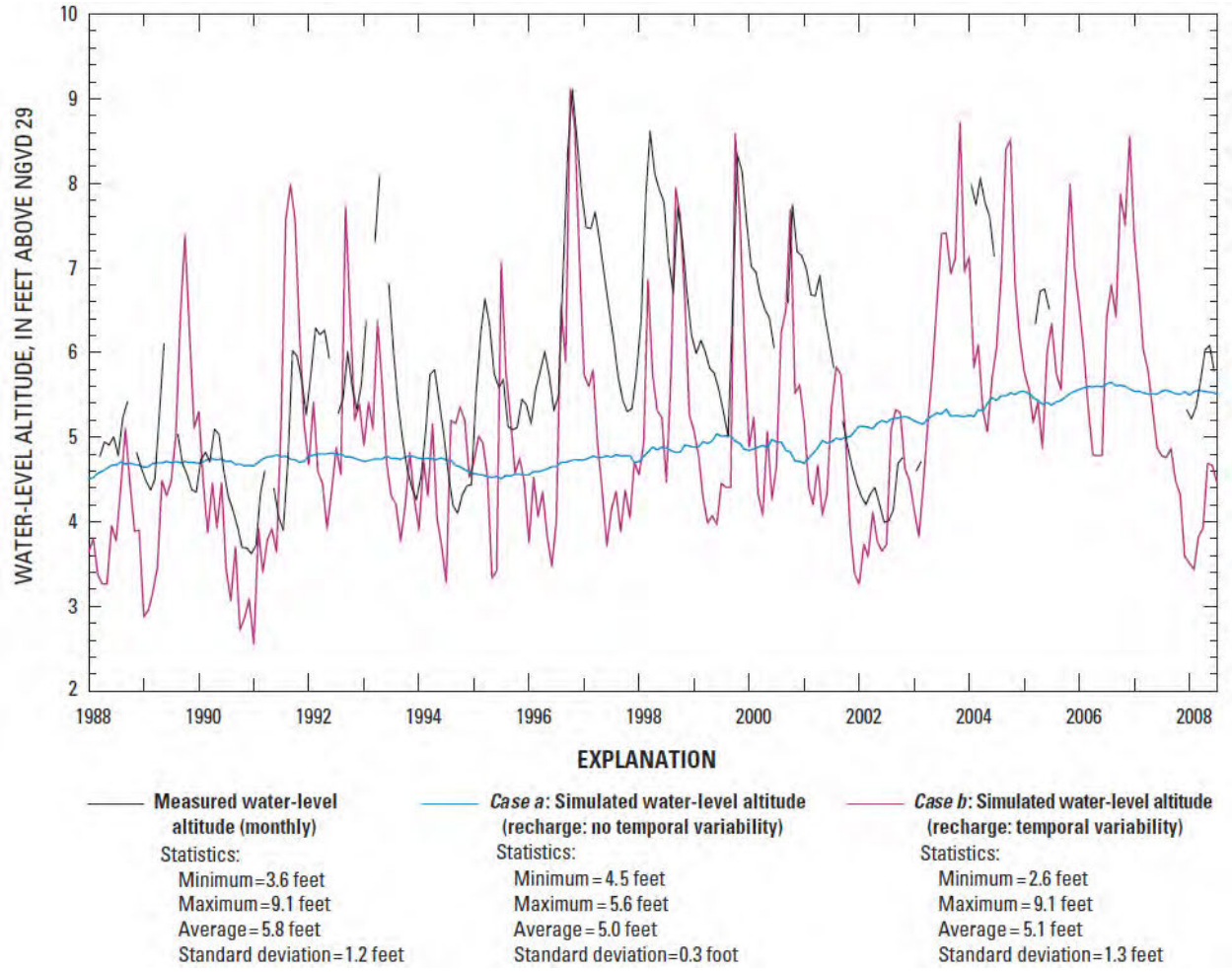


Figure 7.19. Comparison of observed water-level altitude and simulated water-level altitude for well X24S6 for two cases of the transient groundwater-flow model: *case a* with temporal variability of recharge, and *case b* without temporal variability of recharge, Hadnot Point–Holcomb Boulevard study area (from Suárez-Soto et al. 2013). [Note: Date range for measured and simulated water-level altitude for *cases a* and *b* is March 1988 to June 2008].

Level 3 Calibration (Contaminant Fate and Transport)

PCE and TCE

Level 3 calibration for the HP-HB study area involved fitting contaminant migration (fate and transport) parameters to maximize agreement between simulated and measured values at water supply wells. Figure 7.20 shows good agreement between simulated and measured values at four water supply wells. Table 7.14 summarizes calibrated fate and transport parameters.

Figure 7.20 shows the reconstructed (simulated) TCE concentrations for water-supply wells HP-601/660, HP-602, HP-608, and HP-634 within the HPIA. Note, water-supply well HP-660 replaced HP-601 and likely operated from July 1984 to December 1984. Monthly reconstructed TCE concentration results occur on the last day of the month (e.g., 31 January); they are interpreted as being representative of simulated values on any given day of that month. The results are monthly mean

concentrations of TCE. The reconstructed concentrations at water-supply wells are flow-weighted concentration values for supply wells that are open to multiple water-bearing units. As can be seen in the graphs of Figure 7.20, observation data in water-supply wells are limited and, in some instances, provide as few as one data point by which to compare reconstructed TCE concentrations (e.g., HP-634). Given the above limitations, the reconstructed (simulated) TCE concentrations provide reasonable agreement with both observed data and "real-world" conditions.

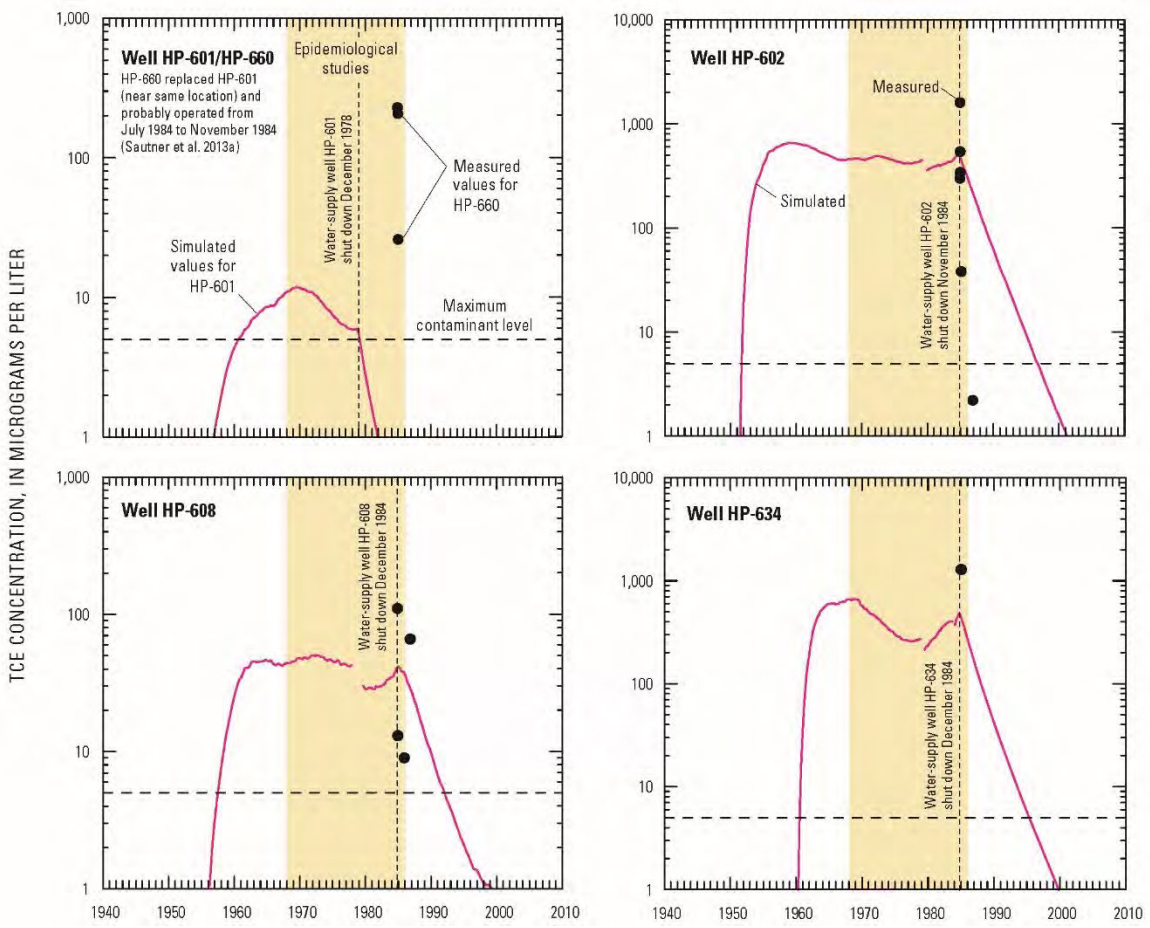


Figure 7.20. Reconstructed (simulated) and measured concentrations of trichloroethylene (TCE) at selected water- supply wells within the Hadnot Point Industrial Area, Hadnot Point-Holcomb Boulevard study area. Groundwater-flow simulation using MODFLOW (Harbaugh 2005) and contaminant fate and transport simulation using MT3DMS (Zheng and Wang 1999), see Figure 7.17 for well location (Jones et al. 2013).

Table 7.14. Calibrated model parameter values used to simulate groundwater flow and contaminant fate and transport, Hadnot Point Industrial Area, Hadnot Point-Holcomb Boulevard study area (Maslia 2013)[1]

[—, not applicable; in/yr, inch per year; ft, foot; ft³, 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]

[2]Model parameter	[3]Model layer number						
	1	2	3	4	5	6	7
[4]Pre-development (steady-state) groundwater-flow model, conditions prior to 1942—Uniform grid (300-ft×300-ft cells)							
Horizontal hydraulic conductivity, K_{xx} (ft/d)	0.5–46.8	1.0–20.0	1.0–50.0	1.0–35.0	2.3–50.0	1.0–20.0	20.0
Ratio of vertical to horizontal hydraulic conductivity, K_{zz}/K_{xx}	1:10	1:15	1:10	1:15	1:10	1:15	1:10
Infiltration (recharge), $I_{i,j}$ (in/yr)	2.5–22.0	—	—	—	—	—	—
[4]Transient groundwater-flow model, January 1942–June 2008—Variably spaced grid (300-ft×300-ft – 50-ft×50-ft cells)							
Specific yield, S_y	0.05	—	—	—	—	—	—
[5]Specific storage, S_s (1/ft) range of values	—	1.3×10^{-5} to 1.9×10^{-4}	4.3×10^{-6} to 3.6×10^{-5}	1.0×10^{-5} to 3.8×10^{-5}	4.0×10^{-6} to 8.3×10^{-6}	1.4×10^{-5} to 3.6×10^{-5}	3.4×10^{-6} to 7.7×10^{-6}
Infiltration (recharge), $I_{i,j}$ (in/yr)	Varies[6]	—	—	—	—	—	—
[7]Pumpage, Q (ft³/d)	Varies	Varies	Varies	Varies	Varies	Varies	Varies
[4]Contaminant fate and transport models, January 1942–June 2008—Subdomain area (50-ft×50-ft cells)							
[8]Distribution coefficient, K_d (ft³/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/ft³)	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^*(ft²/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	—	—	—	—	—	—
HPIA (benzene—LNAPL)	17	—	—	—	—	—	—
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]Refer to Suárez-Soto et al. (2013), Jones et al. (2013), and Jang et al. (2013) for details

[2]Symbolic notation used to describe model parameters obtained from Harbaugh (2005), Zheng and Wang (1999), and Zheng (2010)

[3]See Table A11 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

[4]See Figures A12–A14 for groundwater-flow model domain and contaminant fate and transport model subdomains

[5]Specific storage (S_s) was specified as input for MODFLOW-2005 (Harbaugh 2005); based on cell-by-cell thicknesses, storage coefficient (or storativity) of 4×10^{-4} determined using the equation $S = S_s \times b$, where S is the storage coefficient (dimensionless), S_s is specific storage (1/ft), and b is the cell thickness (ft)

[6]Transient infiltration was varied on a monthly basis using the ratio of monthly precipitation divided by average, long-term precipitation; see Suárez-Soto (2013 for details

[7]Pumpage varies by month and model cell; refer to Sautner et al. (2013a) and Telci et al. (2013) for details on the derivation of historical monthly water-supply well operations; refer to Suárez-Soto et al. (2013) for details pertaining to assigning monthly water-supply well pumpage to cells and model layers using the multi-node well-flow package for MODFLOW-2005

[8]Refer to Jones et al. (2013) for derivation of K_D values based on a survey reported in the scientific literature; to convert from model K_D units of ft³/mg to units of L/kg reported in Jones et al. (2013), multiply model K_D values by 28,381,652.21.

Figure 7.21 (top-left graph) shows the reconstructed (simulated) TCE and PCE concentrations at water-supply well HP-651, located to the east of the TCE contaminant sources and the HPLF (Figure 7.17). Monthly reconstructed results for water-supply well HP-651 also are listed in Maslia et al. (2013, Appendix A3). Observation data at water-supply wells are limited, and in the case of HP-651, three of the five TCE water-quality samples were obtained between January 16 and February 4, 1985, and range from 3,200 µg/L to 18,900 µg/L. Given the data measurement limitations, substantial variation in concentration range within a 1-month period, and interpretive constraints, the reconstructed (simulated) TCE and PCE concentrations shown in Figure 7.21 for water-supply well HP-651 are in reasonable agreement with observed data and "real world" conditions.

As further evidence of successful Level 3 model calibration for the HP-HB area, Figure 7.21 shows good agreement between measured and simulated values for four extraction wells. The additional panels in Figure 7.21 represent four remediation extraction wells (DRW01 to DRW04) that were installed over a decade after HP-651 was decommissioned to clean up the groundwater contamination during the USEPA Installation Restoration Program (IRP). While the historical reconstruction simulation efforts were not focused on (optimized for) remediation activities, comparing simulated values for these groundwater extraction wells with measured values during remediation is instructive. It is encouraging to see that the simulated values generally agree with the observed concentrations, capturing the overall concentration trends versus time. This is even more encouraging given that the remediation values are over a decade after the contaminated well HP-651 was abandoned, providing a longer-term basis for model calibration and increased confidence in the model's ability to reconstruct historical concentrations accurately. It is also instructive to note that concentrations in the remediation wells are similar to or higher than those in HP-651, providing additional data to support the limited measurements available when the contaminated water supply well HP-651 was decommissioned. The higher extraction well values for certain remediation wells in Figure 7.22 reflect the placement of these wells closer to the contamination to maximize contaminant withdrawal. Further, the rise and fall of simulated HP-651 concentrations (Figure 7.22) correspond to that water supply well being activated and decommissioned, while increasing and decreasing simulated values in the remediation wells reflect remediation pumps being turned on and off.

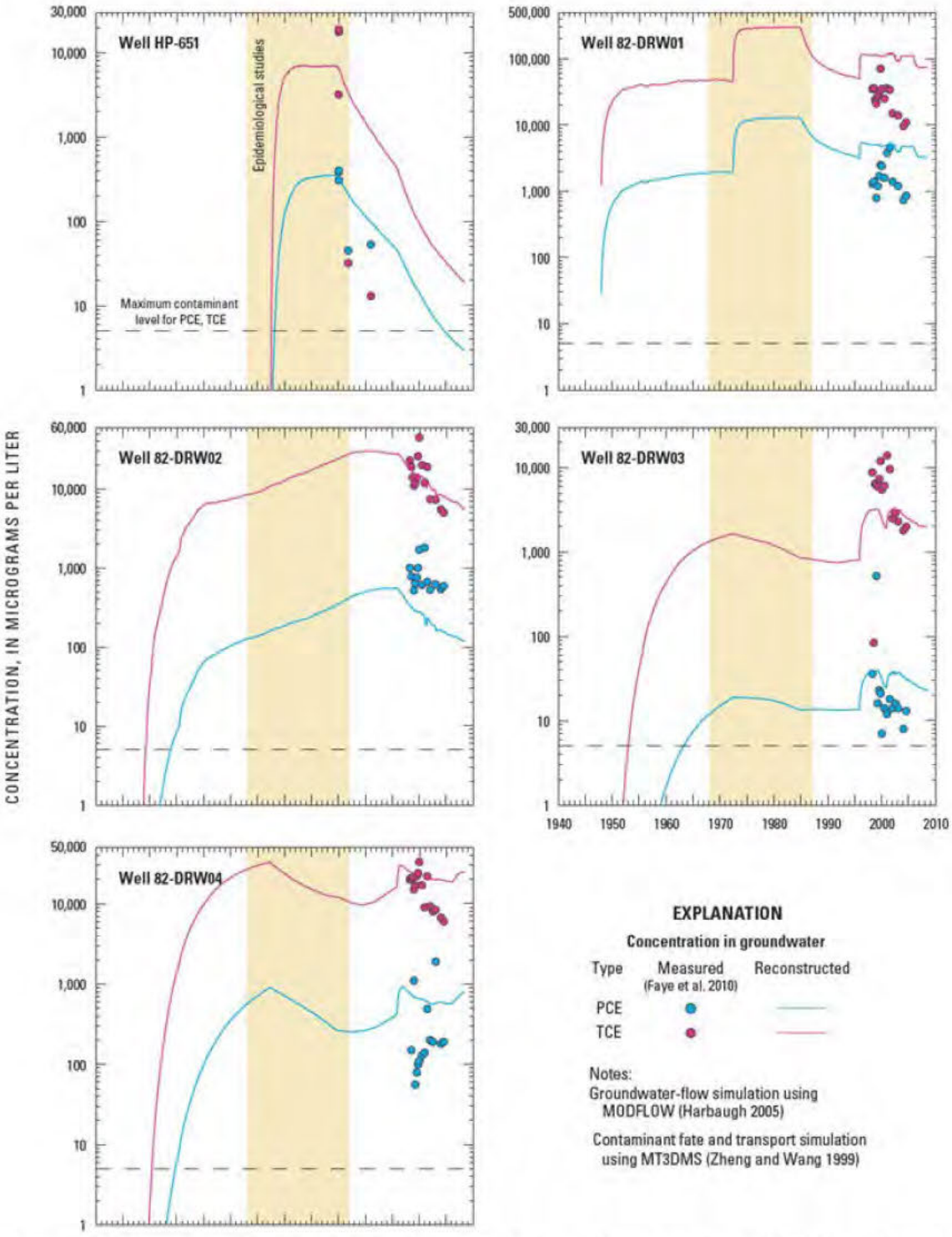


Figure 7.21. Reconstructed (simulated) and measured observed concentrations of trichloroethylene (TCE) and tetrachloroethylene (PCE) at water supply well HP-651 and extraction wells 82-DRW01, 82-DRW02, 82- DRW03, and 82-DRW04, model layer 5, Hadnot Point landfill area, Hadnot Point–Holcomb Boulevard study area (Jones et al. 2013).

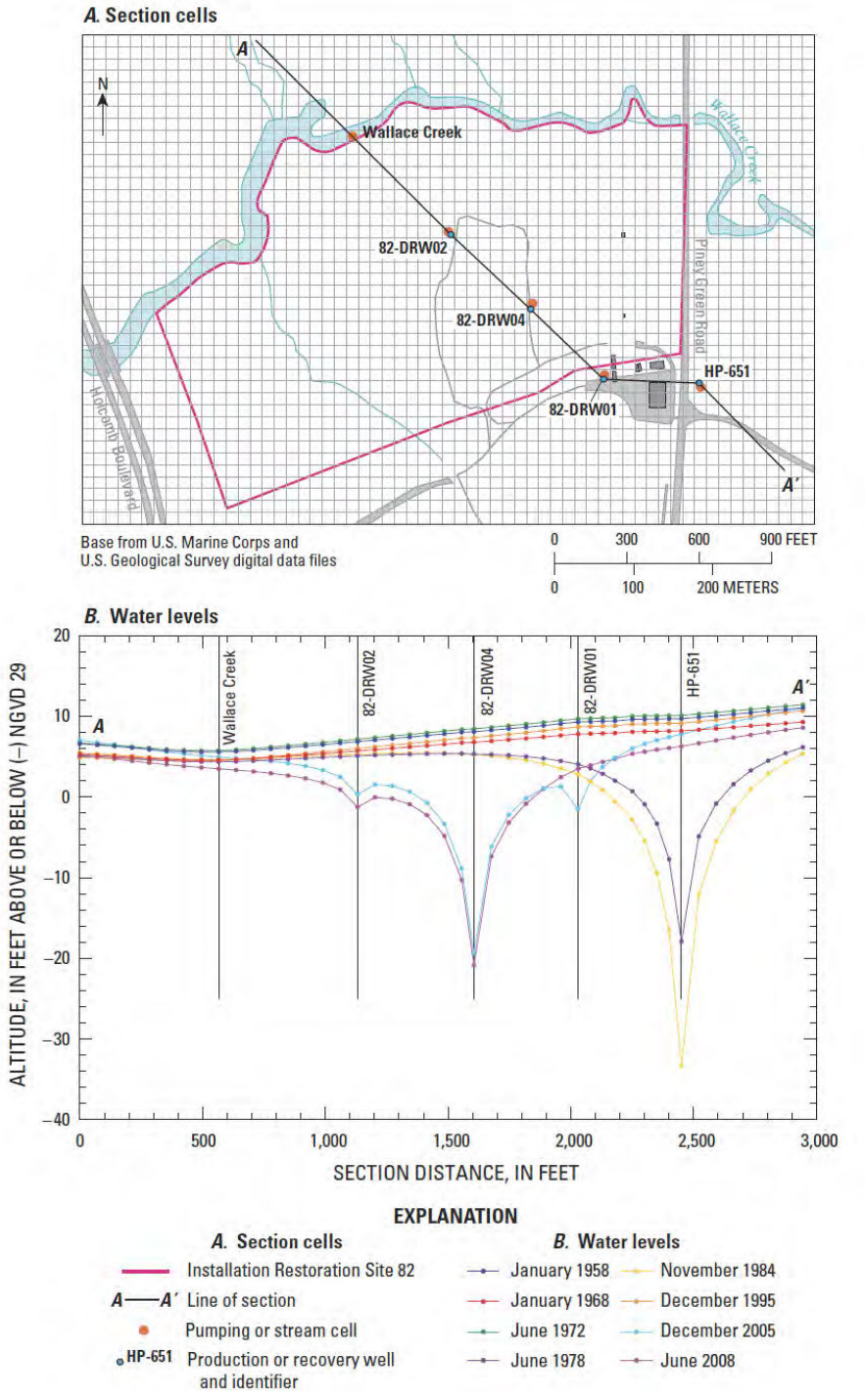


Figure 7.22. *(A)* Line of section *A–A′* and *(B)* simulated water levels within the Hadnot Point landfill area fate and transport model subdomain, model layer 5, Hadnot Point–Holcomb Boulevard study area (Jones et al. 2013).

Benzene

Benzene contamination of groundwater within the HPIA occurred primarily as a result of operations in and around the HPFF and Building 1115 areas (Figure 7.17). Benzene occurs as free product (or "floating light nonaqueous phase liquid (LNAPL)") in vicinity of the HPFF, Building 1115, and IRP site 94/Building 1613 areas and as dissolved-phase benzene contamination in the vicinity of Building 1601 (Faye et al. 2010, 2012). Because benzene occurs as both free product and dissolved phase within the HPIA, *three modeling approaches* were necessary to reconstruct benzene concentrations in groundwater: (1) estimation of the volume of fuel loss and mass of LNAPL in the subsurface using site data and the model TechNAPLVol (Jang et al. 2013), (2) simulation of the dissolution of benzene from LNAPL and the subsequent fate and transport of dissolved benzene using the model TechFlowMP (Jang and Aral 2008) at the HPFF, and in Building 1115 and Building 1613 areas, and (3) simulation of the fate and transport of dissolved-phase benzene in groundwater in the Building 1601 area using the model MT3DMS (Jones et al 2013). Details on the specific simulation approaches are described in these topical ATSDR reports and in Maslia et al. (2013).

The LNAPL source area characterized using the TechNAPLVol model served as input to the three-dimensional finite-element model, TechFlowMP (Jang and Aral 2005, 2007), which was used to reconstruct benzene concentrations in groundwater and at historically operated water-supply wells within the HPIA. Additionally, the three-dimensional finite-difference model, MT3DMS (Zheng and Wang 1999; Zheng 2010), was used to reconstruct benzene concentrations within the HPIA where the benzene source was characterized as dissolved-phase benzene in the vicinity of Building 1601.

Figure 7.23 shows reconstructed (simulated) benzene concentrations in water-supply wells HP-602, HP-603, and HP-608. Reconstructed (simulated) monthly mean benzene concentrations in these water-supply wells and selected others in the HP-HB are listed **Appendix I** (from Maslia et al (2013, Appendix A3) for the entire historical reconstruction period (January 1942–June 2008). During November 1984, 32 water-supply wells provided water to the HPWTP. The reconstructed combined flow rate for all wells was 417,012 cubic feet per day (ft^3/d), whereas the corresponding flow rate for well HP-602 was 10,012 ft^3/d. Comparison of the combined flow rate for all water-supply wells to the flow rate for well HP-602 for November 1984 indicates that the benzene contribution from water-supply well HP-602 to the finished water benzene concentration at the HPWTP is substantially reduced by dilution, both under actual and simulated operating conditions. Simulated (reconstructed) benzene concentrations in water-supply wells HP-602 and HP-603 (**Appendix I**) indicate approximately the same range of concentrations during the core period of interest (1968–1985) to the epidemiological studies. Reconstructed benzene concentrations for well HP-602 are in reasonable agreement with field data. However, reconstructed benzene concentrations for water-supply well HP-603 are inconsistent with field data. One or all of several lines of reasoning possibly explain the disparity between reconstructed and sampled benzene concentrations in well HP-603: (1) the release date of hydrocarbon fuels in the vicinity of Building 1613 is unknown and its representation in the numerical model is uncertain, (2) the source concentration and size of the source area during much of the period of simulation are unknown and their representation in a numerical model is consequently highly uncertain, and (3) local hydraulic, fate, and transport characteristics in the vicinity of Building 1613 and water-supply well HP-603 may be different from the average hydraulic, fate, and transport

properties defined within the model subdomain (Figure 7.17 Table 7.14). Issues pertaining to source release and concentration were addressed by conducting sensitivity analyses varying model source area location, concentration, release date, and the contribution of benzene-contaminated and TCE-contaminated groundwater to finished-water concentrations at the HPWTP. For benzene, results indicated somewhat improved reconstructed concentrations in well HP-603 (Maslia et al. 2013, Figure A35 and Table A25) compared to field data; however, the corresponding changes in reconstructed benzene concentrations at the HPWTP are minimal (Maslia et al. 2013, Figure A36, p. A83).

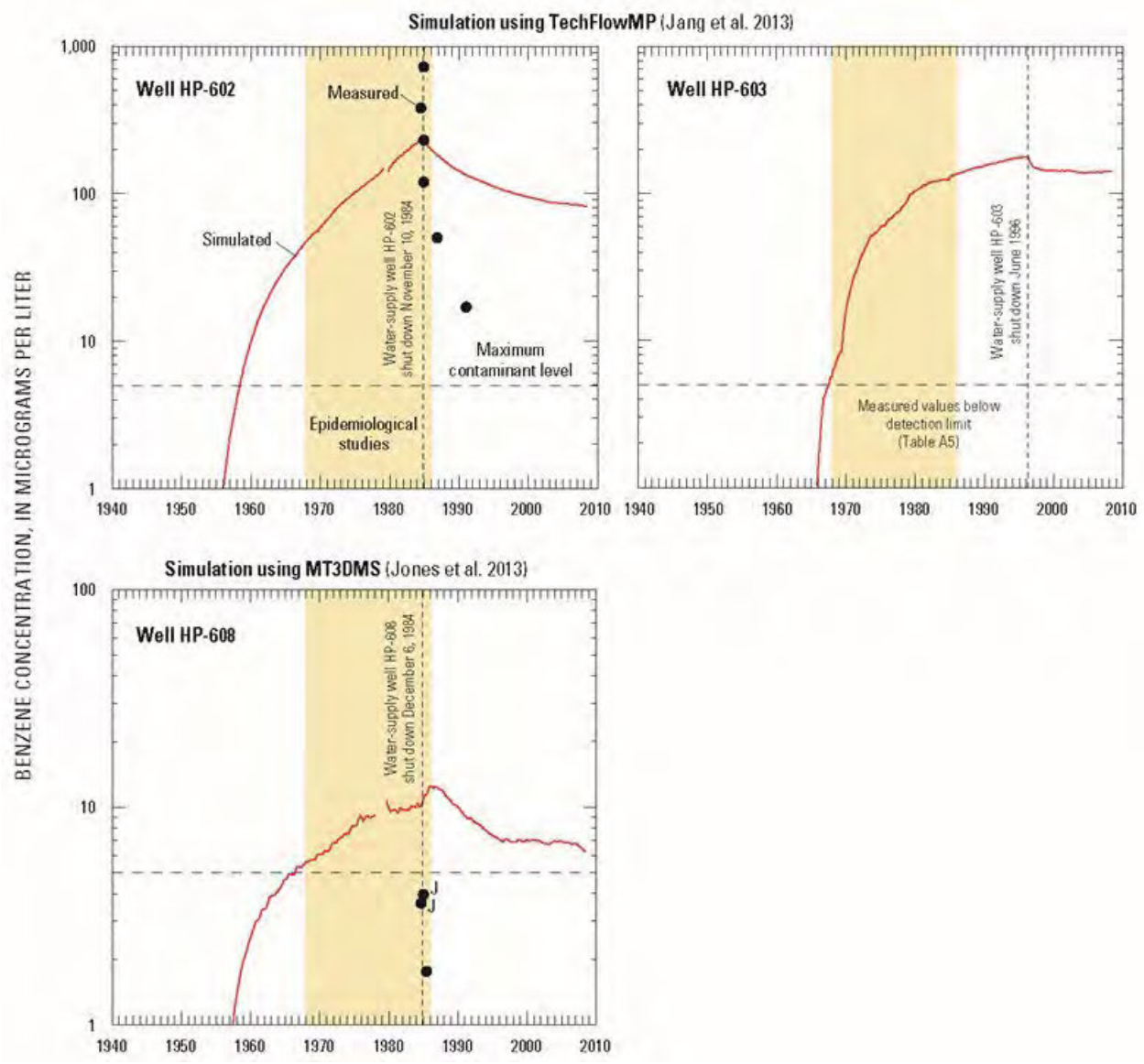


Figure 7.23. Reconstructed (simulated) and measured concentrations of benzene at selected water-supply wells within the Hadnot Point Industrial Area, Hadnot Point study area (Maslia et al. 2013).

Liner Control Model (LCM) Methodology

An alternative and simpler computational method, the Linear Control Model (LCM) methodology, which is a linear state-space representation of a contaminated groundwater aquifer system, was developed to reconstruct contaminant concentrations in water-supply wells and compare results with the MODFLOW and MT3DMS numerical modeling approach. The LCM methodology was investigated because (1) perhaps a simpler computational method requiring fewer resources could yield reliable historical reconstruction results and (2) results from an alternative computational method, if reliable, could be used to assess confidence in results derived from the MODFLOW and MT3DMS simulations. The LCM methodology, which is based on linear control theory, relies on two matrices to describe (1) the subsurface movement of a contaminant under predevelopment or natural conditions and (2) the effects of pumping operations on contaminant concentrations. This method, therefore, *characterizes the aquifer, contaminant sources, and the dynamics of contaminant migration as a "black box."* [10]

Deactivation of water-supply well HP-651, located adjacent to the HPLF (Figure 7.17), presented an opportunity to test and apply the LCM because there were sufficient, although limited, observation data once the well was secured and taken out of service on February 4, 1985 (CLW #4913; Sautner et al. 2013a). Measured data for PCE, TCE, 1,2-tDCE, and VC are shown graphically in Figure 7.24. Reconstructed historical monthly concentrations at water-supply well HP-651, derived using the LCM methodology, are shown in Figure 7.24 for PCE, TCE, 1,2-tDCE, and VC. For PCE and TCE, corresponding reconstructed (simulated) concentrations using the numerical contaminant fate and transport model MT3DMS (Zheng and Wang 1999; Zheng 2010) also are shown for comparison. **The results shown in Figure 7.24 demonstrate very good agreement between the LCM results, the numerical contaminant fate and transport model (MT3DMS) results, and observation data for water-supply well HP-651.** Thus, the application of the LCM to a contaminated water-supply well such as HP-651 demonstrates that historical contaminant concentrations can be reconstructed using a simpler modeling approach; results are reliable when compared with field data and historical reconstruction results from a numerical contaminant fate and transport model (MT3DMS). Details of the development of the LCM methodology and application to water-supply well HP-651 are presented in Guan et al. (2013).

[10] In science and engineering, the term "black box" refers to a device or system that can be analyzed in terms of inputs, transfer properties, and outputs, without specific knowledge of its internal dynamic workings.

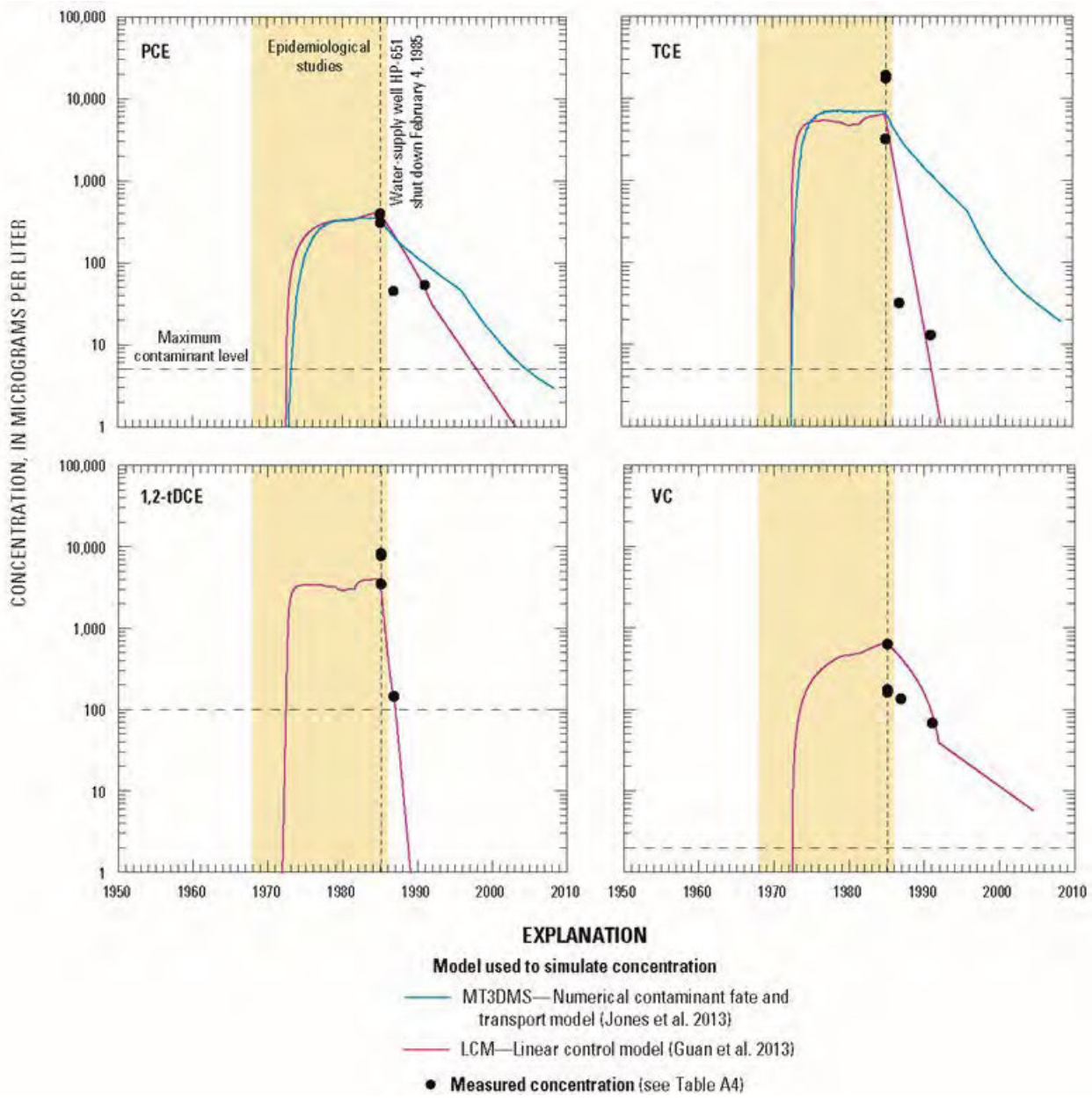


Figure 7.24. Reconstructed (simulated) and measured concentrations of tetrachloroethylene (PCE) and trichloroethylene (TCE), trans-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at water-supply well HP-651 using numerical (MT3DMS) and linear control methodology (LCM; TechControl) models, Hadnot Point study area (from Guan and Aral 2013, Maslia et al. 2013).

Level 4 Calibration (Mixing Model)

As discussed in the report section on Level 4 calibration for TT, the final level of model calibration employed a simple mixing (flow-weighted average) model to compute contaminant concentrations delivered to the HPWTP from all active water-supply wells and subsequently to the Hadnot Point water-distribution system. The model is based on the principles of continuity and conservation of mass (Masters 1998) and is used to compute the flow-weighted average concentration of contaminants in the HPIA, HPLF, and HPFF (PCE, TCE, 1,2-tDCE, VC, and benzene). Reconstructed (simulated) monthly mean concentrations of PCE, TCE, 1,2-tDCE, VC, and benzene in finished water delivered by the HPWTP and measured concentrations of VOCs in finished water are shown in Figure 7.25. Monthly reconstructed concentrations at the HPWTP for the entire historical period (1942–2008) are listed in **Appendix J**. Because the range in values for reconstructed and measured concentrations span several orders of magnitude, Figure 7.25 is plotted using a logarithmic ordinate (y-axis). Of note in Figure 7.25 is the effect of the contribution of contaminated groundwater when pumping began at water-supply well HP-651 (July 1972). TCE concentrations in finished water at the HPWTP ranged from about 10 to 30 µg/L for the period 1955–1972, prior to the onset of pumping from water-supply well HP-651 (Figure 7.25, and Appendix I). Subsequent to the onset of pumping of water-supply well HP-651 during July 1972, finished-water concentrations increased to a maximum computed value of 783 µg/L during November 1983 (Figure 7.25, Table 7.5, and **Appendix J**).

The reconstructed concentrations versus the observed data in Table 7.15 and Figure 7.25 demonstrate successful Level 4 calibration as the observed data from the HPWTP represents a separate, unique data set that has been used assess the "goodness of fit" of the calibrated HP-HB models. Table 7.15 Figure 7.25 demonstrate close agreement between simulated and measured contaminant concentrations (PCE, TCE, 1,2-tDCE, VC, and benzene) at the HPWTP. This close agreement between simulated and measured values (within a factor of ten – Maslia et al., 2016) is acceptable for the complexity of this site and supports the collective ability of the four-level modeling and calibration process to capture the HP-HB system behavior with acceptable accuracy.

Summary statistics of reconstructed (simulated) concentrations of selected water-supply wells located at the HPIA and the HPLF are listed in Table 7.16. Summary statistics for finished water at the HPWTP are also listed in Table 7.16. Results are provided for reconstructed concentrations of PCE, TCE, 1,2-tDCE, VC, and benzene. Included in the statistics of Table 7.16 is the duration in months that these contaminants exceeded their respective MCLs. The reconstructed (simulated) concentrations in finished water at the HPWTP are shown in Figure 7.25 for PCE, TCE, 1,2-tDCE, VC, and benzene. These estimates were computed using a materials mass balance model (simple mixing) to compute the flow-weighted mean concentrations of VOCs as described earlier in this report (using Equations 7.1 and 7.2). Measured concentrations of PCE, TCE, 1,2-tDCE, VC, and benzene and historical reconstruction (simulated) results for the HPWTP are listed in Table 7.15. Given the limited number of measured finished-water concentration data and their substantial variations, **there is reasonable agreement between measured finished-water concentrations and historical reconstruction results for the HPWTP**.

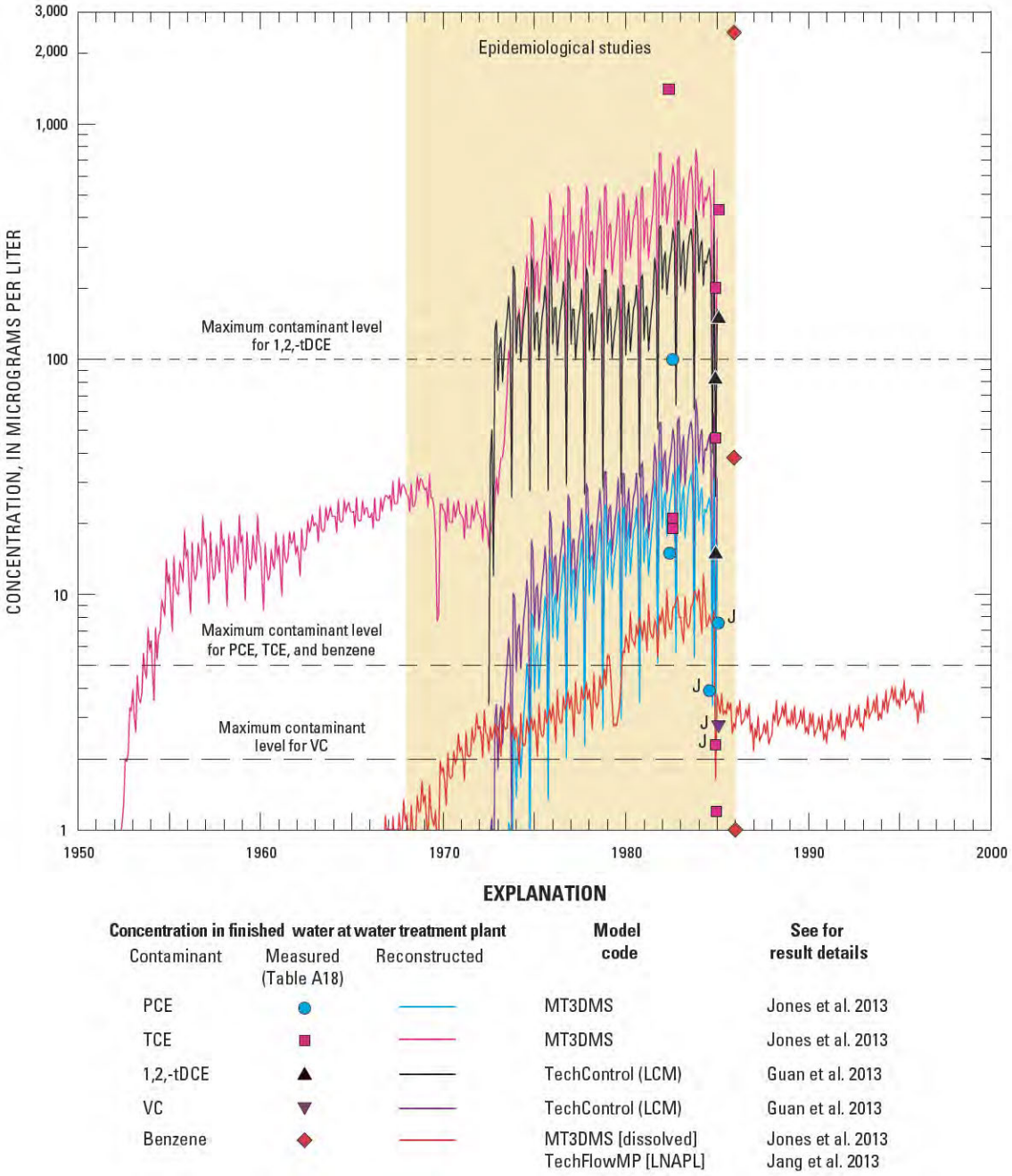


Figure 7.25. Reconstructed (simulated) finished-water concentrations of tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, and measured concentrations (Faye et al. 2010), Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area. (Note: See Appendix J for monthly mean finished-water concentration). (From Maslia et al. 2013) [J, estimated; LCM, linear control model; LNAPL, light nonaqueous phase liquid].

Table 7.15. Selected measured and reconstructed (simulated) concentrations of tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene at the Hadnot Point water treatment plant, Hadnot Point study area (Maslia et al. 2013).

Contaminant	[1]Measured data		[2]Reconstructed (simulated)		[2]Reconstructed (maximum value)	
	Sample date	Concentration, in µg/L	Simulation date	Concentration, in µg/L	Simulation date	Concentration, in µg/L
PCE	5/27/1982[3]	15	May 1982	21	Nov. 1983	39
	7/27/1982[4]	100	July 1982	27		
	12/4/1984[6]	3.9J	Nov. 1984	31		
	2/5/1985[7]	7.5J	Jan. 1985	16		
TCE	5/27/1982[3]	1,400	May 1982	438	Nov. 1983	783
	7/27/1982[5]	19	Aug. 1982	670		
	7/27/1982[6]	21	Aug. 1982	670		
	12/4/1984[5]	46	Nov. 1984	639		
	12/4/1984[6]	200	Nov. 1984	639		
	12/12/1984[6]	2.3J	Dec. 1984	43		
	12/19/1984	1.2	Dec. 1984	43		
	2/5/1985[7]	429	Jan. 1985	324		
1,2-tDCE	12/4/1984[6]	83	Nov. 1984	358	Nov. 1983	435
	12/4/1984[5]	15	Dec. 1984	26		
	12/12/1984[6]	2.3J	Dec. 1984	26		
	2/5/1985[7]	150	Jan. 1985	163		
VC	2/5/1985[7]	2.9J	Jan. 1985	31	Nov. 1983	67
Benzene	11/19/1985[7,8,9]	2,500	Nov. 1985	3	Apr. 1984	12
	12/10/1985[7]	38	Dec. 1985	3		
	12/18/1985[7]	1.0	Dec. 1985	3		

[1] Data from Faye et al. (2010, Tables C11 and C12)
[2] Simulation results represent the last day of each month (e.g., May 31); results reported for simulation month nearest the sample date; refer to Appendix A7 for complete listing of reconstructed finished-water concentrations
[3] Water sample collected at Building NH-1; data reported as unreliable
[4] Water sample collected at Building FC-530
[5] Untreated water
[6] Treated water
[7] Treatment status unknown
[8] Laboratory analysis noted with: "Sample appears to have been contaminated with benzene, toluene, and methyl chloride" (JTC Environmental Consultants 1985)
[9] Data noted with: "Not Representative" (U.S. Marine Corp Base Camp Lejeune Water Document CLW #1356)

Table 7.16. Summary statistics for reconstructed contaminant concentrations at selected water-supply wells and the Hadnot Point water treatment plant, Hadnot Point-Holcomb Boulevard study area (Maslia et al. 2013).[1,2]

Water-supply identification (contaminant)	Reconstructed (simulated) concentration, in micrograms per liter				[2]Duration in months exceeding MCL (month and year first exceeding MCL)	Date well stopped pumping in model
	[3]July 1942–June 1996			Range during health study period of interest (January 1968–February 1985)		
	Maximum (date of maximum)	Mean	Standard deviation			
[4]Hadnot Point Industrial Area (HPIA)						
HP-602 (TCE)	658 (Jan. 1959)	359	222	357–499	390 (Oct. 1951)	Dec. 1984
HP-608 (TCE)	50 (Sept. 1972)	25	20	28–50	307 (Aug. 1957)	Dec. 1984
HP-634 (TCE)	659 (Oct. 1968)	391	170	212–659	283 (Aug. 1960)	Dec. 1984
HP-602 (benzene)	236 (Nov. 1984)	53	65	48–236	309 (July 1958)	Dec. 1984
HP-603 (benzene)	179 (May 1996)	29	43	6–129	345 (Aug. 1967)	June 1996
HP-608 (benzene)	11 (Sept. 1979)	4	4	6–11	201 (June 1966)	Dec. 1984
[4]Hadnot Point landfill (HPLF)						
HP-651 (PCE)	353 (Dec. 1982)	249	122	[5]0–353	142 (Apr. 1973)	Feb. 1985
HP-651 (TCE)	7,135 (Dec. 1978)	5,831	2,071	[5]1–7,135	150 (Aug. 1972)	Feb. 1985
HP-651 (1,2-tDCE)	4,037 (Dec. 1984)	3,284	572	[5]69–4,037	150 (Aug. 1972)	Feb. 1985
HP-651 (VC)	660 (Nov. 1984)	391	173	[5]8–660	151 (July 1972)	Feb. 1985
[6]Hadnot Point water treatment plant (HPWTP)						
HPWTP (PCE)	39 (Nov. 1983)	4	8	0–39	114 (Aug. 1974)	N/A
HPWTP (TCE)	783 (Nov. 1983)	107	180	0–783	374 (Aug. 1953)	N/A
HPWTP (1,2-tDCE)	435 (Nov. 1983)	53	95	0–435	128 (Nov. 1972)	N/A
HPWTP (VC)	67 (Nov. 1983)	6	13	0–67	144 (Nov. 1972)	N/A
HPWTP (benzene)	12 (Apr. 1984)	2	3	0–12	63 (Jan. 1979)	N/A

[1]For periods of time when concentrations are equal to or exceed the current MCLs for TCE, PCE, and benzene; non-rounded concentration values used to calculate statistics

[2] Current MCLs are as follows: vinyl chloride, 2 µg/L; PCE, TCE, and benzene, 5 µg/L; 1,2-tDCE, 100 µg/L (see Maslia et al.

[3] Statistics are computed solely for periods of operation

[4] See Maslia et al. (2013, Appendix A3) for complete listing

[5] Water-supply well HP-651 did not start pumping until July 1972; values shown represent dates of July 1972–February 1985

[6] Finished-water concentrations; see Maslia et al. (2013, Appendix A7) for complete listing

Uncertainty

Best modeling practice requires that evaluations be conducted to ascertain confidence in models and model results by assessing parameter sensitivity, variability, and uncertainty associated with the modeling process and with the outcomes attributed to models (ASTM 1994; Saltelli et al. 2000). There are numerous methods for characterizing a model's sensitivity and uncertainty based on variations of calibrated parameter values (ASTM 1994; Cullen and Frey 1999; Salltelli et al. 2000; Tung and Yen 2005; Hill and Tiedeman 2007). These methods are generally classified into two groups: (1) sensitivity analysis, wherein calibrated model parameter values are varied either manually or through some automated method, and (2) probabilistic uncertainty analysis, wherein probabilistic methods are used to characterize and quantify the input and output parameter variation and uncertainty.

Sensitivity Analysis

A sensitivity analysis enables the modeler to evaluate how model output (simulated concentrations) responds to changes in model input parameters. By identifying parameter sensitivity, the modeler can better determine which input parameters have the greatest and least impact on model output. For the HP models, a number of sensitivity analyses were conducted. These included: varying hydraulic, fate and transport model parameters, benzene source-area and source-release, TCE source-release-date, and numerical model grid size and time-step variations. These sensitivity analyses are discussed in much detail in Maslia et al. (2013, p. A79–A91).

Figure 7.26 shows reconstructed (simulated) values of the HPWTP finished water for three different sensitivity analysis scenarios. Scenario 1, adjusting four variables, Scenario 2, adjusting five variables , and Scenario 3, adjusting seven variables. These sensitivity analyses were conducted to see how increasing levels of uncertainty in the input parameters impact the reconstructed values (see Figure 7.26 explanation for information on which parameters were varied). The darker interior (center) lines on Figure 7.26 represent the average (mean) reconstructed contaminant concentration levels. In contrast, the shaded region represents the variability in reconstructed contaminant concentration levels ranging from minimum (lower end of the shaded region) to maximum (higher end of the shaded region) reconstructed values for varying parameter input.

Based on these results, it is scientifically defensible to conclude that during the period of the 1950s to the mid-1980s, contaminant concentration levels would have occurred within this range of values (the shaded region) at HPWTP, with the average (most likely) values being the solid line in the interior. Although reconstructed concentrations were found to vary for these scenarios (the reconstructed levels were found to be sensitive to input parameter values), **exceedance of the MCL was shown to have occurred in all cases**.

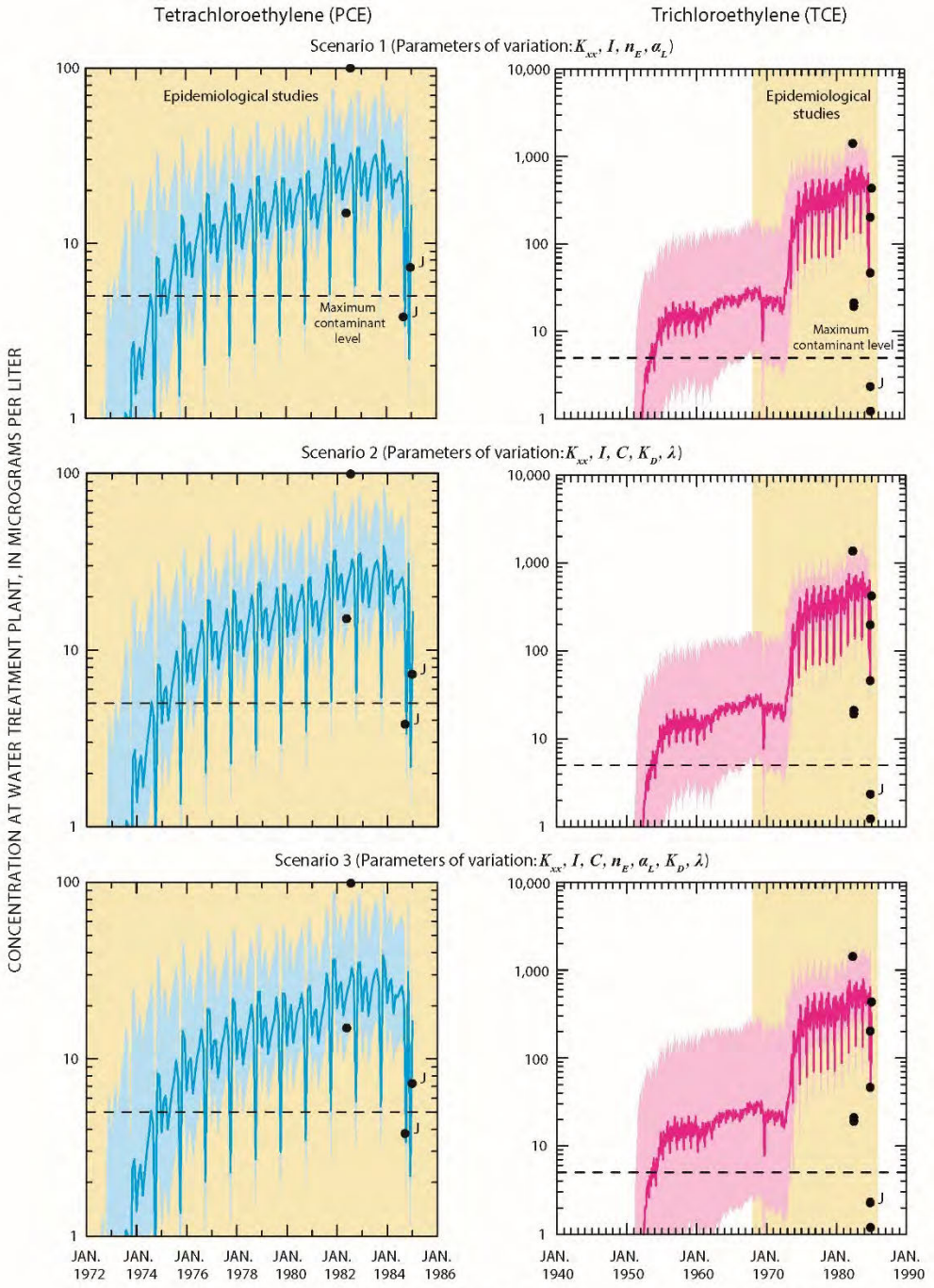


Figure 7.26. Concentrations of tetrachloroethylene (PCE) and trichloroethylene (TCE) in finished water at the Hadnot Point water treatment plant derived from model calibration and hydraulic, fate, and transport model parameter sensitivity analysis, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. [K_{xx}, horizontal hydraulic conductivity; I, infiltration; C, source concentration; n_E, porosity; α_L, longitudinal dispersivity; K_D, distribution coefficient; λ, biodegradation rate; J, estimated]

In all cases, the average of reconstructed values (the values represented by the dark solid line in the center of the shaded region) indicate that contaminant concentration levels were above the drinking water standard (MCL), as do the vast majority of reconstructed values in the sensitivity analyses (the vast majority of the shaded regions are above the drinking water MCL shown by the horizontal dashed line in Figure 7.26). The sensitivity analysis thus demonstrates that even in the worst-case scenario (if all seven input parameters deviated substantially from actual calibrated values and field data), **the historically reconstructed values still indicate PCE and TCE concentration levels above the drinking water MCL**.

Probabilistic Analysis

As discussed in the TT study area of this report, a probabilistic analysis is used to generate uncertainties in model inputs (for example, hydraulic conductivity or contaminant source mass loading rate) so that estimates of uncertainties in model outputs (for example water level or TCE concentration at the HPWTP) can be made. Of particular interest was the uncertainty and variability of water-supply well monthly operational schedules and the impact that the uncertainty and variability would have on the TCE concentrations at the HPWTP. To demonstrate the effect of uncertainty in the pumping schedules of water-supply wells, the 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 MCS by reducing the number of simulations required.

Details of applying the LHS method are described in Maslia et al. (2013, p. A93-A94) and Telci et al. (2013). The revised pumping schedules due to uncertainty and variability relative to the calibrated schedules reported in Telci et al. (2013) are 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 7.27. In this figure, the red line indicates the TCE concentration obtained from the calibrated models (Figure 7.25). The gray lines indicate the TCE concentration variation over time for 10 random scenarios obtained by LHS methodology. Results shown in Figure 7.27 indicate that observed data exhibit substantially greater variation than reconstructed concentrations generated using the LHS-Monte Carlo uncertainty analysis. It also shows that even under uncertainty, there is substantially high concentrations of TCE in finished water at the HPWTP after the onset of pumping at well HP-651.

In summary, effects of parameter uncertainty and variability were analyzed using two approaches—sensitivity analysis and probabilistic analysis. Individually and combined, these analyses demonstrate the high reliability of and confidence in results determined using the calibrated MODFLOW and MT3DMS models.

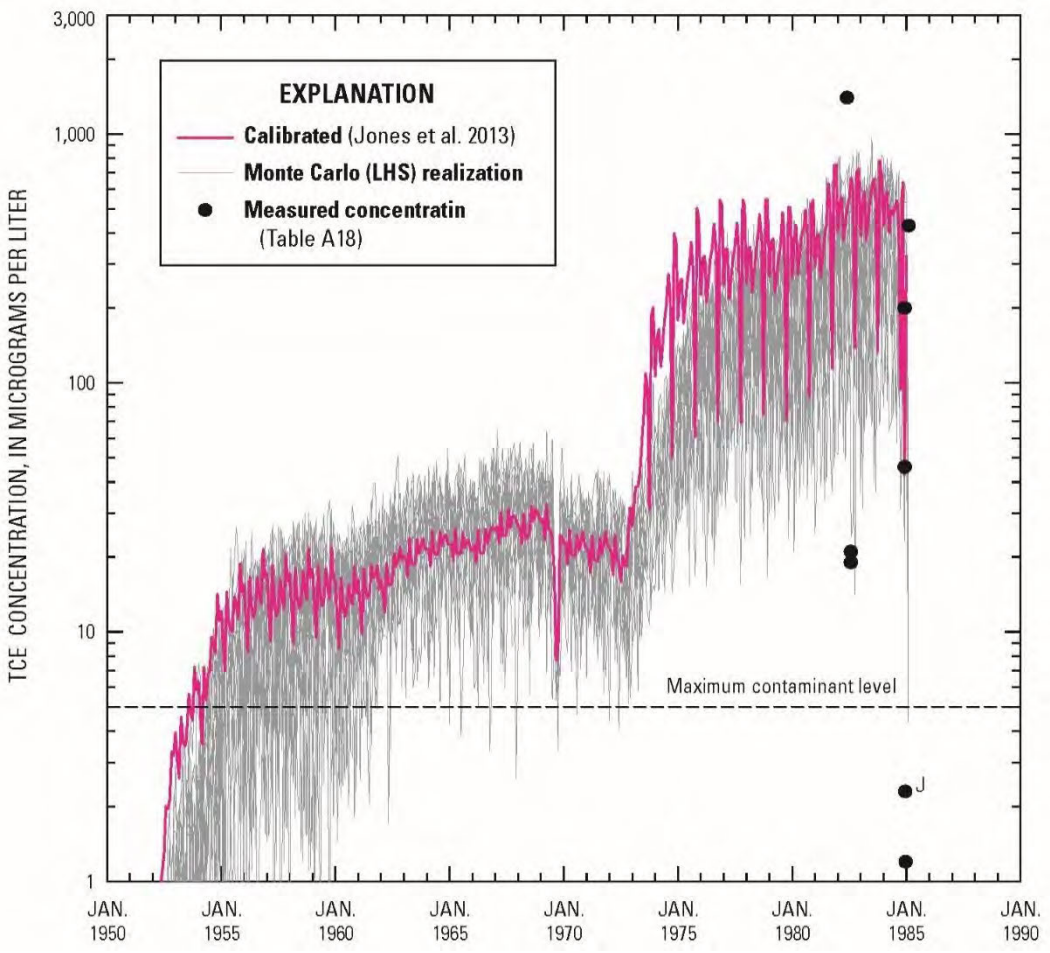


Figure 7.27. Variations in reconstructed (simulated) finished-water concentrations of trichloroethylene (TCE) derived using Latin hypercube sampling (LHS) methodology on water-supply well monthly operational schedules, Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area (Maslia et al. 2013). [J, estimated].

Conclusions Regarding Hadnot Point

Based on information sources, field data, modeling analyses and results, and the historical reconstruction process, the following conclusions are made with respect to groundwater and finished-water contamination for Hadnot Point:

- **For the Hadnot Point water treatment plant (HPWTP) service area:**
    - The reconstructed contamination of finished water exceeding the current maximum contaminant level (MCL) for TCE was 374 months (August 1953–January 1985) (Table 7.14). With the onset of pumping at well HP-651 during July 1972, the concentration of TCE in well HP-651 affected the resulting finished-water concentrations of TCE at the HPWTP, which exceeded 750 µg/L during November 1983 (Table 7.16). Measured TCE concentrations in finished water at the HPWTP during the period May 1982 through February 1985 ranged from 1.2 µg/L to 1,400 µg/L (Table 7.15).

- The reconstructed contamination of finished water exceeding the current MCL for PCE was 114 months (August 1974–January 1985) (Table 7.16), also a consequence of the onset of pumping of well HP-651. The maximum reconstructed finished-water concentration of PCE was about 40 µg/L during November 1983 (Table 7.14). Measured PCE concentrations at the HPWTP ranged from below detection limits (1–10 µg/L) to 100 µg/L during the period May 1982–February 1985 (Table 7.16).
- The reconstructed duration of contamination of finished water exceeding the current MCL for benzene was 63 months (January 1979–November 1984) (Table 7.16); the maximum reconstructed finished water concentration of benzene was about 12 µg/L during April 1984 (Table 7.16). Measured benzene concentrations at the HPWTP ranged from below detection limits (10 µg/L) to 38 µg/L during the period December 1984–December 1985. An unexplained value of 2,500 µg/L of benzene was measured on November 11, 1985 (Table 7.16).
- Monthly mean reconstructed contaminant-specific concentrations at selected water-supply wells and at the HPWTP for the entire historical period are included with this report as **Appendix I** and **Appendix J**, respectively. They represent, within reasonable scientific and engineering certainty, the contaminant levels in supply wells and in finished water (HPWTP) from 1953 to 1987.

- **For the Hadnot Point Industrial Area (HPIA):**
  - The maximum reconstructed (simulated) monthly mean TCE concentrations at water-supply wells HP-602, HP-608, and HP-634 were 658 micrograms per liter (µg/L) during January 1959, 50 µg/L during September 1972, and 659 µg/L during October 1968, respectively (**Appendix I**). Measured TCE concentrations at well HP-602 ranged from an estimated 0.7 µg/L to 1,600 µg/L during the period of record, July 1984 to January 1991 (Table A4(H)). Corresponding concentrations at well HP-608 ranged from 9 µg/L to110 µg/L during the period of record, December 1984 to November 1986. In well HP-634 between December 1984 and January 1991, TCE concentrations ranged from less than detection limits to 1,300 µg/L.
  - At water-supply wells with measured benzene concentrations exceeding detection limits (HP-602 and HP-608), the maximum reconstructed (simulated) monthly benzene concentration was 236 µg/L at well HP-602 during November 1984 and 11 µg/L at well HP-608 during September 1979 (Table 7.16 and **Appendix I**). Measured benzene concentrations at well HP-602 during the period of record, July 1984 to January 1991, ranged from less than 1.0 µg/L to 720 µg/L. Measured benzene concentrations at well HP-608 during the period of record, December 1984 to November 1986, ranged from 1.6 µg/L to an estimated 4.0 µg/L. All measured benzene concentrations in well HP-603 were below detection limits (Maslia et al. 2013, Table A5, p. A32).

- **For the Hadnot Point landfill (HPLF) area:**
    - The maximum reconstructed (simulated) monthly mean TCE concentration at water-supply well HP-651 was 7,135 µg/L during December 1978 (Table 7.16). Measured TCE concentrations during the period of record, January 1985 to January 1991, ranged from 13 µg/L to 18,900 µg/L (Maslia et al. 2013, Table A4, p.A31).
    - The maximum reconstructed (simulated) monthly PCE concentration at water-supply well HP-651 was 353 µg/L during December 1982 (Table 7.16). Measured PCE concentrations during the period of record, January 1985 through January 1991, ranged from 45 µg/L to 400 µg/L (Maslia et al. 2013, Table A4, p.A31).
    - The maximum reconstructed (simulated) monthly mean 1,2-tDCE concentration at water-supply well HP-651 was 4,037 µg/L during December 1984 (Table 7.16). Measured 1,2-tDCE concentrations during the period of record, January 1985 to November 1986, ranged from 140 µg/L to 8,070 µg/L (Maslia et al. 2013, Table A4, p.A31).
    - The maximum reconstructed (simulated) monthly mean VC concentration at water-supply well HP-651 was 660 µg/L during November 1984 (Table 7.16). Measured VC concentrations during the period or record, January 1985 to January 1991, ranged from 70 µg/L to 655 µg/L (Maslia et al. 2013, Table A4, p.A31).

7.5.3 Holcomb Boulevard (HB)

During the period June 1972–December 1985, the HP and HB water-distribution systems were intermittently interconnected during dry spring and summer months. During these periods, contaminated HP finished water (Figure 7.25) was transferred to and distributed within the uncontaminated HB water-distribution system. The interconnection of the two water-distribution systems was primarily accomplished by operating booster pump 742, although on rare occasions, the valve at Marston Pavilion (near Wallace Creek) also was opened (Figure 7.1). Operational records indicating booster pump 742 operations and Marston Pavilion valve openings are only partially documented. Interconnection information and data that are available were obtained from the Camp Lejeune water utility log books (CLW #7023–CLW #8735).

Because of the interconnection of the HP and HB water-distribution systems, a more complex analysis was necessary (compared to the simple mixing-model approach described by Equations 7.1 and 7.2 and used to reconstruct finished-water concentrations for the TTWTP and HPWTP) to determine the concentration of finished water in the HB water-distribution system (Figure 7.28) during periods of interconnection. This required the application of the EPANET 2 water-distribution system model (Rossman 2000) and extended period simulation (EPS). The EPANET 2 water-distribution system model was calibrated for the HB water-distribution system using field data collected by the ATSDR water-modeling team; field data represented operational conditions during 2004 (Sautner et al. 2013). EPSs were used to reconstruct water-distribution system flow and mass transport patterns during discrete interconnection events when booster pump 742 was intermittently operated, resulting in the transfer of contaminated finished water from the HP water-distribution system to the “uncontaminated” HB

water-distribution system. Pipelines represented in the water-distribution system network models coincide with locations of streets within the HP and HB study areas (Maslia et al. 2009b, Figure I3).

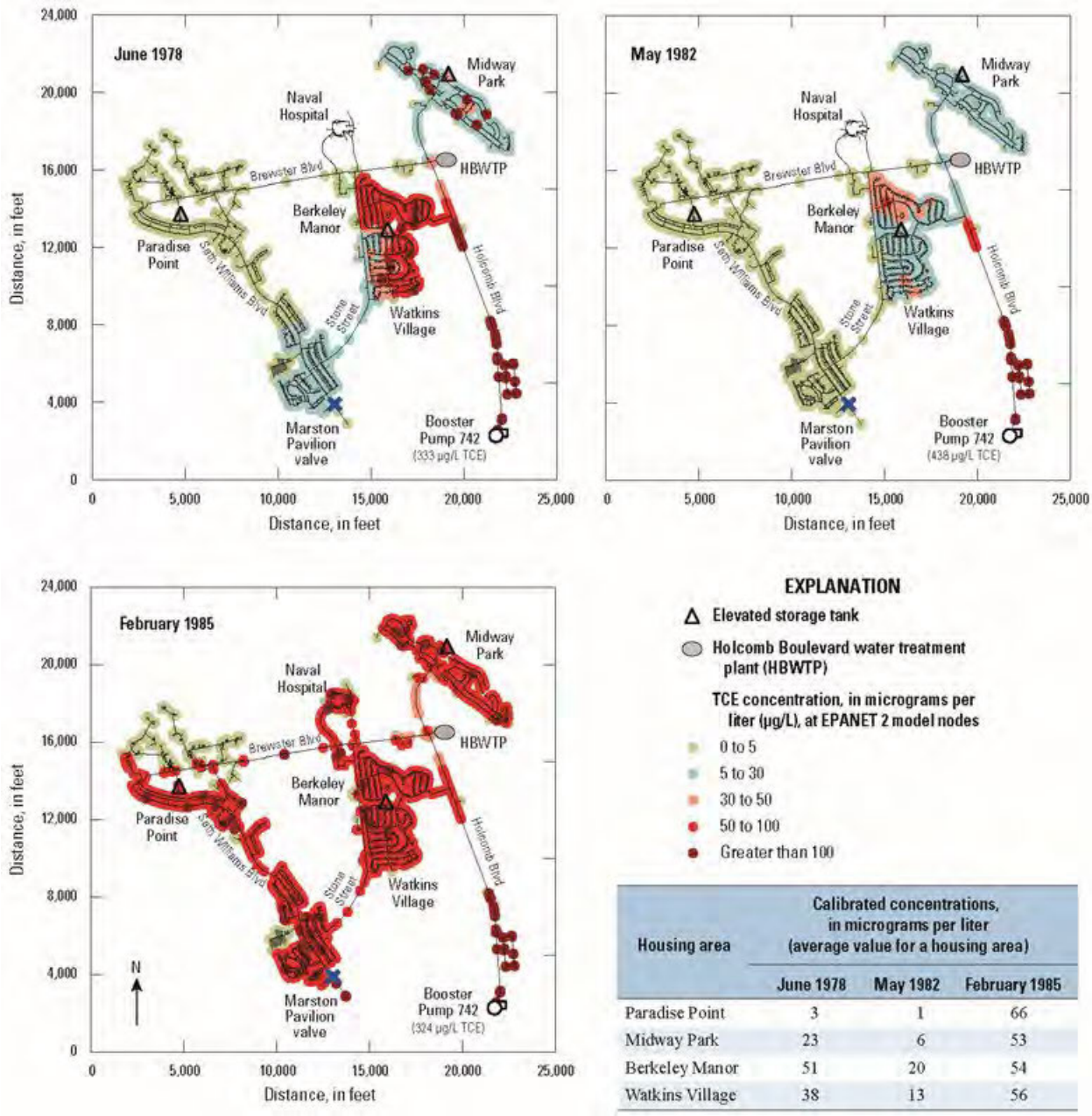
A complete listing of reconstructed contaminant concentrations (PCE, TCE, 1,2-tDCE, VC, and benzene) for the HB water-distribution system for 1972–1985 is provided in **Appendix K**. Spatial distributions of TCE levels within HB housing areas for three time periods—June 1978, May 1982, and February 1985—are shown in Figure 7.28 and listed in Table 7.17. These historical reconstruction results were obtained using the EPANET 2 water-distribution system model for interconnection events. The HB reconstructed drinking-water mean TCE concentrations for the Berkeley Manor and Watkins Village housing areas during June 1978 are 51 µg/L and 38 µg/L, respectively (Figure 7.28, Table 7.17, and **Appendix K**). For May 1982, the Berkeley Manor and Watkins Village housing areas show reconstructed mean TCE concentrations of 20 µg/L and 13 µg/L, respectively. During the 8-day period of 28 January–4 February 1985 (represented by the February 1985 map in Figure 7.28), when the HBWTP was shut down, the reconstructed mean TCE concentrations in all housing areas exceeded 50 µg/L with the exception of the northernmost extent of Paradise Point and a small area to the north of the Marston Pavilion valve (the current MCL for TCE in drinking water is 5 µg/L). Overall, during intermittent transfers of contaminated HP drinking water, the Paradise Point family housing area shows the lowest reconstructed mean TCE concentrations, whereas Berkeley Manor followed by Watkins Village show the greatest reconstructed mean TCE concentrations (except for the pipeline that directly connects booster pump 742 to the HB water-distribution system along Holcomb Boulevard). Spatial distribution maps for the other contaminants of concern (similar to Figure 7.28) are provided in Sautner et al. (2013b). Reconstructed concentrations for the other contaminants of concern (PCE, 1,2-tDCE, VC, and benzene) rarely equaled or exceeded their current MCLs during interconnection periods of interest to the ATSDR health studies (Table 7.17 and **Appendix K**).

Conclusions Regarding Holcomb Boulevard

Based on information sources, field data, modeling analyses and results, and the historical reconstruction process, the following conclusions are made with respect to the contaminated finished water delivered to Holcomb Boulevard:

- When this housing area was serviced by the HPWTP (prior to June 1972), the maximum reconstructed (simulated) monthly mean TCE concentration in finished water of interest to the ATSDR health studies (January 1968–December 1985) was 32 µg/L during August 1968 and August 1969 (**Appendix J**). The minimum reconstructed (simulated) monthly mean TCE concentration in finished water of interest to the health studies (January 1968–December 1985) was 8 µg/L (September and October 1969). TCE concentrations in finished water first exceeded the MCL during August 1953 (**Appendix J**).

- After June 1972 when the HBWTP came online to service this housing area, an interconnection analysis indicates that the maximum reconstructed (simulated) TCE concentration in finished water was 66 µg/L during February 1985 for the Paradise Point area (Figure 7.28, Table 7.17, and **Appendix K**).



Housing area	Calibrated concentrations, in micrograms per liter (average value for a housing area)		
	June 1978	May 1982	February 1985
Paradise Point	3	1	66
Midway Park	23	6	53
Berkeley Manor	51	20	54
Watkins Village	38	13	56

Figure 7.28. Reconstructed (simulated) distribution of trichloroethylene (TCE) contamination within the Holcomb Boulevard water treatment plant service area resulting from supply of contaminated Hadnot Point finished water, June 1978, May 1982, and February 1985 (see Maslia et al. 2013, Figure A1 for location map of Holcomb Boulevard water-distribution system).

Table 7.17. Reconstructed (simulated) mean concentrations of tetrachloroethylene, trichloroethylene, *trans*-1,2-dichloroethylene, vinyl chloride, and benzene in finished water distributed to Holcomb Boulevard family housing areas for selected months, Hadnot Point– Holcomb Boulevard study area (Maslia et al. 2013, Sautner et al. 2013b)[1,2]

[µg/L, microgram per liter; PP, Paradise Point; MP, Midway Park; BM, Berkeley Manor; WV, Watkins Village; —, not applicable]

Month Year	Concentration, in µg/L				Month Year	Concentration, in µg/L				Month Year	Concentration, in µg/L			
	PP	MP	BM	[3]WV		PP	MP	BM	[3]WV		PP	MP	BM	[3]WV
Tetrachloroethylene (PCE)[4]														
June 1978	0	1	2	2	May 1982	0	0	1	1	Jan. 1985[5]	2	2	2	2
June 1980	0	0	1	1	June 1982	0	0	1	0	Feb. 1985[5]	3	3	3	3
Apr. 1981	0	0	2	1	July 1982	0	0	1	0					
May 1981	0	0	1	0	May 1983	0	0	1	0					
Trichloroethylene (TCE)[4]														
Jan. 1972	22	22	22	—	May 1978	0	2	6	4	Apr. 1982	0	3	9	7
Feb. 1972	21	21	21	—	June 1978	3	23	51	38	May 1982	1	6	20	13
Mar. 1972	17	17	17	—	July 1978	0	0	1	1	June 1982	0	4	10	7
Apr. 1972	24	24	24	—	Apr. 1979	0	1	2	1	July 1982	0	4	12	8
May 1972	19	19	19	—	May 1979	0	1	3	2	Aug. 1982	1	3	6	4
June 1972	19	19	19	—	June 1979	0	2	6	4	May 1983	1	5	14	10
July 1972	1	0	0	—	July 1979	0	1	4	2	June 1983	0	0	2	2
June 1973	0	0	1	—	Aug. 1979	0	2	5	3	July 1983	0	0	3	2
June 1976	1	2	3	—	June 1980	2	8	17	13	Aug. 1983	0	2	5	3
Apr. 1977	0	1	2	—	Apr. 1981	0	4	39	28	Apr. 1984	0	2	5	3
May 1977	1	1	3	—	May 1981	0	4	13	10	Jan. 1985[5]	34	31	32	34
June 1977	1	2	3	—	June 1981	0	4	10	7	Feb. 1985[5]	66	53	54	56
July 1977	1	2	3	—	July 1981	0	2	4	3					
Aug. 1977	1	2	4	—	Aug. 1981	0	2	6	4					
Trans-1,2-dichloroethylene (1,2-tDCE)[4]														
June 1973	0	1	1	—	June 1979	0	1	3	2	June 1982	0	2	6	4
June 1976	0	1	2	—	July 1979	0	0	1	1	July 1982	0	2	6	4
Apr. 1977	0	1	1	—	Aug. 1979	0	1	2	1	Aug. 1982	0	2	3	2
May 1977	0	1	1	—	June 1980	1	3	7	5	May 1983	0	3	8	5
June 1977	0	1	1	—	Apr. 1981	0	2	16	12	June 1983	0	0	1	1
July 1977	0	1	2	—	May 1981	0	2	6	4	July 1983	0	0	2	1
Aug. 1977	0	1	2	—	June 1981	0	2	4	3	Aug. 1983	0	1	3	2
May 1978	0	1	3	2	July 1981	0	1	2	1	Apr. 1984	0	1	2	2
June 1978	2	10	22	17	Aug. 1981	0	1	3	2	Jan. 1985[5]	17	16	16	17
Apr. 1979	0	1	1	1	Apr. 1982	0	2	4	3	Feb. 1985[5]	33	27	27	27
May 1979	0	0	1	1	May 1982	0	3	10	7					
Vinyl chloride (VC)[4]														
June 1978	0	1	3	2	June 1981	0	0	1	0	July 1982	0	0	1	1
June 1980	0	1	1	1	Apr. 1982	0	0	1	0	May 1983	0	0	1	1
Apr. 1981	0	0	3	2	May 1982	0	0	1	1	Jan. 1985[5]	3	3	3	3
May 1981	0	0	1	1	June 1982	0	0	1	1	Feb. 1985[5]	6	5	5	5
Benzene[4]														
Jan. 1972	3	3	3	—	Apr. 1972	3	3	3	—	June 1978	0	0	1	0
Feb. 1972	3	3	3	—	May 1972	3	3	3	—	Apr. 1981	0	0	1	1
Mar. 1972	2	2	2	—	June 1972	3	3	3	—	Feb. 1985[5]	1	1	1	1

[1] See Appendix A8 (Tables A8.1–A8.5) for complete monthly listing, January 1972–December 1985

[2] Values for January–June 1972 represent Hadnot Point finished water without any mixing (dilution) with Holcomb Boulevard water treatment plant (WTP) finished water because the Holcomb Boulevard WTP came online after June 1972 (Scott A. Brewer, U.S. Marine Corps Base Camp Lejeune, written communication, September 29, 2005)

[3] Watkins Village housing was not built and occupied until about 1978 (Faye et al. 2010), and the first documented interconnection occurs during May 1978 (U.S. Marine Corps Base Camp Lejeune Water Documents CLW #7023, #7031, and #7033)

[4] Current maximum contaminant level (MCL) for PCE, TCE, and benzene is 5 µg/L; current MCL for 1,2-tDCE is 100 µg/L; current MCL for VC is 2 µg/L; see Table A3

[5] For the 8-day period January 28–February 4, 1985, the Holcomb Boulevard water treatment plant was shut down, and contaminated Hadnot Point finished water was continuously provided to Holcomb Boulevard family housing areas

- After June 1972 when the HBWTP came online to service this housing area, the maximum reconstructed (simulated) monthly concentrations for PCE, 1,2-tDCE, and VC in finished water for the HB housing area occurred during February 1985 and were 3 µg/L, 33 µg/L, and 6 µg/L, respectively (**Appendix K**). The maximum reconstructed (simulated) monthly concentration for benzene was 3 µg/L, occurring during January, February, April, May, and June 1972 (Table 7.15).

- Monthly mean reconstructed contaminant-specific concentrations delivered to HB for the entire historical period included with this report as **Appendix K** represent, within reasonable scientific and engineering certainty, the contaminant levels in finished water from 1953 to 1987.

7.5.4 Discussion and Conclusions

The application and use of water modeling techniques to assist epidemiological studies has been proven to be a reliable and accepted method for obtaining environmental exposure concentrations. Three high-profile, public sites—Woburn, Massachusetts, Dover Township (Toms River), New Jersey, and USMCB Camp Lejeune, North Carolina—have all obtained **definitive results** by using water-modeling techniques (Costas 2002, NJDHSS 2003, Bove et al. 2014a, 2014b, Ruckart et al. 2013, 2014, 2015). The historical reconstruction process, which includes information and data mining activities and water-modeling methods can be used to reliably quantify estimates of mean monthly contaminant-specific concentrations. Based on data, analyses, interpretations, model calibrations, sensitivity analysis, and probabilistic uncertainty analyses, the historical reconstruction process provides reliable and defensible evidence within a reasonable degree of scientific and engineering certainty that drinking-water at Camp Lejeune during the periods of interest was contaminated with VOCs that exceeded drinking-water standards (MCLs) for PCE, TCE, 1,2-tDCE, VC, and benzene. This is demonstrated by the finished water concentrations at the TTWTP and HPWTP for PCE and TCE, respectively, shown in Figure 7.29. The historical reconstruction process was used to reliably quantify estimates of monthly mean contaminant-specific concentrations such as those shown in Figure 7.25 and 7.29, and the results were used in ATSDR's epidemiological studies to estimate the level and duration of exposures. Thus, water-modeling methods described and discussed in this report provide **reliable analysis tools and definitive results** for simulating historical contaminant concentration levels in finished water.

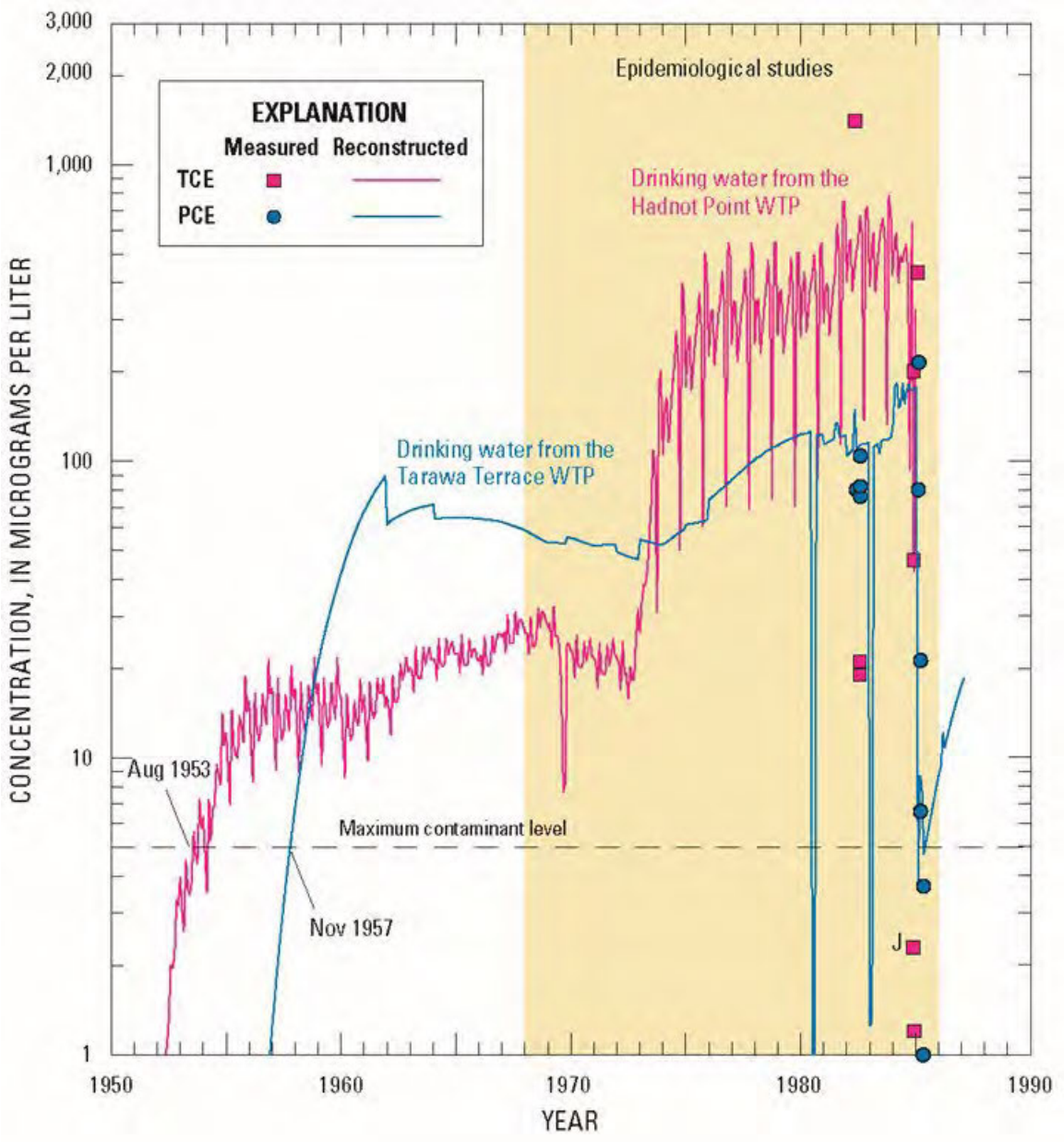


Figure 7.29. Reconstructed (simulated) and measured finished-water concentrations of tetrachloroethylene (PCE) and trichloroethylene (TCE) at the Tarawa Terrace and Hadnot Point water treatment plants (Maslia et al. 2016).

7.6 Peer Review of ATSDR Analyses, Results, and Reports

Throughout the historical reconstruction analysis for USMCB Camp Lejeune, I through the ATSDR sought independent external expert scientific input and review of project methods, approaches, and interpretations to assure scientific credibility of the analyses described in the TT and HP-HB reports. The review process included convening two expert review panels and submitting individual chapter reports to outside experts for peer review. On March 28–29, 2005, ATSDR convened an external expert panel to review the approaches used in conducting the historical reconstruction analysis for Tarawa Terrace and to provide input and recommendations on preliminary analyses and modeling results (available on the ATSDR website and in Maslia 2005). On April 29–30, 2009, ATSDR convened a second external expert panel to review the approaches used in conducting the historical reconstruction analysis for HP and HB and to provide input and recommendations on preliminary analyses and modeling results (available on the ATSDR website and in Maslia 2009). The panels were composed of nationally and internationally recognized experts with professional backgrounds from government, academia, and the private sector. Technical representatives for the Department of the Navy (DON) and the Camp Lejeune Community Assistance Panel (CAP) also served on the panels. Areas of expertise included numerical model development and simulation, groundwater-flow and contaminant fate and transport analyses and model calibration, hydraulic and water-quality analysis of water-distribution systems, epidemiology, and public health. After reviewing data and initial approaches and analyses provided by ATSDR, panel members made recommendations that ATSDR addressed. These panel recommendations and ATSDR responses are found in Maslia (2005, 2009).

In addition to the expert panels and implementing their recommendations, ATSDR sought out independent, external peer review for every chapter report for the TT and HP-HB reports. These peer reviewers were subject matter experts in all topics covered by the ATSDR historical reconstruction analysis reports. Review comments provided by external peer reviewers were used to address technical issues and to improve the scientific credibility of all final reports.

The series of ATSDR reports on historical reconstruction of drinking-water contamination also resulted in two peer reviewed journal articles (Maslia et al. 2009, 2016). Submission of the manuscripts to the scientific journals resulted in another level of external (and independent) peer review for the methods, analyses, and results applied by ATSDR for reconstructing historical drinking-water concentrations at TT, HP, and HB.

An additional endorsement of the quality and scientific validity of the ATSDR Camp Lejeune water-modeling studies came from the American Academy of Environmental Engineers and Scientists, which awarded our team the 2015 Grand Prize for Excellence in Environmental Engineering and Science. This distinguished award was given to the ATSDR team for "Using Environmental Engineering, Scientific Analyses, and Epidemiological Studies to Quantify Human Exposure to Contaminated Drinking Water and to Benefit Public Health."

7.7 Scientific Discourse

When characterizing, analyzing, and investigating sites with historical contamination, limited data, and potential for human exposure, there can naturally arise differences in opinions within the scientific

community. The fact that there are differences is not the issue. Rather, if questions and differences are pointed out to investigators in scientific discourse, the issue becomes, have investigators— ATSDR Exposure-Dose Reconstruction Program scientists and engineers—addressed these questions and responded in an objective, transparent, and professional scientific manner to defend their analyses and results? ATSDR did so in all cases. Discussed below are review comments and ATSDR responses pertinent to DON's comments on ATSDR's Tarawa Terrace Model (ATSDR 2009), the National Research Council report on contaminated drinking-water supplies at Camp Lejeune (NRC 2009), and ATSDR's response to the editor (Maslia et al. 2012) to a published journal article in *Ground Water* that used the Camp Lejeune historical reconstruction analyses as a case study (Clement 2010).

7.7.1 Department of the Navy (DON) Comments on the Tarawa Terrace Models and ATSDR Response

On June 19, 2008, the DON (B.P. Harrison) wrote a letter to ATSDR's Deputy Director, Dr. Thomas Sinks. The letter in part stated, "*As with all modeling efforts, there is a great deal of uncertainty in trying to recreate the past. ATSDR has gone to great efforts to test and validate the model, and the resulting estimated results, using limited available data.*" The DON letter contained an attachment with specific concerns and recommendations. ATSDR Exposure-Dose Reconstruction staff, cooperators, and contractors reviewed the DON's concerns and recommendations and responded to them, point by point. The ATSDR response to the DON letter is provided in this report as **Appendix L** and is also available on the ATSDR website and in ATSDR (2009). An example of one of DON's concerns with the Tarawa Terrace model and ATSDR's response is provided below.

DON Comment

"Furthermore, all of the measured concentrations were used during model calibration, leaving no data available for model validation. As a result, the Tarawa Terrace model was not validated."

ATSDR Response

"A number of terms have been used throughout the published literature that reference the adequacy of model simulation to reliably reproduce real-world conditions based on the fidelity of the model and its intended use. Many groundwater modelers and hydrologists have abandoned the use of terms such as model verification and validation for the terms of history matching and post audits (Bredehoeft and Konikow 1993, Oreskes et al. 1994). However, ATSDR understands that the DON comment was intended to express the DON's concern that the calibrated Tarawa Terrace models were not compared to multiple independent sets of measured data (water levels and concentrations) as part of ATSDR's model calibration process and strategy. To address this concern, definitions of terms such as "verification" and "validation" should be agreed upon, and the consequences of undertaking a useful "validation" program for Tarawa Terrace should be completely understood by ATSDR and the DON. Model verification requires that multiple sets of field data be available for model calibration. These sets of field data should be sufficiently large in quantity and distribution and of sufficient quality to provide at least two equally useful calibration data sets. Each data set also should be sufficiently separated in time so as to represent significantly different water-level and contaminant conditions within the model domain. The field data set at Tarawa Terrace used for model calibration was not of sufficient quantity and was too compressed in time to implement a verification procedure. To appropriately calibrate the Tarawa Terrace models, all available field data were required for a single

calibration data set and effort. This is consistent with and follows ASTM D5981-96 (1996), Standard Guide for Calibrating a Ground-Water Flow Model Application, that states (Note 4): *"When only one data set is available, it is inadvisable to artificially split it into separate 'calibration' and 'verification' data sets. It is usually more important to calibrate to data spanning as much of the modeled domain as possible."*

"Note, once an acceptable calibration was achieved (using a four-stage calibration strategy described in Maslia et al. (2007), Faye and Valenzuela (2007), and Faye (2008), the calibrated models were used to reconstruct historical monthly PCE and PCE degradation by-product concentrations in groundwater and drinking water (Jang and Aral 2008). This is standard practice in the modeling community–using a calibrated model to "predict" (in ATSDR's situation, "reconstruct") results for a period of time when data are not available or cannot be obtained."

7.7.2 National Research Council Report on Camp Lejeune and ATSDR Response

The NRC report (NRC 2009) on contaminated drinking water supplies at Camp Lejeune reviewed, in part, ATSDR's Tarawa Terrace analysis. In the NRC report's Section 2 (Exposure to Contaminants in Water Supplies at Camp Lejeune), the report made a number of comments that were generally at odds with and at times completely contradictory of data and information published in ATSDR's peer-reviewed Tarawa Terrace report series and provided to the NRC by ATSDR. On July 1, 2009, the Exposure-Dose Reconstruction Program staff at ATSDR submitted a response to ATSDR Management and Leadership pertinent to the NRC report Section 2 review of ATSDR's Tarawa Terrace Analyses. The complete Exposure-Dose Reconstruction Program staff response is provided in **Appendix M** of this report. A summary of the response to the NRC report is provided below.

> "The Agency for Toxic Substances and Disease Registry's (ATSDR) Exposure-Dose Reconstruction Program staff has reviewed the National Research Council (NRC) report titled, "*Contaminated Water Supplies at Camp Lejeune—Assessing Potential Health Effects*." Specifically, our review focused on Section 2 of the report (p. 28–66), "Exposure to Contaminants in Water Supplies at Camp Lejeune." Based on our review of Section 2, we conclude the following:
>
> "The National Research Committee report (NRC 2009) contains numerous misrepresentations and distortions of ATSDR water-modeling analyses, field data and related interpretations and conclusions that are clearly contradicted by findings in ATSDR technical reports. Those ATSDR reports that describe groundwater contamination and the results of model studies related to contamination of drinking water at the Tarawa Terrace base housing area, Camp Lejeune, North Carolina, along with additional supporting information from the Department of Navy, the U.S. Marine Corps, and other sources were provided to the NRC committee during the course of their deliberations. Because the NRC report contains many errors and misrepresentations with respect to the findings of the ATSDR water-modeling analyses and because conclusions and recommendations contained in the NRC report are at such odds with recommendations rendered by several review panels consisting of national and international experts in water modeling and epidemiology, the NRC report cannot be considered an authoritative interpretation or guidance document related to the historical exposure assessment of contaminated drinking water at Camp Lejeune.

"We base the aforementioned statements on four overarching issues discussed below. In addition, we present specific examples wherein the NRC committee arrived at erroneous conclusions by using incorrect data and otherwise misrepresenting data and information contained in reports that summarize ATSDR investigations at Tarawa Terrace and vicinity. Additional supporting documentation and in-depth technical reviews related to specific NRC report comments are provided in Appendix I and II of this document."

The four overarching issues pertinent to ATSDR's Exposure-Dose Reconstruction Group's response to the NRC report are listed below:

- **Issue 1: Use of Historical Reconstruction for Exposure Assessment**
- **Issue 2: Characterization of PCE as a Dense Non-Aqueous Phase Liquid (DNAPL)**
- **Issue 3: Evaluation of Uncertainty**
- **Issue 4: Reliability of Reconstructed Historical Concentrations**

Refer to **Appendix M** for the complete, point-by-point ATSDR Exposure-Dose Reconstruction Program staff's response to the NRC (2009) report.

7.7.3 ATSDR Response to Ground Water Journal Article on Camp Lejeune

In issue number 5 (September-October) of the 2010 *Ground Water* Journal, author T.P. Clement published the article, "*Complexities in Hindcasting Models-When Should We Say Enough is Enough?*" (Clement, 2010).[11] The goal of the article appeared to be to use the USMCB Camp Lejeune water-modeling studies (specifically Tarawa Terrace analyses) to highlight issues that the author saw as relating to complexities in fate and reactive transport modeling of contaminants in groundwater systems. While the author correctly pointed out limitations with models in general and specifically reactive fate and transport models and shares some thought-provoking points of view, ATSDR believed that there was a lack of detail on several key issues with respect to modeling approaches and methods, the physics of contaminant transport in the subsurface, and agency policies for the review and dissemination of data and reports. Therefore, ATSDR submitted an editorial response to Clement's article (Clement, 2010) and this response was published in issue number 1 (January-February) of the 2012 *Ground Water* journal. A copy of the ATSDR editorial response (Maslia et al. 2012) is provided in **Appendix N** of this report.

The ATSDR editorial response discusses several issues and topics mentioned in the Clement article (2010). These include: (1) "Hindcasting" vs. Historical Reconstruction, (2) Application of "Complex" Models vs. "Simple" Models to simulate subsurface reactive transport, (3) Correction and clarifications of specific contaminant data analyses and modeling issues, (4) Research models vs. public domain codes, (5) Uncertainty and variability of simulation results, and (6) review and dissemination of water-modeling results. In their editorial response, Maslia et al. (2012) conclude:

[11] Dr. T. P. Clement was a member of the NRC Committee reviewing ATSDR's water-modeling analyses at Camp Lejeune (NRC 2009). It appears that he was the only recognized groundwater expert on the NRC committee.

(1) In the situation 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,

(2) 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—by using expert panels and external peer review, and

(3) 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.

8.0 References

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9.0 Glossary and Abbreviations

Definitions of terms and abbreviations used throughout this report are listed below.

A

AAEE American Association of Environmental Engineers

AAEES American Association of Environmental Engineers and Scientists

ACTS Analytical contaminant transport analysis system, a computational p[platform to assist with assessing and quantifying environmental multimedia fate and transport within air, soil, surface water and groundwater; can be run in deterministic or probabilistic mode (Aral 1998, Maslia and Aral 2004)

ATSDR Agency for Toxic Substances and Disease Registry; https://www.atsdr.cdc.gov

ASCE American Society of Civil Engineers

AST Above-ground storage tank

B

BAH Booz-Allen-Hamilton

BHC Benzene hexachloride, HCH, or hexachlorocyclohexane

BTEX Benzene, toluene, ethylbenzene, and xylenes

C

CAP Community assistance panel

CDC U.S. Centers for disease Control and Prevention: https://www.cdc.gov

CERCLA The Comprehensive Environmental Response, Compensation, and Liability Act of 1980, also known as Superfund

CLW Camp Lejeune Water document

CPSC Consumer Product Safety Commission

CV Curriculum vitae

D

DCE 1,1-dichloroethylene or 1,1-dichloroethene

1,2-DCE *cis*-1,2-dichloroethylene or *trans*-1,2-dichloroethylene

1,2-cDCE *cis*-1,2-dichloroethylene or *cis*-1,2-dichloroethene

1,2-tDCE *trans*-1,2-dichloroethylene or *trans*-1,2-dichloroethene

DON Department of the Navy

DNAPL Dense nonaqueous phase liquid

E

EDB Ethylene dibromide

EDRP Exposure-Dose Reconstruction Program developed by ATSDR in 1993

EPA U.S. Environmental Protection Agency, https://www.epa.gov, also see USEPA

EPANET A water-distribution system (network) model developed by the USEPA (Rossman 1994)

EPANET 2 Version 2 of the EPANET model (Rossman 2000)

EPM Equivalent porous medium

EPS Extended period simulation

F

F-D Finite-difference solver; a transport equation solution method used by MT3DMS

ft Foot or feet

ft^3/d Cubic foot per day

G

Ga. Tech Georgia Institute of Technology, Atlanta, Georgia

GIS Geographic information system

g Grams

H

HB Holcomb Boulevard

HBWTP Holcomb Boulevard water treatment plant

HCOH Formaldehyde

HP Hadnot Point

HPFF Hadnot Point fuel farm

HPIA Hadnot Point Industrial Area

HPLF Hadnot Point landfill

HPWTP Hadnot Point water treatment plant

I

IHMod A suite of mathematical models used to estimate air concentrations of chemicals; can be run in deterministic or probabilistic modes; available from the American Industrial Hygiene Association (AIHA)

IRP Installation Restoration Program

L

LCL Lower confidence limit

LCM Linear control model; a model based on linear control theory methodology developed to reconstruct historical contaminant concentrations in water-supply wells (Guan et al. 2013)

LHS Latin hypercube sampling

LNAPL Light nonaqueous phase liquids

M

Markov process A process that analyzes the tendency of one event to be followed by another event based on the sequence of events. Using this analysis, one can generate a new sequence of random but related events, which will look similar to the original; a stream of events is called a Markov Chain

MCS Monte Carlo simulation; see Monte Carlo analysis

MOC Method of characteristics solver; a transport equation solution method used by MT3DMS

Monte Carlo analysis Also referred to as Monte Carlo simulation; a computer-based method of analysis that uses statistical sampling techniques to obtain a probabilistic approximation to the solution of a mathematical equation or model

MODFLOW A family of three-dimensional groundwater-flow models, developed by the U.S. Geological Survey, https://www.usgs.gov/mission-areas/water-resources/science/modflow-and-related-programs

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 Hadnot Point–Holcomb Boulevard study area analyses

MCL Maximum contaminant level

MESL Multimedia Environmental Simulations Laboratory, School of Civil and Environmental Engineering, Georgia Institute of Technology

mg/L micrograms per liter; 1 part per billion

Model calibration The process of adjusting model input parameter values until reasonable agreement is achieved between model-predicted outputs or behavior and field observations

N

NAVFAC Naval Facilities Engineering Command, Norfolk, Virginia

NCEH National Center for Environmental Health; a center within the U.S. Centers for Disease Control and Prevention (CDC)

ND nondetect

NJDHSS New Jersey Department of Health and Senior Services

NPL National Priorities List

NRC National Research Council

P

PCE Tetrachloroethene, tetrachloroethylene, 1,1,2,2-tetrachloroethylene, or perchloroethylene; also known as PERC® or PERK®

PDF Probability density function

PRNG Pseudo-random number generator

R

RASA Regional Aquifer System Analysis program of the U.S. Geological Survey

S

SCADA Supervisory control and data acquisition

SGS Sequential Gaussian simulation

T

TCE 1,1,2-trichloroethene, or 1,1,2-trichloroethylene, or trichloroethylene

TechFlowMP A three-dimensional multispecies, multiphase mass transport model developed by the Multimedia Environmental Simulations Laboratory at the Georgia Institute of Technology, Atlanta, Georgia

TechNAPLVoL LNAPL estimate model developed by the Multimedia Environmental Simulations Laboratory at the Georgia Institute of Technology, Atlanta, Georgia

TENSOR2D A computer program to automate computing components of the two-dimensional anisotropic transmissivity tensor (Maslia and Randolph 1986, 1987)

TT Tarawa Terrace

TTWTP Tarawa Terrace water treatment plant

TVD Total variation diminishing solver; a transport equation solution method used by MT3DMS

U

UCL Upper confidence limit

USEPA U.S. Environmental Protection Agency, https://www.epa.gov, also see EPA

USGS U. S. Geological Survey

USMC U.S. Marine Corps

USMCB U.S. Marine Corp Base

UST Underground storage tank

V

VC Vinyl chloride

VOC Volatile organic compound

W

WTP Water treatment plant

Appendix A — Curriculum Vitae for Morris L. Maslia, P.E.

Curriculum Vitae

MORRIS L. MASLIA, P.E., D.WRE, DEE, Fellow EWRI
Water Resources — Environmental Analyses — Public Health
3360 Norfolk Chase Drive, Peachtree Corners, GA 30092
Mobile: +1 404-431-0035 — Email: H2OBoy54@gmail.com

EDUCATION

Georgia Institute of Technology, Atlanta, Georgia

- Coursework towards Ph.D. (Water Resources and Environmental Analysis)
- Master of Science, Civil Engineering (Water Resources), 1980
- Bachelor of Civil Engineering, 1976

PROFESSIONAL HISTORY

M. L. Maslia Consulting Engineer, Peachtree Corners, Georgia
Owner, 2018–Present

Agency for Toxic Substances and Disease Registry, Atlanta, Georgia
Environmental Engineer and Project Officer, 1992–2017

Rollins School of Public Health, Emory University, Atlanta, Georgia
Adjunct Faculty, Department of Environmental Health, 2000–2018

Geosyntec Consulting Engineers, Norcross, Georgia
Water Resources Group Manager and Hydrologist, 1989–1992

U.S. Geological Survey, Water Resources Division, Doraville, Georgia
Research Hydrologist, 1980–1989

Federal Energy Regulatory Commission, Washington, DC/Atlanta, Georgia
Civil Engineer, 1976–1980

PROFESSIONAL LICENSE AND CERTIFICATION

Registered Professional Engineer (GA), #PE012689 (active)
Certified Ground Water Professional, National Ground Water Association #115205
Diplomate, American Academy of Water Resources Engineers, D.WRE #00066
Diplomate, American Academy of Environmental Engineers & Scientists, DEE #00-20013
OSHA HAZWOPR 40-hour certification with annual 8-hour refresher; CPR/AED certified

REPRESENTATIVE EXPERIENCE

Morris L. Maslia, PE, has conducted consulting engineering, research, and scientific studies in the areas of environmental fate and transport, water resources (including water-distribution systems), hazardous waste remediation, environmental health, exposure assessment, and public health. He has worked with international organizations, non-profit organizations, U.S. federal agencies, state government agencies, engineering consulting firms, and private industry. He has developed and presented workshops, lectures, and training courses for international, government, and academic institutions (*e.g.*, Emory University and Georgia Tech). His areas of experience, expertise, and continued interests include environmental and public health, water resources and sanitation, global impacts of contamination of water resources, environmental analyses, epidemiological studies, exposure assessment, water-distribution system analysis, engineering and research report review, and volunteering and working with non-profit organizations.

KNOWLEDGE, SKILLS, AND ABILITIES

- Consultant to Bell Legal Group (Georgetown, SC) on historical reconstruction of groundwater contamination, fate and transport modeling of contaminants in groundwater, and water-distribution system analyses; July 2022–Present.
- Professional engineering review of "Semiannual Groundwater Monitoring and Corrective Action Reports, Plant McManus Inactive Ash Pond 1," for Resolute Environmental & Water Resources Consulting, LLC; 2022–2024.
- Consultant to Resolute Environmental & Water Resources Consulting, LLC, on groundwater monitoring, groundwater modeling, and fate and transport modeling at a site in Athens, GA; August 2021–March 2022.
- Member of Review Panel evaluating a National Science Foundation EPSCoR Track-2 IGM Project, The University of Alabama, Tuscaloosa, AL; June 2023 and June 2024.
- Developed and lead agency wide (ATSDR) program for estimating human exposures to environmental contaminants and documenting resulting public health impacts. Direct involvement with three of the most high-profile U.S. environmental contamination and public health cases to date: (1) Love Canal/Hyde Park, NY; (2) Toms River (Dover Township), NJ; and (3) Marine Corps Base Camp Lejeune, NC.
- Deployment to San Juan, Puerto Rico for Hurricane Maria response (October—November 2017) Deployment to CDC Emergency Operations Center for ZIKA response (May 2016)
- International teaching and travel experience; volunteer work with international environmental, water resources, and non-profit organizations.
- Outstanding project proposal/request for proposal development and writing skills.

- Outstanding written and oral communication skills. Presentations given to academic audiences, to top military officers at the Pentagon, to an Assistant Secretary of the Navy, and to Congressional staff. Ability to communicate highly scientific and technical analyses for a lay person's and media understanding at community and public meetings.
- Extensive experience, abilities, and skills to interface with the public in meetings and diverse settings.
- Ability to work effectively with minimal supervision in a multidisciplinary and diverse team environment.
- Outstanding skills with WIN OS, MAC OS, MS Office Suite, ADOBE, geographic information systems (GIS), multimedia presentations, and scientific visualization.
- OSHA 40-hour HAZWOPER certified with annual 8-hour refresher, CPR/AED certified, annual ethics, scientific integrity, and diversity training certifications.
- National Incident Management System (NIMS, IS-00700.a) training and certification.
- Knowledge and experience with CERCLA and RCRA sites and regulations.
- Extensive experience with water resources, water-distribution systems analysis, environmental and public health analyses (including epidemiological studies).
- Non-profit organization volunteer experiences ranging from being a Board of Directors member to President where I was responsible for engaging clergy, hiring and directing administrative and educational staff, and balancing an annual budget.

INTERNATIONAL ASSISTANCE, TEACHING AND TRAINING

Provided international government representatives with technical advice, training, and consultation. Coordinated workshops and presented seminars at training centers and universities in the areas of water resources, exposure assessment, public health implications of exposure to contaminated environmental media, and the use and application of geographic information systems (GIS) and spatial analysis techniques. Mr. Maslia is an Adjunct Faculty Member in the Department of Environmental Health, Rollins School of Public Health, Emory University, Atlanta, Georgia, USA.

- Requested by the Pan American Health Organization's Center for Human Ecology and Health, to develop, coordinate, and present a two-week workshop on Geographic Information Systems and Human Exposure to Chemical Substances. The course was presented at the Autonomous University of San Luis Potosi', Mexico; February 1996.
- Requested by the Autonomous University of San Luis Potosi', Mexico, to develop a three-day course on Quantitative Exposure Assessment. Course conducted as part of the universities Health Risk Assessment graduate course, San Luis Potosi, Mexico; May 24–30, 2003.

- Invited to present a seminar at the Munro Center for Civil and Environmental Engineering at the University of New South Wales, Australia; October 1995.
- Provided technical advice on modeling variably saturated flow and contaminant transport to a representative from the People's Republic of China visiting the USGS's Georgia office; 1988.
- Requested by USGS (on behalf of USAID) to provide advice to Jordanian Government on flow and transport modeling of contamination of a carbonate aquifer system underlying Amman, Jordan; 1986.
- Provided training, technical advice, and consultation to the Head of the Water Authority of Jordan on use of USGS documented groundwater-flow and transport computer models; 1985.
- Requested by the Director, Department of Environmental and Occupational Health, Rollins School of Public Health of Emory University, to develop and teach a course in Environmental and Occupational Hazards (EOH541) for students enrolled in the Master's of Public Health Degree; September 1999.
- Adjunct Faculty, Rollins School of Public Health of Emory University, Department of Environmental and Occupational Health, 2000–2015; taught EOH541, Environmental and Occupation Health, Hazards II course, January – May 2000–2004; Faculty advisor/student mentor; guest seminar presenter.
- Co-developed Water Distribution System Analysis (WDSA) Workshop on "Distribution System Tracer Studies: Design, Implementation and Case Studies." Presented at 8th WDSA Symposium 2006, Cincinnati, OH; August 27, 2006.
- Developed a five-day workshop for ATSDR and Cooperative State Health Assessors on the use and application of the Analytical Contaminant Transport Analysis System (ACTS) computational software; June 1999.

ADMINISTRATIVE ACCOMPLISHMENTS

- Authored and project officer of U.S. Government agency (ATSDR) strategy for Exposure-Dose Reconstruction.
- Organized administrative logistics and technical aspects for expert panels to review water-modeling analyses conducted at U.S. Marine Corps Base Camp Lejeune, North Carolina (April 2009 and March 2005) and Dover Township (Toms River), New Jersey (August 2001 and December 1998).
- Detailed to the National Center for Injury Prevention and Control (NCIPC), Office of the Associate Director for Science, 2003. Served as the acting Executive Secretary for NCIPS's study

section and as a Designated Federal Official (DFO) during the NCIPC peer review of extramural grant proposals.

- Developed and wrote sole-source contracts for external technical assistance on behalf of ATSDR.
- Developed and wrote cooperative agreement for ATSDR's Research Program on Exposure-Dose Reconstruction, 1993, 1998, 2003, and 2008.
- Developed and wrote interagency agreements (IAA) with the U.S. Geological Survey (Connecticut, North Carolina, Georgia, and National Research Program) to provide technical assistance, hydrogeologic site characterization, training in geochemical modeling, and report preparation, 1995, 1996, and 2004–2013.
- Developed technical and computational specifications and reviewed interim and final analyses for conducting a multi-pathway environmental exposure assessment at the Otis Air Force Base site, Massachusetts, on behalf of ATSDR's Division of Health Studies and the Massachusetts Department of Health.
- Developed ATSDR's analytical, computational, and scientific visualization capabilities so that the agency now has a state-of-the-art computational laboratory that is the envy of many state environmental and public health agencies. The analysis capabilities of the laboratory are respected throughout the environmental and public health community.

TECHNICAL AND SCIENTIFIC ACCOMPLISHMENTS

- Briefed Deputy Assistant Secretary of the Navy for Environment and U.S. Marine Corps General Staff on water-modeling analyses at U.S. Marine Corps Base Camp Lejeune, North Carolina, April 29, 2011, The Pentagon, Washington, DC
- Presented scientific findings before the National Academies, National Research Council Committee on Contaminated Drinking Water at Camp Lejeune, September 24, 2007, Washington, DC.
- Responded to Congressional Inquiry on Contamination of Drinking Water at U.S. Marine Corps Base Camp Lejeune, North Carolina. U.S. House of Representatives Committee on Energy and Commerce, Subcommittee on Oversight and Investigations, June 13, 2007, Washington, DC.
- Provided technical assistance to ATSDR's Division of Health Studies in assessing potential associations between drinking-water contamination at U.S. Marine Corps Base Camp Lejeune, North Carolina and birth defects and childhood cancer.
- Assisted U.S. Environmental Protection Agency in providing Federal Circuit Judge in Buffalo, New York with groundwater flow analyses of the Hyde Park landfill area near Niagara Falls; this

formed the basis for one of the first consent decrees under CERCLA (Superfund) legislation for a hazardous waste site analysis and clean up.

- Assisted the New Jersey Department of Health with determining the possible locations and extent of historical exposures from environmental contaminants that have led to an increased number of cases of childhood brain cancers in the Toms River section of Dover Township, NJ. Developed strategy and protocol for using water-distribution system model to assist with estimating proportionate amount of public water used by residents of Dover Township in a case-control epidemiologic investigation.
- Developed and successfully implemented a protocol for continuous and simultaneous monitoring and recording of pipeline pressures and hydraulic characteristics for a large water-distribution system. Pressures were recorded at 25 locations throughout the system that was operating under winter-time and summer-time demand conditions.
- Assisted the U.S. Environmental Protection Agency's (USEPA), National Risk Management Laboratory (Cincinnati, OH), with refining and upgrading the EPANET water-distribution system model for use with large-scale distribution systems (>10,000 pipe) in simulating hydraulics and contaminant transport.
- Provided technical assistance and expertise to CDC's National Center for Environmental Health (NCEH) in the area of integrating the use of GIS, numerical modeling, and demographic analysis.
- In conjunction with the Multimedia Environmental Simulations Laboratory in the Georgia Tech School of Civil and Environmental Engineering, developed and tested ATSDR's analytical contaminant transport and health risk analysis system software (ACTS/RISK). This is a WINDOWS-based software platform that is used to compute fate and transport of contaminants and exposure to contaminants by the groundwater, surface-water, air, and biota pathways. The ACTS/RISK software can be run in deterministic (single parameter value) or Monte Carlo (uncertainty) modes.
- Requested by the National Cancer Institute to serve on a panel of national experts to assess the use of geographic information system (GIS) technology as it relates to exposure assessment.
- Provided assistance to health assessors working on Tucson International Airport NPL site. Used innovative analysis and application of flow and transport modeling to assess TCE contamination of Tucson, AZ area in order to reconstruct historical exposures.
- Requested by the attorney general's office for the State of Connecticut and citizens of Somers, CT to conduct groundwater flow and contaminant transport modeling to characterize the extent and duration of citizens' exposure to PCE.
- Requested by the Connecticut Department of Health to conduct analysis of municipal water distribution system to assess exposure to VOC contamination. Hydrodynamic and water-quality modeling were integrated with geographic information systems (GIS) and demographic characteristics for the Town of Southington, CT.

- Assisted health assessors in determining historical exposures by conducting groundwater flow and contaminant transport modeling of the Gratuity Road site, Groton, MA.

VOLUNTEER AND OUTSIDE ACTIVITIES

- Coordinated and raised more than $58,000 in scholarship funds for the Arava Institute for Environmental Studies (www.arava.org) that brings together Palestinians, Jordanians, and Israel Jews and Arabs to work on local and regional Middle-East issues at the grass-roots level using environmental study as a framework. Cycled more than 280 miles during a five-day period during November 2014 and November 2016 from Jerusalem to Eilat as part of the scholarship fundraising program; Team Captain and coordinator for the 16-person Atlanta cycling team that raised the scholarship funds.
- Participated in a cycling event to honor the 50th anniversary of the Selma to Montgomery Voting Rights March during February 2015. More than 300 cyclists participated in the ride sponsored by the Montgomery Bicycle Club on February 21, 2015. The ride began at the historic Edmund Pettus Bridge in Selma, Alabama and ended 54 miles away at the steps of the Alabama state capital in Montgomery.
- Presented with the Jewish National Fund's Community Service Award, May 2014.
- Associate Editor, American Society of Civil Engineers (ASCE) Journal of Water Resources Planning and Management.
- Associate Editor, International Journal of Water Quality, Exposure, and Health (Springer).
- Adjunct Faculty, Department of Environmental Health, Rollins School of Public Health, Emory University.

AWARDS AND HONORS

Presentation of Opening Keynote Address: *Hurricane Maria Deployment Experiences, October 23-November 20, 2017*. EWRI World Environmental & Water Resources Congress, 2017 Extreme Weather Events Panel, Minneapolis, MN, June 3-7, 2018. **Invited Presentation**

American Academy of Environmental Engineers and Scientists (AAEES), 2015 Excellence in Environmental Engineering Award, Grand Prize, Research Category, April 2015.

Environmental and Water Resources Institute, American Society of Civil Engineers (ASCE), Elected to Fellow-Grade Member, May 2013.

American Society of Civil Engineers (ASCE), 2011 James R. Croes Medal, for the paper, "*Optimal Design of Sensor Placement in Water Distribution Networks*," Journal of Water Resources Planning and Management, January-February 2010.

U.S. Public Health Service Engineering Literary Award (Peer-Reviewed Publication Category) for the publication: *Reconstructing Historical Exposures to Volatile Organic Compound-Contaminated Drinking Water at a U.S. Military Base*, April 2010.

U.S. Public Health Service Engineering Literary Award (Publications Category) for the publication: *Analytical Contaminant Transport Analysis System (ACTS)—Multimedia Environmental Fate and Transport*, June 2005.

American Academy of Environmental Engineers (AAEE), 2003 Excellence in Environmental Engineering Award, Grand Prize, Research Category, April 2003.

Assistant Administrator's Award for Special Service to ATSDR, June 2002.

U.S. Public Health Service, ATSDR, Quality Increase Award, February 2002.

Cumming Award, American Society of Military Engineers, 2000 to the Dover Township Water-Distribution System Modeling Team.

Environmental and Water Resources Research Institute (EWRI), American Society of Civil Engineers (ASCE), Best Practice-Oriented Paper of 2000 for the paper, *"Using Water-Distribution System Modeling to Assist Epidemiologic Investigations,"* ASCE Journal of Water Resources Planning and Management, Vol. 126, July/August 2000.

Agency for Toxic Substances and Disease Registry, Engineer of the Year Award, 1998. Agency for Toxic Substances and Disease Registry, Science Award, 1998.

U.S. Public Health Service Engineering Literary Award (Publications Category) for the publication:

Exposure Assessment Using Analytical and Numerical Models: Case Study, May 1998.

U.S. Public Health Service Engineering Literary Award (Publications Category) for the publication: *Estimating Exposure to VOCs from Municipal Water System Pipelines: Use and Application of a Computational Model*, May 1996.

AFFILIATIONS

American Academy of Environmental Engineers and Scientists (Diplomate)

American Academy of Water Resources Engineers (Diplomate)

American Society of Civil Engineers–ASCE (Member)

Environmental & Water Resources Institute (EWRI) of ASCE (Fellow-Grade Member)

- Vice-Chair, Hydraulic Fracturing Committee, EWRI/ASCE
- Chair, Hydraulic Fracturing Task Committee, EWRI/ASCE

- Fellow, Environmental and Water Resources Institute (EWRI)
- Vice-Chair, Water Distribution Systems Analysis Committee (October 2014–2016)
- Chair, Groundwater Hydrology Committee (2009–2011)
- Chair, Emerging and Innovative Technologies Technical Committee (2008–2009)
- Co-Chair, 17th Water Distribution Systems Analysis Symposium, EWRI Congress, May 2015
- Co-Chair, 15th Water Distribution Systems Analysis Symposium, EWRI Congress, May 2013
- Member, Organizing Committee, 12th International Symposium on Water-Distribution System Analysis, Tucson, AZ, 2011
- Member, Organizing Committee, 8th International Symposium on Water Distribution System Analysis, Cincinnati, OH, 2007

American Water Resources Association

American Water Works Association

Georgia Ground Water Association

International Society for Exposure Science

- Co-Chairman, 2002 Joint Symposium on Computation Techniques/Multimedia Multipathway Models

Associate Editor, ASCE Journal of Water Resources, Planning, and Management, https://ascelibrary.org/page/jwrmd5/editorialboard; July 2006—2016.

Member, Peer Review Committee for Massachusetts Department of Health on, "*An Epidemiologic Study of Childhood Cancer and Exposure to Drinking Water Contaminated with N-nitrosodimethylamine (NDMA), Wilmington, Massachusetts*," 2014–2018.

Member, External Advisory Board to University of Kentucky, for National Institute of Hometown Security funded project, "*Studying Distribution System Hydraulics and Flow Dynamics to Improve Utility Operational Decisions*," 2011–2014.

Member, External Advisory Board to University Consortium, for National Institute of Hometown Security funded project, "*Protocols for Response and Recovery Operations in Contaminated Water Systems*," 2010–2013.

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UNIVERSITY LECTURES

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Quantifying Exposure to Contaminated Drinking Water—Case Study: Camp Lejeune, NC: Risk Assessment II Class (EOH 525), Department of Environmental and Occupational Health, Rollins School of Public Health of Emory University, March 16, 2010, Atlanta, Georgia. **Invited Lecture**.

Quantifying Exposure to Contaminated Drinking Water—Concepts and Case Studies: Risk Assessment I Class (EOH 522), Department of Environmental and Occupational Health, Rollins School of Public Health of Emory University, November 19, 2008, Atlanta, Georgia. **Invited Lecture**.

Using Water-Distribution System Analyses to Benefit Public Health: Environmental Hydraulics Class (CE633), Department of Civil and Environmental Engineering, University of Cincinnati, February 9, 2006, Cincinnati, Ohio. **Invited Lecture**.

Engineering Graduate Seminar, School of Civil and Environmental Engineering, Georgia Institute of Technology, January 21, 2004, Atlanta, Georgia. **Invited Lecture**.

Quantitative Exposure Assessment: Health Risk Assessment Course, Autonomous University of San Luis Potosi, May 27–29, 2003, San Luis Potosi, Mexico. **Invited Lecture**.

Computational Tools for Conducting Exposure Assessments and Assisting Epidemiologic Investigations: CEE 8094, Graduate Environmental Engineering Seminar, School of Civil and Environmental Engineering, Georgia Institute of Technology, October 3, 2001, Atlanta, Georgia. **Invited Lecture**.

Environmental and Occupational Hazards II: EOH 541 graduate class, Rollins School of Public Health of Emory University, Atlanta, Georgia, January – May 2001–2004. **Adjunct Professor**.

MISCELLANEOUS LECTURES

Using Environmental Engineering Tools, Scientific Analyses, and Epidemiological Studies to Quantify Human Exposure to Contaminated Drinking Water and to Benefit Public Health. American Academy of Environmental Engineers & Scientists Awards Luncheon and Conference, National Press Club, Washington, DC, April 23, 2015. **Invited Presentation**.

Water Mapping—From Exposure to Disease: TEDMed@CDC/Ignite, Centers for Disease Control and Prevention, U.S. Department of Health and Human Services, April 30, 2014, Atlanta, Georgia. **Invited Presentation**.

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Uncertainty and Variability of Measurements. ATSDR Exposure Investigations Workshop, March 11, 1999, Atlanta, Georgia.

Appendix B — The ATSDR Water Modeling Team for Historical Reconstruction at U.S. Marine Corps Base Camp Lejeune, North Carolina

				Tarawa Terrace									Hadnot Point												
Name	Occupation	Position	Company	TT-A	TT-B	TT-C	TT-D	TT-E	TT-F	TT-G	TT-H	TT-I	HP-A	HP-S1	HP-S2	HP-S3	HP-S4	HP-S5	HP-S6	HP-S7	HP-S8	HP-B	HP-C	HP-D	Total
Morris L. Maslia, MSCE, PE, D.WRE, DEE	Research Environmental Engineer and Project Officer	Exposure-Dose Reconstruction Project	Agency for Toxic Substances and Disease Registry, Atlanta GA	X	O	O	O	O	O	O	O	X	X	X	X	O	X	X	X	X	X	O	O	X	11
René J. Suárez-Soto, MS EnvE, EIT	Environmental Health Scientist	Division of Health Assessment and Consultation	Agency for Toxic Substances and Disease Registry, Atlanta GA	X								X	X	X	X	X	X		X	X			X	X	11
Robert E. Faye, MSCE, PE	Civil Engineer/Hydrologist	Robert E. Faye and Associates, Inc	Consultant to Eastern Research Group, Inc. Lexington, Massachusetts	X	X	X		X	X			X	X			X						X	X	X	11
Mustafa M. Aral, PhD, PE	Director and Professor	Multimedia Environmental Simulations Laboratory	School of Civil and Environmental Engineering Georgia Institute of Technology Atlanta, Georgia	X						X	X	X	X		X			X		X	X				9
Jason B. Sautner, MSCE, EIT	Environmental Health Scientist	Division of Community Health Investigations	Agency for Toxic Substances and Disease Registry, Atlanta, Georgia	X								X	X	X	X						X		X		7
Barbara A. Anderson, MSEnvE, PE	Environmental Health Scientist	Division of Community Health Investigations	Agency for Toxic Substances and Disease Registry, Atlanta, Georgia										X	X	X			X	X	X			X		7
L. Elliott Jones, MS, PE	Hydrologist	Georgia Water Science Center	U.S. Geological Survey, Atlanta, Georgia										X			X	X		X						4
Wonyong Jang, PhD	Post Doctoral Fellow	Multimedia Environmental Simulations Laboratory	School of Civil and Environmental Engineering Georgia Institute of Technology Atlanta, Georgia	X						X			X							X					4
Walter M. Grayman, PhD, PE	Consulting Engineer		W.M. Grayman Consulting Engineer, Cincinnati OH	X								X	X								X				4
Jinjun Wang, MSCE	Ph.D. Candidate	Multimedia Environmental Simulations Laboratory	School of Civil and Environmental Engineering Georgia Institute of Technology Atlanta, Georgia	X							X	X													3
Claudia Valenzuela, MSCE	Post Graduate Research Fellow	Oak Ridge Institute for Science and Education	Agency for Toxic Substances and Disease Registry, Atlanta, Georgia	X		X						X													3
Jiabao Guan, PhD	Research Engineer	Multimedia Environmental Simulations Laboratory	School of Civil and Environmental Engineering Georgia Institute of Technology Atlanta, Georgia										X					X							2
Frank J. Bove, ScD	Senior Epidemiologist	Division of Toxicology and Human Health Services	Agency for Toxic Substances and Disease Registry, Atlanta, Georgia	X									X												2
Perri Z. Ruckart, MPH	Epidemiologist and Principal Investigator	Division of Toxicology and Human Health Services	Agency for Toxic Substances and Disease Registry, Atlanta, Georgia	X									X												2
Ilker T. Telci, PhD	Post-Graduate Research Fellow	Oak Ridge Institute for Science and Education	Agency for Toxic Substances and Disease Registry, Atlanta, Georgia												X						X				2
Joseph W. Green, Jr., MA	Post Graduate Research Fellow	Oak Ridge Institute for Science and Education	Agency for Toxic Substances and Disease Registry, Atlanta, Georgia	X				X																	2
Ilker T. Telci, PhD	Post-Graduate Research Fellow	Oak Ridge Institute for Science and Education	Agency for Toxic Substances and Disease Registry, Atlanta, Georgia										X												1
Susan M. Moore, MS	Environmental Health Scientist and Branch Chief	Division of Community Health Investigations	Agency for Toxic Substances and Disease Registry, Atlanta, Georgia										X												1
Amy L. Krueger, MPH	Post Graduate Research Fellow	Oak Ridge Institute for Science and Education	Agency for Toxic Substances and Disease Registry, Atlanta, Georgia	X																					1
Stephen J. Lawrence	Water-Quality Specialist	Georgia Water Science Center	U.S. Geological Survey, Atlanta, Georgia				X																		1
				13	1	2	1	2	1	2	2	8	14	4	6	3	3	4	4	5	5	1	4	3	

Senior Author	X
Contributing Author	X
Project Management & Coordination	O

Appendix C — Exposure-Dose Reconstruction Program: Overview of Strategy, Agency for Toxic Substances and Disease Registry, March 1993

March 26, 1993

From: Assistant Administrator, ATSDR, (E28)

Subject: ATSDR's Exposure-Dose Reconstruction Program
Overview of Strategy

To: Division Directors
Office Directors
Dose Reconstruction Committee Members

A critical activity in achieving ATSDR's mission is characterizing past and current human exposures to, and doses received from hazardous substances. On December 23, 1992 I requested that a coordinated, comprehensive plan be developed that would serve as the agency's strategy for exposure dose reconstruction activities. Since that time, members of the Dose Reconstruction Committee have developed a plan that will enable ATSDR to address issues ranging from total human exposure to early biological effects.

Attached to this memorandum is the document developed by the Dose Reconstruction Committee. The document sets forth the agency's program objectives and priorities for conducting exposure-dose reconstruction activities. As agency and division needs and requirements are identified, specific projects under the auspices of the Exposure-Dose Reconstruction Program will be proposed, developed, and funded.

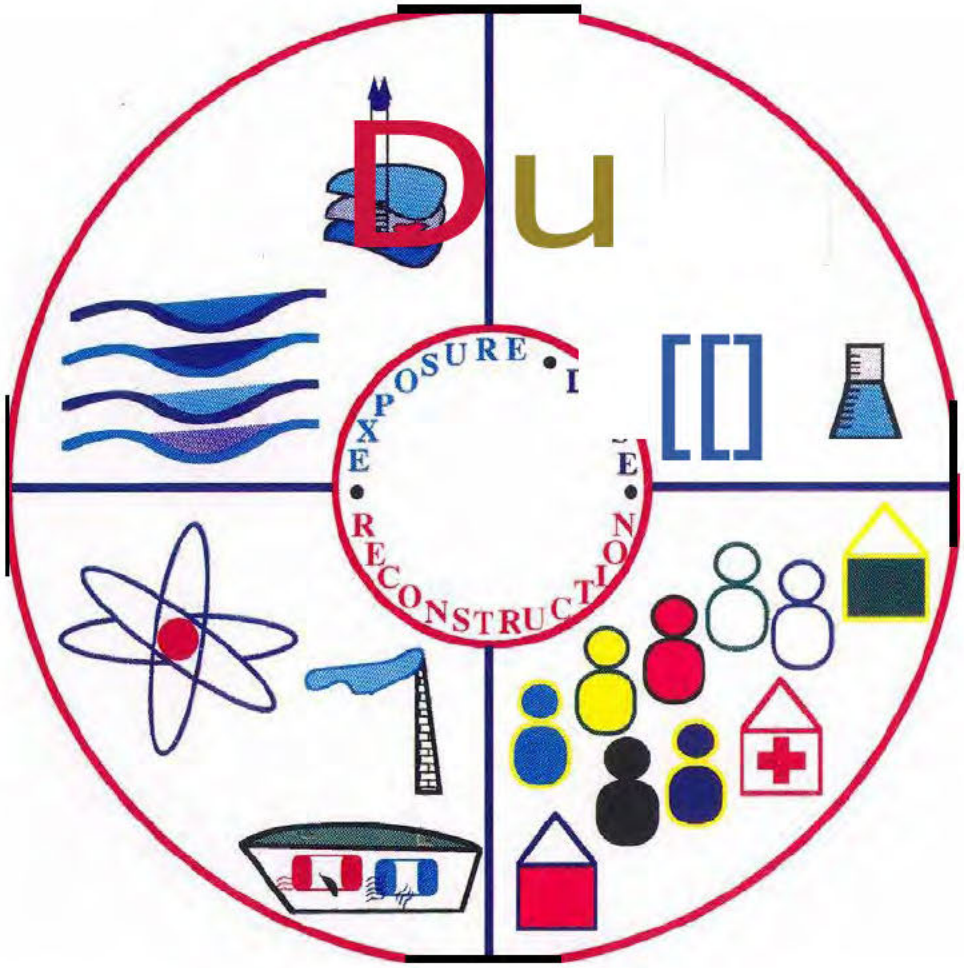
If additional copies of the report are needed, they may be obtained from Dr. Allan S. Susten, Assistant Director for Science, DHAC (E32).

_____
Barry L. Johson, Ph.D.

AGENCY FOR TOXIC SUBSTANCES AND DISEASE **REGISTRY**

EXPOSURE-DOSE RECONSTRUCTION **PROGRAM**

OVERVIEW OF STRATEGY



MARCH 1993

Agency for Toxic Substances and Disease Registry

EXPOSURE-DOSE RECONSTRUCTION PROGRAM

OVERVIEW OF STRATEGY

MARCH 1993

PREFACE

A critical activity in achieving ATSDR's mission is characterizing past and current human exposures to, and doses received from, hazardous substances. Because direct measures of exposure and dose are often unavailable to agency health assessors and health scientists, sensitive, integrated, science-based methods for exposure-dose characterization need to be developed. On December 23, 1992, Dr. Barry L. Johnson, Assistant Administrator, ATSDR, requested that a coordinated, comprehensive plan be developed that would serve as the agency's strategy for exposure-dose reconstruction activities. Since that time, members of the Dose Reconstruction Committee have developed a plan that will enable ATSDR to address issues ranging from total human exposure to early biological effects.

The overall goal of the Exposure-Dose Reconstruction Program is to enhance the agency's capacity to characterize exposure and dose to better support health assessments and consultations, health studies, and exposure registries. As agency and division needs and requirements are identified, specific projects under the auspices of the Exposure-Dose Reconstruction Program will be proposed and developed. This document, therefore, sets forth ATSDR's program objectives and priorities for conducting exposure-dose reconstruction activities.

AUTHORS AND CONTRIBUTORS

PRINCIPAL AUTHORS

Allan S. Susten, Ph.D., DABT

Assistant Director for Science
Division of Health Assessment and Consultation

Morris L. Maslia, MSCE, P.E.

Environmental Engineer
Division of Health Assessment and Consultation

CONTRIBUTORS

Paul A. Charp, Ph.D.

Chief, Energy Facilities Assessment Section Division
of Health Assessment and Consultation

Mark W. Evans, Ph.D.

Environmental Geologist
Division of Health Assessment and Consultation

Joseph L. Hugart, MPH

Deputy Director
Office of Federal Programs

Dennis E. Jones, Ph.D.

Senior Toxicologist
Office of the Associate Administrator for Science

M. Moiz Mumtaz, Ph.D.
Senior Toxicologist Division
of Toxicology

Ralph C. O'Connor, Jr., Ph.D.
Assistant Director for Science
Division of Health Education

Timothy M. Radtke, MSEH
Environmental Health Scientist
Division of Health Studies

Robert F. Spengler, Sc.D. Assistant
Director for Science Division of
Health Studies

Agency for Toxic Substances and Disease Registry

EXPOSURE-DOSE RECONSTRUCTION PROGRAM

OVERVIEW OF STRATEGY

INTRODUCTION

The Agency for Toxic Substances and Disease Registry (ATSDR) was created by the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA), otherwise known as Superfund. ATSDR's mission is to mitigate the adverse human health effects and diminished quality of life resulting from hazardous substances in the environment (ATSDR, 1992). A critical activity necessary to achieve this mission is characterizing past and current human exposures to, and doses received from, hazardous substances.

Because direct measures of exposure and dose, especially historical exposures, are often unavailable to ATSDR's health assessors and health scientists, the agency is embarking on a coordinated, comprehensive effort to develop sensitive, integrated, science-based methods for exposure-dose characterization. The agency's Exposure-Dose Reconstruction Program will coordinate relevant intramural and extramural projects covering environmental, geochemical, and biomedical disciplines.

For its purposes, ATSDR defines exposure-dose reconstruction as *an approach that uses computational models and other approximation techniques to estimate cumulative amounts of hazardous substances internalized by persons at presumed or actual risk from contact with substances associated with hazardous waste sites*. The emphasis of the program is to estimate past exposures. ATSDR is also beginning an exposure-dose determination initiative that uses direct personal space and biologic sampling to determine current exposure levels. This initiative will complement the Exposure-Dose Reconstruction Program.

In complying with CERCLA, ATSDR conducts activities at hazardous waste sites contaminated with radioactive or non-radioactive substances. Complexity of the sites varies with respect to the number, type and concentrations of contaminants, the number and characteristics of waste disposal areas for a site, site use, weather patterns, and the hydrogeologic and geochemical features of the site and surrounding areas. Whether sites are simple or complex, agency scientists require improved tools and methods for assessing exposures and doses that have the potential to produce adverse health effects if they are to arrive at credible conclusions regarding the health impact of hazardous waste sites. Moreover, ATSDR's policy is to determine the dose of an exposure whenever that is practicable (Johnson, 1992). The continuum that relates sources of contamination to clinical disease is illustrated in Figure 1.

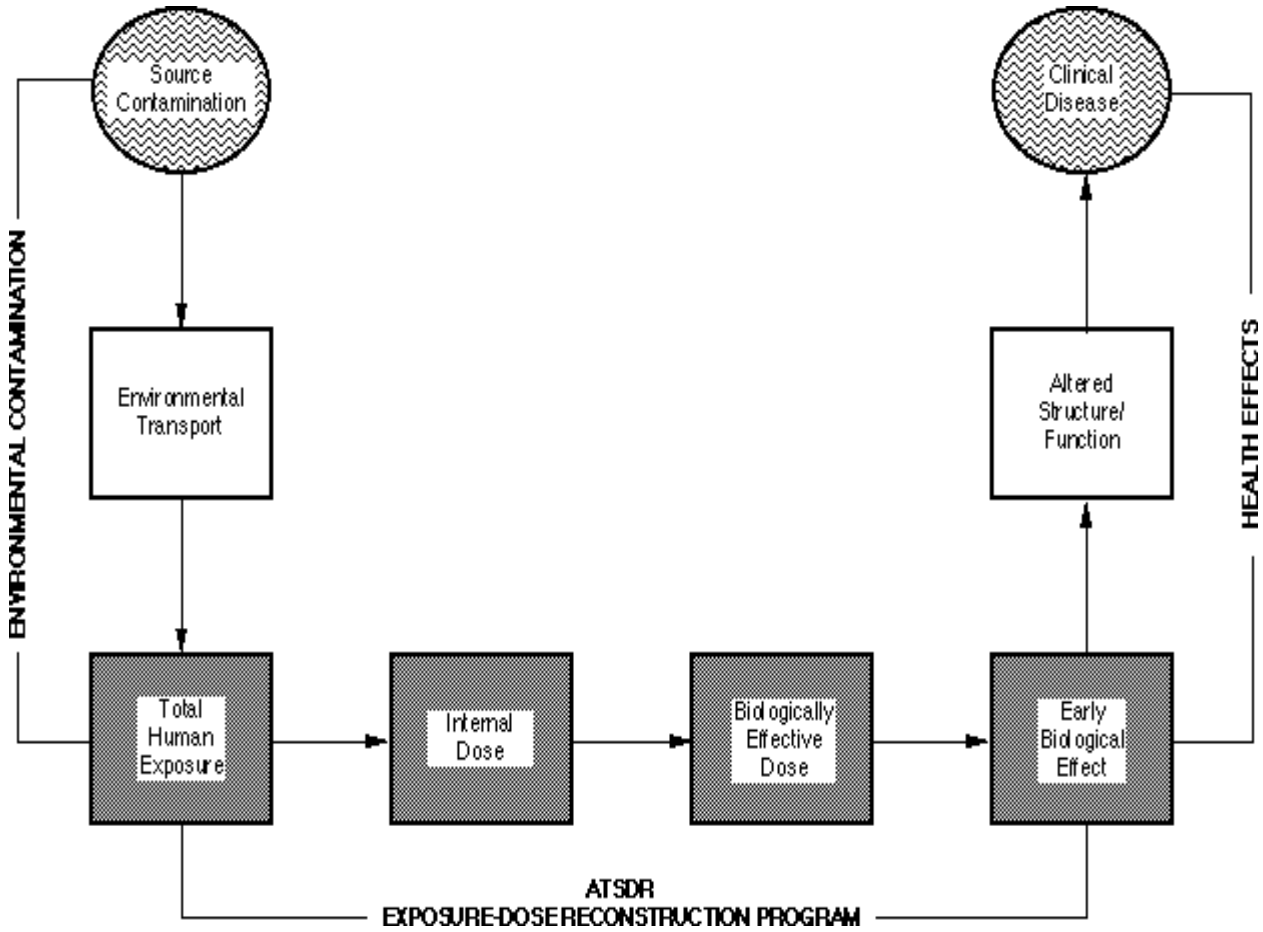


Figure 1. Continuum for relating environmental contamination with clinical disease. (From Lioy, 1990; Johnson and Jones, 1992)

PROGRAM GOAL

The goal of the Exposure-Dose Reconstruction Program is to enhance ATSDR's capacity to assess exposure and dose (with special emphasis on characterizing past exposures) to better support health assessments and consultations, health studies, and exposure registries.

PROGRAM OBJECTIVES

To set program priorities and focus activities, two objectives to meet the broad goal have been set. It is expected that the objectives will evolve over time as the agency begins to better understand the complexities of exposure-dose reconstruction. The objectives are these.

Over the next four years, significantly enhance the agency's ability to understand and use existing science-based methods and tools to assess past and current exposure and dose.

This objective will provide a stimulus to agency staff to focus on and identify specific areas of needs and activities, including training on existing tools and equipment, modifying existing techniques, and acquiring equipment and information.

Over the next four years, encourage developing new and improved technologies and methods that can be used by agency and non-agency scientists.

This objective can be met by developing a focused program that promotes using and developing mathematical models and computational tools for assessing total human exposure and by identifying and quantifying specific and sensitive biological indicators of exposure, disease, and susceptibility for assessing internal and biologically effective doses (Johnson and Jones, 1992)

STRATEGY

The strategy includes the following action elements:

- obtain and develop new and improved computational and mathematical tools for estimating past exposures and dose;
- obtain and develop tools for personal space monitoring and biologic testing for correlation with environmental sampling; and
- support research to fill specific information needs for use in environmental and biological models used for exposure-dose reconstruction.

The results of a number of completed agency projects (National Academy of Science (NAS) Studies) provide an important platform for planning future activities related to exposure-dose reconstruction. In addition, the results of several ongoing programs at ATSDR as well as programs at other agencies should provide additional relevant information.

A review of the approaches being used by other agencies revealed that a number of large-scale, exposure-dose reconstruction efforts are underway at several federal facility sites, including Hanford (Washington State), Idaho National Engineering Laboratory (Idaho), Rocky Flats Arsenal (Colorado), Fernald (Ohio), Oak Ridge (Tennessee), and Savannah River (South Carolina). At many of these sites, the primary concern is for radiological hazards; although, chemical hazards may also be present.

At several U.S. Department of Energy sites, the Centers for Disease Control and Prevention (CDC) have the lead in estimating public health impact of past and current radiation levels. Because many of ATSDR's efforts are directed toward hazardous substances and because techniques developed for quantifying radiological dose and risks are probably not applicable for estimating exposure to and dose received from chemicals, ATSDR, given resource constraints, believes it should focus its attention on the problems concerned with reconstructing exposures and doses to single and multiple chemicals. Completed, ongoing, and future activities relevant to the major action elements are presented below.

Obtain and develop improved computational and mathematical tools for estimating past exposures and dose:

Current Activities

An intramural project begun in FY93 will use existing computational and mathematical programs for assessing exposures to contaminated groundwater. This four-year project is the responsibility of the Division of Health Assessment and Consultation. Within the first two years, the existing programs will be applied to 12 sites, including four Exposure Registry sites. Advanced computer equipment and support hardware have been identified and purchased.

A four-year extramural project was begun in FY93 with first-year funding of $165,000 (recipient to be selected during 3rd Quarter FY93). The purpose of the project is to develop computational tools and a decision support system (software and a user's manual) for estimating exposures resulting from using contaminated groundwater at selected NPL sites. Deliverables scheduled in the 3rd and 4th years of the project are expected to provide agency staff with user-friendly methods that can be used to assess and reconstruct total exposures and estimates of dose from groundwater pathways.

The agency is continuing to develop a Geographic Information System (GIS) network. To date, six workstations have been purchased. The purpose of this activity is to use GIS

technology to obtain information from geographic databases, and in conjunction with the agency's HAZDAT database, assess population demographics to assist in estimating past exposures in communities surrounding hazardous waste sites.

Future Activities

Additional equipment will be needed if the agency's capacity is to be expanded beyond the limited number of staff members currently able to apply and use the existing programs and equipment. Because the goal is total exposure/dose assessment, enhanced agency capacity to do exposure assessments in other media (air, soil, surface water) in addition to groundwater is also needed. Plans to expand present activities to include other media should be initiated during FY93 and FY94.

Plans should be developed to apply and evaluate the existing groundwater methods at additional sites. A formal ranking scheme or screening tool should be developed to identify other sites for analysis during FY94, FY95, and beyond, if appropriate.

Studies to validate the predictive capabilities of the exposure models should be conducted.

Protocols for conducting such studies, if feasible, could be a topic of a scientific meeting.

Support research to fill specific information needs for use in environmental and biological models used for exposure-dose reconstruction:

Of particular interest are the following:

- improved tools and methods for estimating past, **total human exposure or potential dose** (exposure multiplied by contact rate [NAS, 1991, p. 29]) to one or more hazardous substances as a result of contact with one or more media;
- improved approaches for estimating past internal doses (amount absorbed or deposited in the body of exposed individuals or interactions with membrane surfaces [NAS, 1991, p. 29]); and
- improved tools and methods for modeling and measuring **biologically effective doses** (amount of deposited or absorbed contaminant that reaches the cells or target site where an adverse effect occurs [NAS, 1991, p. 29]).

Current Activities

An extramural project was begun in FY93 to develop assessment methods that will bridge the gap between internalized dose and subtle alterations in structure/function (disease). The three-year project is being funded under a cooperative agreement with the Environmental & Occupational Health

Sciences Institute (EOHSI), Piscataway, New Jersey. First-year funding was $200,000. A workshop is planned in FY93 to prioritize future activities.

ATSDR is funding CDC's National Center for Health Statistics to develop reference ranges for 38 substances measured in biologic media. This is being accomplished through the latest population-based survey, the National Health and Nutrition Examination Survey (NHANES III). Such "baseline" data are useful when evaluating persons at health risk from exposure to any of the 38 substances.

Through a cooperative agreement with the National Research Council (NRC), ATSDR has sponsored biological marker studies that have resulted in four monographs that address biological markers for specific clinical or toxicologic endpoints (Johnson and Jones, 1992). The monographs address reproductive toxicology, pulmonary toxicology, neurotoxicology, and immunotoxicology. Ongoing projects include reports on Urinary Tract Biomarkers and Measuring Lead in Critical Populations.

ATSDR's Division of Toxicology is evaluating a model that estimates total body burdens of lead based on published slope factors for people exposed to known concentrations of lead in environmental media. Testing and validation of the model is planned for the latter part of FY93. This activity is also being monitored under the agency's lead program.

Future Activities

ATSDR's Division of Toxicology has formed a workgroup to focus on the development and use of integrated uptake/biokinetic (IU/BK) models for assessing the distribution and body burdens of environmental contaminants. The Exposure-Dose Reconstruction Committee should work closely with this group to promote development and validation of IU/BK models that will increase ATSDR's capacity to evaluate health impacts of specific site contaminants. Through an analysis of completed health assessments and consultations, a list of selected substances can be identified for which the development of IU/BK models should be considered.

The Division of Toxicology's substance-specific research program should be used to fill in data that will be needed for the environmental and biological models. These needs can be identified through the activities of the Dose-Reconstruction Program in addition to the to those identified by the Toxicological Profiles.

ATSDR's Division of Health Assessment and Consultation will develop an initiative to focus on exposure-dose determination. Exposure-dose measurements, taken as part of the public health assessment process when ongoing exposures appear likely, will help to prevent or mitigate adverse health effects. Levels of toxic substances in biologic samples and personal space will be correlated with environmental samples. This activity is critical because direct measurements of many substances such as volatile organic compounds (VOCs) cannot be obtained once exposure has ended. Site-specific exposure-dose information will complement exposure-dose reconstruction activities.

COORDINATION

In pursuing agency objectives, the Dose Reconstruction Committee will coordinate intramural and extramural activities with CDC, EPA, NTP, and other organizations that are actively involved with exposure-dose assessment and reconstruction. The committee will monitor and provide status reports on a regular basis to the Assistant Administrator, ATSDR.

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Appendix D — Dover Township, Toms River, New Jersey Childhood Cancer Cluster Investigation

Background

Toms River, located in Dover Township, Ocean County, New Jersey, USA, experienced an increased incidence in childhood leukemia, brain, and central nervous system cancers from the mid-1980s through the early 1990s. (See Figure D.1 for location and Figure D.2 for cancer incidence, located at end of this section). These findings initiated a series of community-based activities that lead to the establishment of a successful partnership between the community, public health, and environmental agencies. The common goal of this partnership was to investigate linkages between environmental exposures and childhood cancers. The case–control study focused on two age groups in which elevated rates of cancer were previously found in Dover Township — children diagnosed before 20 years of age and children diagnosed before age five. The study was designed to focus on specific hypotheses about certain environmental exposure pathways. These hypotheses included: (1) exposure to two public drinking water supply sources with documented historical contamination (Parkway and Holly well fields), (2) exposure to contaminated private wells in Dover Township, and (3) exposure to major air pollution sources.

Exposure Indexes

To develop exposure indexes that would test the study hypotheses for drinking-water exposure, the study area's municipal drinking water distribution system was assessed using advanced numerical modeling techniques to reconstruct historical conditions (EPANET; Rossman 1994). For example, to derive exposure indexes for the municipal water supply and water-distribution system, modeling focused on reconstructing and estimating the percentage of water that a study subject might have received from each well and well field that historically supplied the water-distribution system. This modeling approach led to a novel development of the "proportionate contribution" concept wherein at any given point in the distribution system, water may be derived from one or more sources in differing proportions.

Using Water-Distribution System Modeling to Assist Exposure Assessment

Because the Dover Township area was primarily served by public water supply that relies solely on groundwater, ATSDR developed a protocol for using a water-distribution model as a tool to assist the exposure assessment component of the epidemiologic investigation (the EPANET model). Components of the water-distribution modeling approach included: (1) gathering data during field tests conducted in March and August 1998, (2) the development, calibration, and testing of the water-distribution system model for 1998 conditions, (3) a water-quality simulation of a naturally occurring conservative element in the groundwater, barium, to further test the reliability of the model calibration, (4) simulation of the proportionate contribution of water from points of entry (i.e., well fields) to various locations throughout the distribution system for 1998 conditions, and (5) reconstructing the water-distribution system networks on an monthly basis from 1962 through 1996 to determine the historical monthly "proportionate contribution" of water from all municipal well fields to any point served by the water-distribution system.

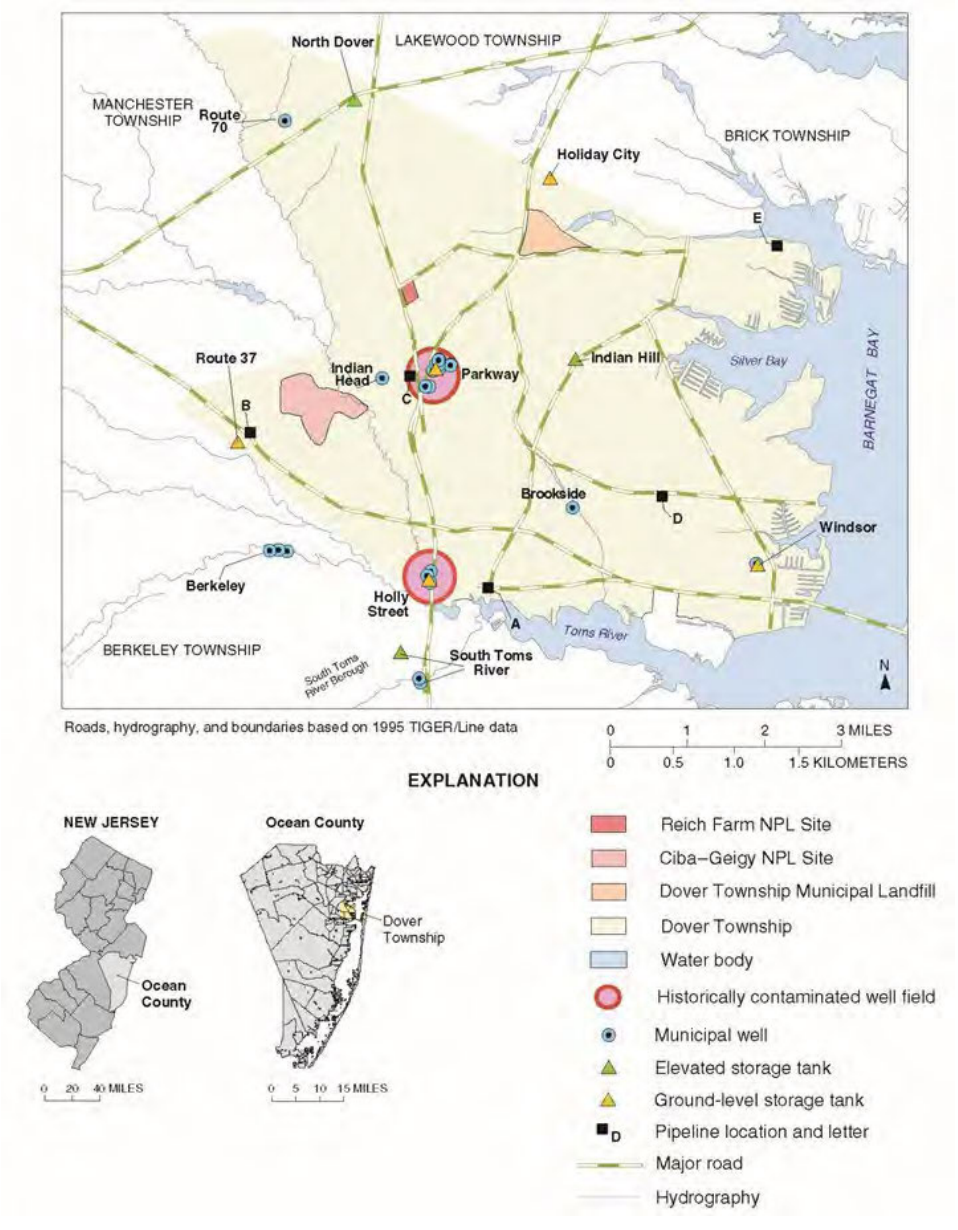


Figure D.1. Investigation area, Dover Township, Ocean County, New Jersey (modified from Maslia et al. 2001).

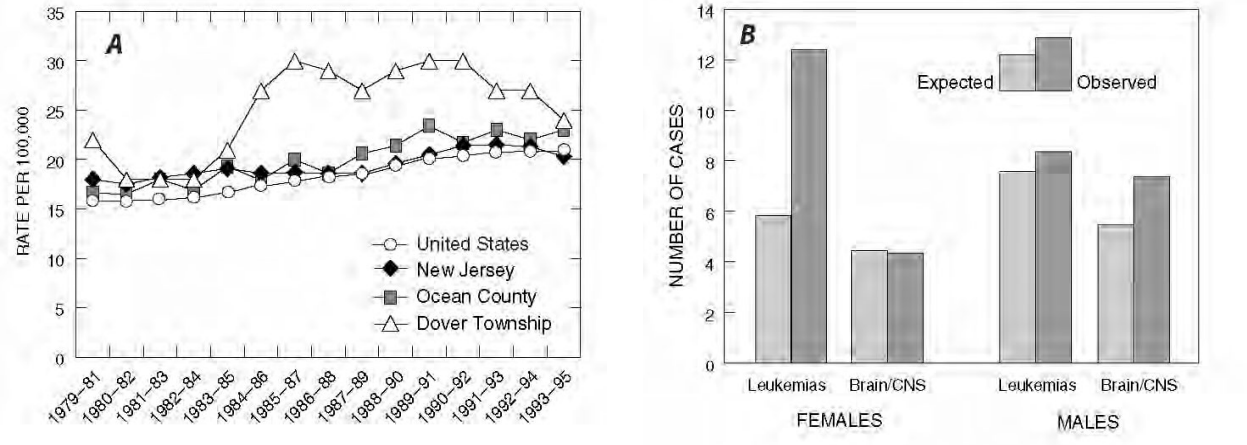


Figure D.2. Childhood cancer incidence analysis: (A) time trend in childhood cancer rates (1979–1995). (B) childhood cancer incidence, ages 0–19 years, Dover Township, New Jersey (1979–1995). (From Maslia et al. 2005).

Historical Reconstruction

Because of the lack of appropriate historical data, the EPANET model was calibrated to the present-day (1998) water-distribution system characteristics using data collected during March and August 1998. The reliability of the calibrated model was demonstrated by successfully conducting a water-quality simulation of the transport of a naturally occurring (in groundwater) conservative element—barium—and comparing results with data collected at 21 schools and 6 points of entry to the water-distribution system during March and April 1996. Results of the field-data collection activities, model calibration, and reliability testing are described in Maslia et al. (2000a, b). Following calibration, the model was used to reconstruct historical characteristics of the water-distribution system serving the Dover Township area on a monthly basis from 1962 through 1996.

Examples of historical results for the proportionate contribution of water are shown in Figure 5.3 (located at end of this section) for May 1962 and June 1996. In these examples, five geographically distinct locations (A–E) are selected from the historical distribution-system networks (see Figure 5.1 for locations A–E). In May 1962 (Fig. 5.3A), only two well fields (Holly and Brookside) provided water to any one location (e.g., locations A and C); whereas, in June 1996 (Fig. 5.3B), as many as seven well fields provided water to the distribution system (e.g., location E). Additionally, in May 1962, the Holly well field provided approximately 70% of the drinking water to location C (Fig. 5.3A), whereas, in June 1996 the Parkway well field provided approximately 70% of the drinking water to location C (Fig. 5.3B). Health scientists conducting the case–control epidemiologic study used the results described above (Fig. 5.3) to derive exposure indexes for each study subject.

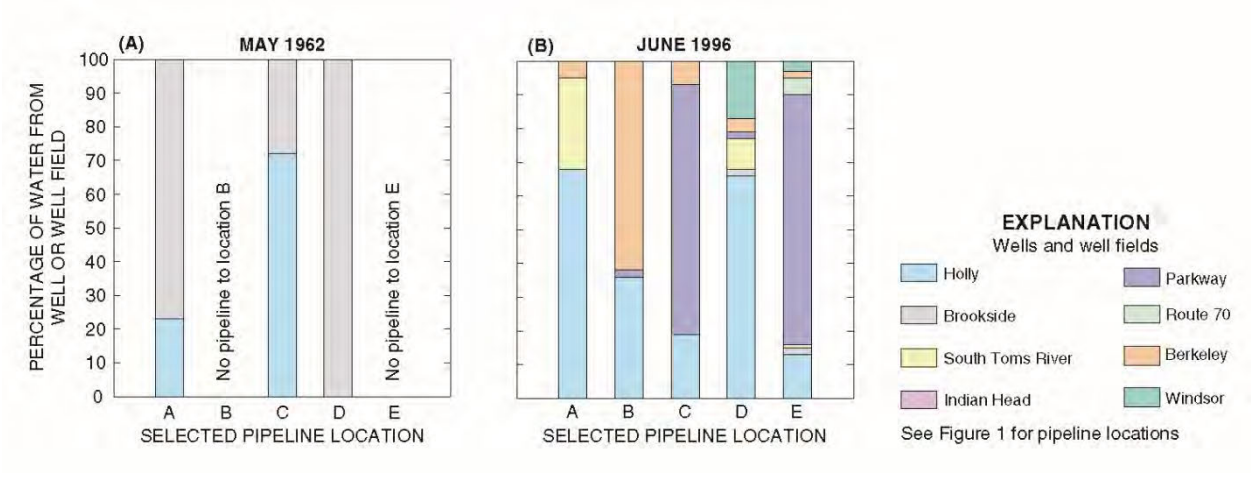


Figure D.3. Reconstructed (simulated) proportionate contribution of water from wells and well fields to selected locations in Dover Township area, New Jersey: (A) May 1962, and (B) June 1996 (see Figure 5.1 for locations A–E). (From Maslia et al. 2001, 2005).

Results from the case–control study showed (NJDHSS, 2003):

- A statistically significant association and consistency in multiple measures of association between prenatal exposure to time-specific Parkway well field water (1982–1996) and leukemia in female children of all ages, and
- a consistent elevation in the odds ratios and an apparent dose response effect was seen in interview and birth records studies between prenatal exposure to Ciba-Geigy ambient air and leukemia in female children diagnosed prior to age five.

Innovative methods were developed and used in the Toms River childhood cancer cluster investigation. With respect to characterizing the Dover Township water-distribution system, pressure data were gathered *simultaneously at 25 hydrants* throughout the distribution system using *continuous recording pressure data loggers* during 48-hour tests in March and August 1998. Data for storage tank water levels, system demand, and pump and well status (on/off) were obtained from the supervisory control and data acquisition (SCADA) system at the same time. Results of this aspect of the study were presented in the peer-reviewed American Society of Civil Engineers (ASCE) *Journal of Water Resources, Planning and Management* (Maslia et al. 2000). This paper was subsequently awarded (by ASCE in 2001), Best Practice-Oriented Paper of 2000 for the paper, *"Using Water-Distribution System Modeling to Assist Epidemiologic Investigations,"* ASCE Journal of Water Resources Planning and Management, Vol. 126, July/August 2000.

Results of the Dover Township, Toms River, New Jersey, childhood cancer cluster investigation are presented in ATSDR and NJDHSS reports (all independently peer reviewed) and published in peer-reviewed scientific journals (Maslia 2000a, b, 2001, 2005, NJDHSS 2003).

The American Academy of Environmental Engineers (AAEE) also recognized the Dover Township, Toms River, New Jersey, historical reconstruction effort. This environmental engineering professional organization awarded the

ATSDR and NJDHSS effort the 2003 Excellence in Environmental Engineering Award, Grand Prize, Research Category (April 2003) for the project, "*Enhancing Environmental Engineering Science to Benefit Public Health, Dover Township, Ocean County, New Jersey.*"

The Dover Township, Toms River, New Jersey childhood cancer investigation results are significant because out of hundreds of cancer cluster investigations, only two — Woburn, Massachusetts and Dover Township, New Jersey — have shown an association between environmental exposures and childhood cancer.

Appendix E — Information Sources Used to Extract Model-Related Data for Historical Reconstruction

Appendix A2. Information sources used to extract model-specific data for historical reconstruction analyses, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[Refer to end of Appendix A2 for a list of abbreviations and acronyms]

Information source	Original media	Supplier or location of information source	Approximate quantity or size	Description	Date obtained (date of information)
ATSDR information requests and selected authored reports					
ATSDR information request, July 11, 2003	CD–ROM	Camp Lejeune	CD–ROMs with numerous files	Final Basewide Remediation Assessment Groundwater Study (Baker 1998a); GIS data for Camp Lejeune; historical water-supply well data from wellhead management program study (Geophex Ltd. 1991); wellhead protection plan update (AH Environmental Consultants 2002); historical water treatment plant booster pump information (Henry Von Oesen and Associates, Inc. 1979)	Aug. 2003 (varies)
ATSDR information request, 2004	CD–ROM, DVD	Camp Lejeune	About 25 gigabytes	Natural color digital orthophotography; data layers maintained in the integrated geographic information repository (IGIR) master database, Feb. 2004; TIFF files	Nov. 2004 (Feb. 2004)
ATSDR information request, 2005	Paper	Camp Lejeune	12 pages	Documentation for startup of Holcomb Boulevard water treatment plant; acquisition data form, April 1973; plant account record card, July 1990; Newspaper (Globe) article, August 1972; Command chronology, July–Dec 1972	Sept. 2005 (June–Dec. 1972)
ATSDR information request, Dec. 1, 2005	CD–ROM	Camp Lejeune	3 CD–ROMs	VOC impacted drinking water document database (CLW database); TCE/PCE sample result summary spreadsheet; JTC historical laboratory analytical results (subset of CLW database, about 34 files)	Dec. 2005 (1980–1986)
ATSDR information request, 2006	CD–ROM, DVD	Camp Lejeune	1 CD–ROM, 1 DVD	Natural color digital orthophotography of entire base, Feb. 2004, MrSID image format; color infrared color digital orthophotography of entire base, Mar. 1996, MrSID image format	Sept. 2006 (Nov. 2004; Mar. 1996)
ATSDR information request, May 2009	CD–ROM, DVD, paper	Camp Lejeune	CD–ROM, DVD, paper	186 documents (PDFs) from the Camp Lejeune Historic Drinking Water Consolidated Document Repository (f/k/a BAH files); 31 sets of contract drawings from Public Works vault; Raw Water Master Plan (AH Environmental Consultants 2005); Draft (2009) USGS groundwater- level report, (published as McSwain 2010); Permit to Construct Municipal Solid Waste Landfill (Dewberry and Davis 1995); Evaluation of Cogdell's Creek (CH2M HILL, Inc. 1998); Corrosion Control Study, Hadnot Point and Marine Corps Air Station (MCAS) New River (Malcolm Pirnie 1999)	July 2009 (varies)
ATSDR information request, Nov. 2009	CD–ROM	Camp Lejeune	1 CD–ROM (about 160 megabytes)	Site Management Plans for 2007, 2008, 2009, and 2010 (CH2M HILL 2007a,b, 2008, 2009)	Dec. 2009 (Apr. 2007–Aug. 2009)
ATSDR information request, Apr. 2011	CD–ROM	USEPA, Region IV	57 files, 19 megabytes	JTC Laboratory analyses on Naval samples	Sept. 2011 (Feb. 1985–Apr. 1986)

Appendix A2. Information sources used to extract model-specific data for historical reconstruction analyses, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[Refer to end of Appendix A2 for a list of abbreviations and acronyms]

Information source	Original media	Supplier or location of information source	Approximate quantity or size	Description	Date obtained (date of information)
ATSDR information requests and selected authored reports—Continued					
Hadnot Point–Holcomb Boulevard reports	Paper; electronic (PDF)	ATSDR *http://www.atsdr.cdc.gov/sites/lejeune/watermodeling.html*	Three reports (Chapters B, C, and D), about 40 megabytes	Analyses and interpretations of data to develop geohydrologic framework of the Brewster Boulevard and Castle Hayne aquifer systems and the Tarawa Terrace aquifer; analyses of selected contaminants within the HPWTP and HBWTP service areas and vicinities at Camp Lejeune; among contaminants of interest in this report series, PCE, TCE, 1,2-tDCE, benzene, and vinyl chloride	Oct. 2010, Jan. 2012, Dec. 2012 (1940s–2008)
Public Health Assessment for ABC One-Hour Cleaners	Paper	ATSDR records room and LAN	1 folder in records room	Administrative records for 1990 public health assessment; 1996 site review and update also available	Aug. 1990; Sept. 1996 (Aug. 1990; Sept. 1996)
Public Health Assessment for Camp Lejeune	Paper	ATSDR records room and LAN	52 folders in records room and numerous electronic files	Administrative records for 1997 public health assessment	Aug. 1997 (Aug. 1997)
Tarawa Terrace reports	Paper; electronic (PDF)	ATSDR *http://www.atsdr.cdc.gov/sites/lejeune/watermodeling.html*	Executive summary report and 9 report volumes (Chapters A–I); about 100 megabytes	Analyses of the Tarawa Terrace drinking-water system at Camp Lejeune that was contaminated with PCE and its degradation by-products from the nearby, off-base, ABC One-Hour Cleaners	2007–2009 (1950s–1994)
Databases and information portals					
ABC One-Hour Cleaners site reports	Paper; electronic (PDF)	USEPA Web site: *http://www.epa.gov/*	About 25 electronic files (PDF), 125 megabytes	Reports primarily related to CERCLA activities at ABC One-Hour Cleaners site; files vary in size from a few pages to several hundred pages	2003–2007 (1986–2007)
Camp Lejeune Historic Drinking Water Consolidated Document Repository (CLHDW CDR)	Electronic (PDF)	Camp Lejeune	514 pages (index only); about 8,000–10,000 documents	The index (f/k/a BAH index) is a list of documents compiled from a base-wide search of buildings and documents; a single index entry may reference several boxes to tens of boxes of documents and information records	Apr. 2009 (varies)
Camp Lejeune Historic Drinking Water Consolidated Document Repository (CLHDW CDR)	Electronic (PDF)	Camp Lejeune	7,403 files, 158 gigabytes	Documents, handwritten notes, reports, lab analyses, water-supply data, compiled from a base-wide search of buildings and documents; a single file may reference several one-page documents or several hundred pages of information and records	Mar. 2011 (varies)
Camp Lejeune water document (CLW files)	CD–ROM	Camp Lejeune	About 574 megabytes; about 1,100 files	Documents, handwritten notes, reports, lab analyses primarily related to water supply, distribution, and water-quality issues; files vary in size from a few pages to several hundred pages	Dec. 2005 (varies)
CERCLA administrative record for ABC One-Hour Cleaners	Paper and electronic (PDF)	USEPA Web site: *http://www.epa.gov/*	About 100 files listed on CERCLA administrative record index	Documents, handwritten notes, and reports primarily related to CERCLA activities at ABC One-Hour Cleaners site; files vary in size from a few pages to several hundred pages	2003–2007 (1986–1994)

Appendix A2. Information sources used to extract model-specific data for historical reconstruction analyses, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[Refer to end of Appendix A2 for a list of abbreviations and acronyms]

Information source	Original media	Supplier or location of information source	Approximate quantity or size	Description	Date obtained (date of information)
Databases and information portals—Continued					
CERCLA administrative record for Camp Lejeune	Hard drive (provided by Camp Lejeune)	Baker Engineers, Inc., Web portal; *http://www.bakerenv.com/camplejeune_irp*	About 15 gigabytes; about 3,700 files	Documents, handwritten notes, and reports primarily related to installation restoration program sites at Camp Lejeune; files vary in size from a few pages to several hundred pages	Jan. 2006 (varies)
Environmental Management Division (EMD) document index	Electronic (MS Excel; PDF)	Camp Lejeune	Hundreds to thousands of reports and documents	Reports and documents related to base IRP, wastewater, drinking water, surface water, groundwater, indoor air quality, vapor intrusion, solid waste, landfill activities, environmental conservation, compliance, wellhead management, etc.	2003–2010 (varies)
Terrabase—IRP sites	CD–ROM (MS Access)	Catlin/Camp Lejeune	About 1.3 million records of analytical data	Analytical data associated with base IRP provided to Catlin by Camp Lejeune; IRP data derived from other source documents	Apr. 2010 (1984–2010)
Terrabase—UST sites	CD–ROM (MS Access)	Catlin/Camp Lejeune	About 700,000 records of analytical data	Time frame of data is 1984 to 2005. Database developed from database provided to Catlin by Camp Lejeune during November 2005; contains analytical data for UST sites	Mar. 2010 (1984–2005)
UST files	Electronic (Web portal)	Camp Lejeune; Catlin Engineers and Scientists *http://lejeune.Webmainframe.com* (proprietary)	1,535 files	Information, site data, meeting minutes, monitoring data, etc., related to all UST sites and activities at Camp Lejeune; files vary in size from a few pages to exceeding 1,000 pages	Mar. 2010 (1986–2009)
Drinking-water system information and data					
AH Environmental reports on drinking-water systems	Paper	Camp Lejeune	6 reports, about 250 pages	Cataloging and information gathering of drinking-water systems at Camp Lejeune; all reports by AH Environmental Consultants: (1) Long Term Water System Master Plan (Dec. 2001), (2) Wellhead Protection Plan—2002 Update (Aug. 2002), (3) Water Distribution System Modeling Support (Aug. 2004), (4) ATSDR Support—Estimation of VOC Removal (Dec. 2004), (5) Meter Installation Work Plan (Dec. 2004), and Raw Water Master Plan (March 2005)	Aug. 2003–Dec. 2005 (2001–2005)
Golf course watering information	Paper	Camp Lejeune	5 electronic files	Scanned images (PDFs and TIFFs) of golf course sprinkler locations and information	Sept. 2010 (Mar. 1969; Aug. 1991; June 1993)
Pump rating curves	Paper	Camp Lejeune	4 pages	Pump rating curves for finished water pumps at Hadnot Point and Holcomb Boulevard water treatment plants	Mar. 2004 (~1985?)

Appendix A2. Information sources used to extract model-specific data for historical reconstruction analyses, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[Refer to end of Appendix A2 for a list of abbreviations and acronyms]

Information source	Original media	Supplier or location of information source	Approximate quantity or size	Description	Date obtained (date of information)
Drinking-water system information and data—Continued					
Survey of selected water-distribution system locations	Electronic (MS Excel)	U.S. Geological Survey, North Carolina Water Science Center	27 fire hydrants and 7 water-storage tanks	Horizontal and vertical survey data for selected hydrants and water-storage tanks	May–July 2004 (May–July 2004)
Survey of selected water-distribution system locations	Electronic (MS Excel)	Parker and Associates (subcontractor to Eastern Research Group, Inc.)	56 fire hydrants, 21 monuments, and 6 water-storage tanks	Horizontal and vertical survey data for selected hydrants and water-storage tanks	Oct. 2004 (Oct. 2004)
Water treatment plant flow data	CD–ROM	Camp Lejeune	About 100 megabytes	2-minute SCADA data for various times during 2004–2005	2004–2007 (Mar. 2004–Sept. 2005)
Water treatment plant flow data	Electronic (MS Excel); paper	Camp Lejeune	About 15 megabytes	Daily and monthly flows from water treatment plants; 1995–1999 in paper format; 2000–2005 in electronic format	2004–2009 (1999–2005)
Water utility maps	CD–ROM; paper	Camp Lejeune	About 100–150 files, 500 megabytes	Historical (1956–1987) water utility maps, scanned in as TIFFs, showing water-distribution systems aboard Camp Lejeune	July 2006 (1956–1987)
Water utility and housing maps	CD–ROM	Camp Lejeune	About 500 files, 525 megabytes	Historical (1940s and 1950s) water utility and housing maps, scanned in as TIFFs, 50-ft and 500-ft scales	Oct. 2003 (1940s–1950s)
Water plant log books	Paper	Camp Lejeune	About 2,100 pages	CLW files 6610.pdf–8761.pdf; handwritten entries in water utility log books containing information on mechanical repairs, water-supply operations, water-quality issues, and customer contacts and complaints	Dec. 2005 (varies)
Water-supply wells capacity data	Paper	Camp Lejeune	About 110 wells	Historical and present-day notes, information and data on operations and capacity histories of Tarawa Terrace, Holcomb Boulevard, and Hadnot Point water-supply wells	Aug. 2003–Aug. 2010 (1940s–2010)
Water-supply well operational data	CD–ROM	Camp Lejeune	10,000 scanned pages	Ten years of daily records, 1999–2008, indicating water-supply well on-off cycling operations—handwritten entries	2009 (1999–2008)
Housing records and information					
Housing maps	Paper	Camp Lejeune	About 10 maps (sheets)	Paper maps that show housing units, addition of housing units, and estimated number of housing units	Date unknown (1940s–1990s)
Housing records	Paper	Camp Lejeune	About 90,000 records	Camp Lejeune housing records used for identifying enlisted and officer personal housing locations; obtained for small for gestational age study (ATSDR 1998)	About 1994 (1950s–1995)

Appendix A2. Information sources used to extract model-specific data for historical reconstruction analyses, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

(Refer to end of Appendix A2 for a list of abbreviations and acronyms)

Information source	Original media	Supplier or location of information source	Approximate quantity or size	Description	Date obtained (date of information)
Drinking-water system information and data—Continued					
Survey of selected water-distribution system locations	Electronic (MS Excel)	U.S. Geological Survey, North Carolina Water Science Center	27 fire hydrants and 7 water-storage tanks	Horizontal and vertical survey data for selected hydrants and water-storage tanks	May–July 2004 (May–July 2004)
Survey of selected water-distribution system locations	Electronic (MS Excel)	Parker and Associates (subcontractor to Eastern Research Group, Inc.)	56 fire hydrants, 21 monuments, and 6 water-storage tanks	Horizontal and vertical survey data for selected hydrants and water-storage tanks	Oct. 2004 (Oct. 2004)
Water treatment plant flow data	CD–ROM	Camp Lejeune	About 100 megabytes	2-minute SCADA data for various times during 2004–2005	2004–2007 (Mar. 2004–Sept. 2005)
Water treatment plant flow data	Electronic (MS Excel); paper	Camp Lejeune	About 15 megabytes	Daily and monthly flows from water treatment plants; 1995–1999 in paper format; 2000–2005 in electronic format	2004–2009 (1999–2005)
Water utility maps	CD–ROM; paper	Camp Lejeune	About 100–150 files, 500 megabytes	Historical (1956–1987) water utility maps, scanned in as TIFFs, showing water-distribution systems aboard Camp Lejeune	July 2006 (1956–1987)
Water utility and housing maps	CD–ROM	Camp Lejeune	About 500 files, 525 megabytes	Historical (1940s and 1950s) water utility and housing maps, scanned in as TIFFs, 50-ft and 500-ft scales	Oct. 2003 (1940s–1950s)
Water plant log books	Paper	Camp Lejeune	About 2,100 pages	CLW files 6610.pdf–8761.pdf; handwritten entries in water utility log books containing information on mechanical repairs, water-supply operations, water-quality issues, and customer contacts and complaints	Dec. 2005 (varies)
Water-supply wells capacity data	Paper	Camp Lejeune	About 110 wells	Historical and present-day notes, information and data on operations and capacity histories of Tarawa Terrace, Holcomb Boulevard, and Hadnot Point water-supply wells	Aug. 2003–Aug. 2010 (1940s–2010)
Water-supply well operational data	CD–ROM	Camp Lejeune	10,000 scanned pages	Ten years of daily records, 1999–2008, indicating water-supply well on-off cycling operations—handwritten entries	2009 (1999–2008)
Housing records and information					
Housing maps	Paper	Camp Lejeune	About 10 maps (sheets)	Paper maps that show housing units, addition of housing units, and estimated number of housing units	Date unknown (1940s–1990s)
Housing records	Paper	Camp Lejeune	About 90,000 records	Camp Lejeune housing records used for identifying enlisted and officer personal housing locations; obtained for small for gestational age study (ATSDR 1998)	About 1994 (1950s–1995)

Appendix A2. Information sources used to extract model-specific data for historical reconstruction analyses, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[Refer to end of Appendix A2 for a list of abbreviations and acronyms]

Information source	Original media	Supplier or location of information source	Approximate quantity or size	Description	Date obtained (date of information)
Map information and data					
Airborne laser digital imagery; spatial data, Onslow County, NC	DVD	Spectrum Mapping Corporation, North Carolina	44 DVDs (about 170 gigabytes)	Digital orthophotographs of Onslow County, North Carolina	Nov. 2004 (Feb. 2003?)
AutoCAD files	CD–ROM	Camp Lejeune	About 100 megabytes; 70 files	Quadrangle maps of Camp Lejeune containing features such as topography, utility lines, wastewater and water-distribution systems, housing locations, etc.	Oct. 2003 (1996)
Camp Lejeune survey control data	Paper	Camp Lejeune	1 report (85 pages)	Report on geodetic survey to upgrade and update horizontal control aboard U.S. Marine Corps Base Camp Lejeune	2005 (Sept. 1984)
Digital elevation model (DEM) data	DVD	U.S. Geological Survey, North Carolina Water Science Center	1.9 gigabytes	LIDAR-derived DEM data for Camp Lejeune area, 20-ft and 5-ft grids; obtained from the NC Flood Mapping Program	Jan. 2004; Aug. 2010 (May 31, 2002)
Digital topographic contour data	CD–ROM	U.S. Geological Survey, North Carolina Water Science Center	650 megabytes	2-ft contours created from the 20-ft LIDAR-derived DEM, available from the NC Flood Mapping Program; projection is NC State Plane, NAD 83, units feet	Feb. 2004 (May 31, 2002)
Geographic information system files	CD–ROM; DVD	Camp Lejeune	Several dozen CD–ROMs and DVDs	Installation geospatial information and historical satellite imagery files	Aug. 2003–July 2009 (1938–June 2009)
Soil Survey Geographic (SSURGO) database for Onslow County, North Carolina	Electronic	Natural Resources Conservation Service, United States Department of Agriculture *http://soildatamart.nrcs.usda.gov*	1.6 megabytes	Georeferenced digital map data and tabular data of soils and attribute data for Onslow County, NC, provided in ESRI Arcview shapefile format	Nov. 2010 (Sept. 2003–June 2009)
North Carolina documents and reports					
Central Coastal Plain Capacity Use Investigation Report	Electronic (PDF)	NCDENR, Division of Water Resources	1 report (24 pages)	Report describing the central coastal plain capacity use area under the 1967 Water Use Act (NCDENR 1998)	Nov. 2003 (Nov. 1998)
Detailed soil maps for Onslow County, NC	CD–ROM	North Carolina Center for Geographic Information and Analysis	52 megabytes	Detailed digital soils maps for Onslow County, North Carolina	Apr. 2005 (2003–2004)
North Carolina water-supply plan	Electronic (PDF)	North Carolina Department of Environment and Natural Resources (NCDENR)	1 report and 20 appendixes (about 150 pages)	Compilation of more than 500 water-supply plans developed by local government water systems to assess water-supply needs over the next 20 years; report dated January 2001 and based on local water-supply plans developed during 1998 and 1999	Nov. 2003 (1998–1999)

Appendix A2. Information sources used to extract model-specific data for historical reconstruction analyses, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[Refer to end of Appendix A2 for a list of abbreviations and acronyms]

Information source	Original media	Supplier or location of information source	Approximate quantity or size	Description	Date obtained (date of information)
North Carolina documents and reports—Continued					
State of North Carolina Records	CD–ROM, DVD, paper	NCDENR and historical archives in Raleigh and Wilmington[1]	5 CD–ROMs, 1 DVD, (historical files unknown)	Historical and present-day water-supply information; water-supply well construction information; site information for Hadnot Point fuel farm (IR site 22) and Hadnot Point Industrial Area (IR site 78)	Mar. 2004; June 2010; Aug. 2010 (1980–2007)
State of North Carolina vital statistics data files	Paper	NCDENR	1 report (116 pages)	Documentation of North Carolina vital statistic data files available for public use	Unknown (Oct. 1993)
Miscellaneous information, data, and reports					
Community group Web sites	Electronic	*http://www.watersurvivors.com* *http://www.tfiptf.com/*	N/A	Former marine's and citizen's Web sites containing miscellaneous information and numerous Camp Lejeune documents (current and historical). Historical obtained from the U.S. Marine Corps through FOIA requests	N/A (N/A)
National Climatic Data Center (NCDC)	Electronic	NCDC, Asheville, NC *http://www.ncdc.noaa.gov/oa/ncdc.html*	6 files, about 6 megabytes	Precipitation and evaporation data for the Hoffman/Maysville station, NC	Dec. 2008 (Dec. 1945–Dec. 2008)
National Geophysical Data Center (NGDC)	Electronic	NGDC, Boulder, CO *http://www.ngdc.noaa.gov*	4 files, about 600 kilobytes	Bathymetry survey data for New River area of Camp Lejeune, NC; 5 surveys: H04697 (1927), H05277 (1933), H05301 (1933), H05302 (1933), and H09882 (1980)	Dec. 2008 (1927, 1933, 1980)
Onslow County, NC Soil Survey	Paper	U.S. Department of Agriculture, Soil Conservation Service	1 report (152 pages)	Information that can be used for land-planning programs in Onslow County; report contains predictions of soil behavior for selected land uses	May 2003 (1982)
Specific DON and USMC reports	CD–ROM; electronic (PDF); paper	Camp Lejeune	10–15 volumes	Base Master Plans for 1972 (CERCLA Administrative Record File #0368) and 1988 (NAVFAC 1988?); Water Conservation Study (ECG Inc. 1999); Site Management Plans 2005–2011 (CH2M HILL and Baker Environmental, Inc. 2005; CH2M HILL 2006, 2007a, 2007b, 2008, 2009, 2010); Range Environmental Vulnerability Assessment report (Malcolm Pirnie 2009); Vapor Intrusion report (AGVIQ–CH2M HILL 2009)	2005–2010 (1984–2009)
Technical Memoranda	Electronic (PDF)	Camp Lejeune	Several electronic files	SWMU 350, IR site 88, Area of Potential Concern reports 9, 10, and 11	May 2010 (Mar.–May 2010)
U.S. Geological Survey open files and reports	Paper	USGS, North Carolina Water Science Center, Raleigh	Several hundred to thousand pages; published reports	Files on well construction, well locations, and water use at Camp Lejeune; published reports on Camp Lejeune	Mar. 2004 (1940s–1987)
Vapor intrusion activities	Electronic (PDF); paper	USEPA; NAVFAC (Camp Lejeune)	Several reports including one 6-volume report	Reports describing vapor intrusion activities at ABC One-Hour Cleaners, Tarawa Terrace Elementary School, and Camp Lejeune (Mainside)	2007–2009 (2007–2009)

[1]In searching the historical archives in Raleigh, North Carolina, information contained in files folders dated 1969–1989 were missing.

Appendix A2. Information sources used to extract model-specific data for historical reconstruction analyses, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[Refer to end of Appendix A4 for a list of abbreviations and acronyms]

List of abbreviations and acronyms:

1,2-tDCE, *trans*-1,2-dichloroethylene
ATSDR, Agency for Toxic Substances and Disease Registry
BAH, Booze Allen Hamilton
Catlin, Richard Catlin and Associates, Inc. or Catlin Engineers and Scientists (see Rerference Section)
CD–ROM, computer disc, read-only memory
CERCLA, Comprehensive Environmental Response, Compensation, and Liability Act of 1980
CLW, Camp Lejeune water document
DEM, digital elevation model
DON, Department of the Navy
DVD, digital video disc
ESRI, Environmental Systems Research Institute
f/k/a, formerly known as
FOIA, Freedom of Information Act
ft, foot
GIS, geographic information system
HBWTP, Holcomb Boulevard water treatment plant
HPWTP, Hadnot Point water treatment plant
IGIR, integrated geographic information repository
IRP, Installation Restoration Program
JTC, JTC Environmental Consultants, Inc. (see Reference Section)
LAN, local area network
LIDAR, line detection and ranging
MS, Microsoft, Excel, and Access are either registered trademarks or trademarks of Microsoft Corporation in the United States and/or other countries
N/A, not available
NAD 83, North American Datum of 1983
NAVFAC, Naval Facilities Engineering Command
NC, North Carolina
NCDC, National Climatic Data Center
NCDENR, North Carolina Department of Environment and Natural Resources
NGDC, National Geophysical Data Center
PCE, tetrachloroethylene
PDF, portable document file format
PHA, public health assessment
SCADA, supervisory control and data acquisition
SWMU, solid waste management unit
TCE, trichloroethylene
TIFF, tagged image file format
USEPA, U.S. Environmental Protection Agency
USGS, U.S. Geological Survey
USMC, U.S. Marine Corps
UST, underground storage tank
VOC, volatile organic compound

Appendix F — Summaries of ATSDR's Tarawa Terrace Chapter Reports

Summaries of **Tarawa Terrace** chapter reports are described below. Electronic versions of each chapter report and their supporting information and data will be made available on the ATSDR Camp Lejeune Web site at *http://www.atsdr.cdc.gov/sites/lejeune/index.html.*

Chapter A: Summary of Findings (Maslia et al. 2007) provides a summary of detailed technical findings (described in Chapters B–K) focusing on the historical reconstruction analysis and present-day conditions of groundwater flow, contaminant fate and transport, and distribution of drinking water at Tarawa Terrace and vicinity. Among the topics that this report summarizes are: (1) methods of analyses, (2) data sources and requirements, (3) the four-stage hierarchical approach used for model calibration and estimating PCE concentrations in drinking water, (4) presentation, discussion, and implications of selected simulation results for PCE and its degradation by-products, and (5) quantifying confidence in simulation results by varying water- supply well historical pumping schedules and by using sensitivity and probabilistic analyses to address issues of uncertainty and variability in model parameters. In addition, this report provides a searchable electronic database—using digital video disc (DVD) format—of information and data sources used to conduct the historical reconstruction analysis. Data were obtained from a variety of sources, including ATSDR, USEPA, Environmental Management Division of U.S. Marine Corps Base Camp Lejeune, U.S. Geological Survey, private consulting organizations, published scientific literature, and community groups representing former marines and their families.

Chapter B: Geohydrologic Framework of the Castle Hayne Aquifer System (Faye 2007) provides detailed analyses of well and geohydrologic data used to develop the geohydrologic framework of the Castle Hayne aquifer system at Tarawa Terrace and vicinity. Potentiometric levels, horizontal hydraulic conductivity, and the geohydrologic framework of the Castle Hayne aquifer system east of the New River are described and quantified. The geohydrologic framework is com- posed of 11 units, 7 of which correspond to the Upper, Middle, and Lower Castle Hayne aquifers and related confining units. Overlying the Upper Castle Hayne aquifer are the Brewster Boulevard and Tarawa Terrace aquifers and confining units. Much of the Castle Hayne aquifer system is composed of fine, fossiliferous sand, limestone, and shell limestone. The sands are frequently silty and contain beds and lenses of clay. Limestone units are probably discontinuous and occasionally cavernous. Confining units are characterized by clays and silty clays of significant thickness and are persistent across much of the study area. Maximum thickness of the Castle Hayne aquifer system within the study area is about 300 ft. In general, geohydrologic units thicken from northwest to the south and southeast. The limestones and sands of the Castle Hayne aquifer system readily yield water to wells. Aquifer-test analyses indicate that horizontal hydraulic conductivities of water-bearing units at supply wells commonly range from 10 to 30 feet per day. Estimated predevelopment potentiometric levels of the Upper and Middle Castle Hayne aquifers indicate that groundwater- flow directions are from highland areas north and east of the study area toward the major drainages of New River and Northeast Creek.

Chapter C: Simulation of Groundwater Flow (Faye and Valenzuela 2007) provides detailed analyses of groundwater flow at Tarawa Terrace and vicinity, including the development of a predevelopment (steady-state) and transient groundwater-flow model using the model code MODFLOW-96 (Harbaugh and McDonald 1996). Calibration and testing of the model are thoroughly described. The groundwater-flow model was designed with seven layers largely representing the Castle Hayne aquifer system. Com- parison of 59 observed water levels representing esti- mated predevelopment conditions and corresponding simulated potentiometric levels indicated a high degree of similarity throughout most of the study area. The average absolute difference between simulated and observed

predevelopment water levels was 1.9 ft, and the root-mean-square (RMS) of differences was 2.1 ft. Transient simulations represented pumping at Tarawa Terrace supply wells for 528 stress periods representing 528 months—January 1951–December 1994. Assigned pumpage at supply wells was estimated using reported well-capacity rates and annual rates of raw water treated at the Tarawa Terrace water treatment plant (WTP) during 1975 –1986. Calibrated model results of 263 paired water levels representing observed and simulated water levels at monitor wells indicated an average absolute difference between simulated and observed water levels of 1.4 ft, a standard deviation of water-level difference of 0.9 ft, and a RMS of water-level difference of 1.7 ft. Calibrated model results of 526 paired water levels representing observed and simulated water levels at water-supply wells indicated an average absolute difference between simulated and observed water levels of 7.1 ft, a standard deviation of water-level difference of 4.6 ft, and a RMS of water-level difference of 8.5 ft.

Chapter D: Properties of Degradation Pathways of Common Organic Compounds in Groundwater (Lawrence 2007) describes and summarizes the properties, degradation pathways, and degradation by-products of VOCs (non-trihalomethane) commonly detected in groundwater contamination sites in the United States. This chapter also is published as U.S. Geological Survey Open-File Report 2006-1338 (Lawrence 2006) and provides abridged information describing the most salient properties and biodegradation of 27 VOCs. This report cross-references common names and synonyms associated with VOCs with the naming conventions supported by the IUPAC. In addition, the report describes basic physical characteristics of those compounds such as Henry's Law constant, water solubility, density, octanol-water partition (log *Kow*), and organic carbon partition (log *Koc*) coefficients. Descriptions and illustrations are provided for natural and laboratory biodegradation rates, chemical by-products, and degradation pathways.

Chapter E: Occurrence of Contaminants in Groundwater (Faye and Green, Jr. 2007) describes the occurrence and distribution of PCE and related contaminants within the Tarawa Terrace aquifer and the Upper Castle Hayne aquifer system at and in the vicinity of the Tarawa Terrace housing area. The occurrence and distribution of benzene, toluene, ethylbenzene, and xylene (BTEX) and related compounds also are briefly described. This report describes details of historical investigations of VOC contamination of groundwater at Tarawa Terrace with emphasis on water-supply wells TT-23, TT-25, and TT-26 (Figure A1). Detailed analyses of concentrations of PCE at monitor wells, at hydrocone sample locations, and at Tarawa Terrace water-supply wells during the period 1991–1993 were sufficient to estimate the mass of PCE remaining in the Tarawa Ter- race and Upper Castle Hayne aquifers. Similar methods were applied to compute the mass of PCE in the unsaturated zone (zone above the water table) at and in the vicinity of ABC One-Hour Cleaners using concentration- depth data determined from soil borings. The total mass of PCE computed in groundwater and within the unsaturated zone equals about 6,000 pounds and equates to a volume of about 430 gallons. This volume represents an average minimum loss rate of PCE to the subsurface at ABC One-Hour Cleaners of about 13 gallons per year for the period 1953–1985.

Chapter F: Simulation of the Fate and Transport of Tetrachloroethylene (PCE) in Groundwater (Faye 2008) describes: (1) the fate and transport of PCE in groundwater from the vicinity of ABC One-Hour Cleaners to the intrusion of PCE into individual water- supply wells (for example, TT-23 and TT-26, Figure A1), and (2) the concentration of PCE in finished water at the Tarawa Terrace WTP computed using a materials mass balance model (simple mixing). The materials mass balance model was used to compute a flow-weighted average PCE concentration, which was assigned as the finished water concentration at the Tarawa Terrace WTP for a specified month. The contaminant fate and trans- port simulation was conducted using the code MT3DMS (Zheng and Wang 1999) integrated with the calibrated groundwater-flow model (Faye and Valenzuela In press 2007) based on the code

MODFLOW-96. Simulated mass loading occurred at a constant rate of 1,200 grams per day using monthly stress periods representing the period January 1953–December 1984. The complete simulation time was represented by the period January 1951–December 1994. Until 1984, the vast majority of simulated PCE-contaminated groundwater was supplied to the Tarawa Terrace WTP by well TT-26. Simulated breakthrough of PCE at well TT-26 at the current MCL of 5 µg/L occurred during January 1957. Corresponding breakthrough at the location of well TT-23 occurred during December 1974; however, well TT-23 was not operational until about August 1984.

Simulated maximum and average PCE concentrations at well TT-26 following breakthrough were 851 µg/L and 414 µg/L, respectively. Corresponding maximum and average concentrations at well TT-23 subsequent to the onset of operations were 274 µg/L and 252 µg/L, respectively. Simulated breakthrough of PCE in finished water at the Tarawa Terrace WTP occurred at the current MCL concentration of 5 µg/L during November 1957 and remained at or above a concentration of 40 µg/L from May 1960 until the termination of pumping at water-supply well TT-26 during February 1985. Computed maximum and average PCE concentrations at the WTP were 183 µg/L and 70 µg/L, respectively, during the period November 1957–February 1985, when well TT-26 was removed from service.

Chapter G: Simulation of Three-Dimensional Multispecies, Multiphase Mass Transport of Tetra- chloroethylene (PCE) and Associated Degradation By-Products (Jang and Aral 2008) provides detailed descriptions and analyses of the development and application of a three-dimensional model (TechFlowMP) capable of simulating multispecies and multiphase (water and vapor) transport of PCE and associated degradation by-products—TCE, 1,2-tDCE, and VC. The development of the TechFLowMP model is described in Jang and Aral (2005) and its application to Tarawa Terrace and vicinity also is published as report MESL-02-07 by the Multimedia Environmental Simulations Laboratory in the School of Civil and Environmental Engineering, Georgia Institute of Technology (Jang and Aral 2007). Simulation results show that the maxi- mum concentrations of PCE degradation by-products, TCE, 1,2-tDCE, and VC, generally ranged between10 µg/L and 100 µg/L in Tarawa Terrace water-supply well TT-26 and between 2 µg/L and 15 µg/L in finished water delivered from the Tarawa Terrace WTP. As part of the degradation by-product simulation using the TechFlowMP model, results were obtained for PCE and PCE degradation by-products dissolved in groundwater and in the vapor phase (above the water table in the unsaturated zone). Analyses of the distribution of vapor- phase PCE and PCE degradation by-products indicate there is potential for vapors to enter buildings at Tarawa Terrace, thereby providing a potential exposure pathway from inhalation of PCE and PCE degradation by-product vapors. At Tarawa Terrace these buildings would include family housing and the elementary school.

Chapter H: Effect of Groundwater Pumping Schedule Variation on Arrival of Tetrachloroethylene (PCE) at Water-Supply Wells and the Water Treatment Plant (Wang and Aral 2008) describes a detailed analysis of the effect of groundwater pumping schedule variation on the arrival of PCE at water-supply wells and at the Tarawa Terrace WTP. Analyses contained in this chapter used the calibrated model parameters described in Chapter C (Faye and Valenzuela In press 2007) and Chapter F (Faye In press 2007b) reports in combination with the groundwater pumping schedule optimization system simulation tool (PSOpS) to assess the influence of unknown and uncertain historical well operations at Tarawa Terrace water-supply wells on PCE concentrations at water-supply wells and at the Tarawa Terrace WTP. This chapter also is published as report MESL-01-07 by the Multimedia Environmental Simulations Laboratory in the School of Civil and Environ- mental Engineering, Georgia Institute of Technology (Wang and Aral 2007). Variation in the optimal pumping schedules indicates that the arrival time of PCE exceeding the current MCL of 5 µg/L at water-supply well TT-26 varied between May 1956 and August 1959. The corresponding arrival time of PCE exceeding the current MCL of 5 µg/L at the Tarawa Terrace WTP varied between December 1956 and June 1960.

Chapter I: Parameter Sensitivity, Uncertainty, and Variability Associated with Model Simulations of Groundwater Flow, Contaminant Fate and Trans- port, and Distribution of Drinking Water (Maslia et al. 2009b) describes the development and application of a probabilistic analysis using Monte Carlo and sequential Gaussian simulation analysis to quantify uncertainty and variability of groundwater hydraulic and transport parameters. These analyses demonstrate quantitatively the high reliability and confidence in results determined using the calibrated parameters from the MODFLOW-96 and MT3DMS models. For example, 95% of Monte Carlo simulations indicated that the current MCL for PCE of 5 µg/L was exceeded in finished water at the Tarawa Terrace WTP between October 1957 and August 1958; the corresponding breakthrough simulated by the calibrated fate and transport model (Chapter F report, Faye 2008) occurred during November 1957.

Appendix G — Summaries of ATSDR's Hadnot Point–Holcomb Boulevard Chapter Reports and Supplemental Information

Summaries of Hadnot Point–Holcomb Boulevard (HP-HB) chapter reports (A, B, C, and D) and supplemental information sections of Chapter A (Supplements 1–8) are described below. Electronic versions of each chapter report and each Chapter A supplement are on the computer disc, read-only memory (CD-ROM) media provided in the back pocket of the Chapter A report. The chapter reports and supplements will be made available on the ATSDR Camp Lejeune Web site at *http://www.atsdr.cdc.gov/sites/lejeune/index.html*.

Chapter A: Summary and Findings (Maslia et al. 2013—this report) provides both a summary of technical findings and detailed analyses of historical reconstruction of groundwater flow, contaminant fate and transport, and distribution of finished water within the Hadnot Point and Holcomb Boulevard water treatment plant (HPWTP and HBWTP, respectively) service areas. Contaminants of concern to the ATSDR health studies described in this report are tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene. Among the topics covered in this chapter are (1) the purpose of the HPHB study area historical reconstruction analysis, (2) review of contaminants of concern (volatile organic compounds [VOCs])for ATSDR health studies, (3) base-housing information and water-supply data (4) methods for reconstructing historical concentrations in finished water, which include data mining and contaminant-source identification and characterization, (5) application of numerical models and computational tools, (6) historical reconstruction analyses and results for the Hadnot Point Industrial Area (HPIA) and Hadnot Point landfill (HPLF) area, (7) reconstructed concentrations in finished water at the HPWTP, (8) analyses of intermittent transfers of contaminated finished water from the HPWTP to the Holcomb Boulevard family housing areas during years 1972–1985, and (9) selected bounding estimates of historical reconstruction results using sensitivity and uncertainty analyses. Historical reconstruction results summarized in Chapter A provide considerable evidence that concentrations of several contaminants of interest in finished water delivered by the HPWTP substantially exceeded current maximum contaminant levels (MCLs) during all or much of the epidemiological study period of 1968–1985. Included in this chapter report is a comprehensive table listing disparate information sources used to extract pertinent information and data that were needed to develop model input databases used to conduct historical reconstruction analyses. In this report, a CD-ROM is included that contains all chapter reports (A–D), Chapter A supplements (1–8), selected calibrated model input files, and reconstructed (simulated) concentrations at selected water-supply wells and in finished-water at the HPWTP and within the Holcomb Boulevard water-distribution system.

Chapter A–Supplement 1: Descriptions and Characterizations of Data Pertinent to Water-Supply Well Capacities, Histories, and Operations (Sautner et al. 2013a) provides specific documentation for 96 water-supply wells in terms of capacities, histories, and operations that operated during the period 1942–June 2008 and provided groundwater to the HPWTP and HBWTP. Hundreds of documents and reports were reviewed, and numerous discussions with former and current water treatment plant (WTP) operators took place. Notable information was recorded and analyzed for each specific water-supply well to determine the chronological record of a well's operation (well history) starting from the time the well was placed into service and ending with the time the well was abandoned. A listing of the documented historical well operations has been created for each water-supply well and is used to better understand how the Hadnot Point and Holcomb Boulevard water-distribution systems were historically operated. This information and data are used to assist with the reconstruction of historical monthly operations for each water-supply well when little or no information is available. Tabulated well histories from the 96 water-supply wells described in this Supplement 1 report were used to reconstruct historical monthly operations for water-supply wells.

Information contained in Chapter A–Supplement 1 was necessary to conduct groundwater-flow and contaminant fate and transport modeling as part of the historical reconstruction process.

Chapter A–Supplement 2: Development and Application of a Methodology to Characterize Present-Day and Historical Water-Supply Well Operations (Telci et al. 2013) describes a methodology that is developed to estimate the historical monthly volume of groundwater pumped from water-supply wells in the HPHB study area. The available data on operational patterns of water-supply wells consist of the capacities of the wells, the operational state of the wells on a daily basis, and the volume of water delivered to the WTPs on a daily and monthly bases. The overall operational timeframe of the Hadnot Point and Holcomb Boulevard water-distribution systems is divided into two periods: "present-day" (1998–2008) and "Reconstruction" (1942–1997). In Supplement 2, the present-day period is defined as the time during which daily water-supply well operational data are available. The reconstruction period is defined as the time when water-supply well operational data are limited or unavailable. The methodology is an efficient and effective way of integrating available data for present-day conditions (1998–2008) with the prediction process for the historical years (1942–1998). Results demonstrate that historical estimates of water-supply well operations using this methodology are reasonable, and therefore, can be readily applied to groundwater-flow and contaminant fate and transport model simulations for the HPHB study area.

Chapter A–Supplement 3: Descriptions and Characterizations of Water-Level Data and Groundwater Flow for the Brewster Boulevard and Castle Hayne Aquifer Systems and the Tarawa Terrace Aquifer (Faye et al. 2013) provides summaries of the results of analyses of groundwater-level data and describes corresponding elements of groundwater flow such as vertical hydraulic gradients useful for groundwater-flow model calibration. Field data and theoretical concepts indicate that potentiometric surfaces within the study area are shown to resemble to a large degree a subdued replica of surface topography. Consequently, precipitation that infiltrates to the water table flows laterally from highland to lowland areas and eventually discharges to streams such as Northeast and Wallace Creeks and New River. Vertically downward hydraulic gradients occur in highland areas, resulting in the transfer of groundwater from shallow relatively unconfined aquifers to underlying confined or semi-confined aquifers. Conversely, in the vicinity of large streams such as Wallace and Frenchs Creeks, diffuse upward leakage occurs from underlying confined or semi-confined aquifers. Point water-level data indicating water-table altitudes, water-table altitudes estimated using a regression equation, and estimates of stream levels determined from a digital elevation model (DEM) and topographic maps were used to estimate a predevelopment water-table surface in the study area. Approximate flow lines along hydraulic gradients are shown on a predevelopment potentiometric surface map and extend from highland areas where potentiometric levels are greatest toward streams such as Northeast and Wallace Creeks. The distribution of potentiometric levels and corresponding groundwater-flow directions conform closely to related descriptions of the conceptual model.

Chapter A–Supplement 4: Simulation of Three-Dimensional Groundwater Flow (Suárez-Soto et al. 2013**)** provides detailed analyses of groundwater flow based on data and model simulations for the HPHB study area. Predevelopment (steady state) and transient three-dimensional groundwater-flow models were developed using MODFLOW-2005 (Harbaugh 2005). Multiple groundwater-flow models were necessary to describe both predevelopment and transient conditions, which focused on the HPIA and HPLF subdomain areas. The predevelopment model is characterized by a uniform finite-difference grid consisting of 300-ft × 300-ft cells. Transient models—one for the HPIA and one for the HPLF subdomain areas—were

characterized by variably spaced finite-difference grids consisting of cells ranging in size from 300 ft × 300 ft to 50 ft × 50 ft—the 50-ft × 50-ft cells being necessary to meet fate and transport numerical modeling requirements. The variably spaced grid models were used to simulate local transient conditions and contaminant fate and transport in the HPIA and HPLF subdomain areas (Jones et al. 2013). All models consist of seven layers representing the Brewster Boulevard and Castle Hayne aquifer systems and Tarawa Terrace aquifer described by Faye (2012). The predevelopment calibration represents long-term average conditions, and transient simulations represent conditions occurring as a consequence of water-supply well operations. The 798 monthly stress periods were used to represent transient conditions during the period January 1942–June 2008. Model cells coincident with water-supply wells were assigned reconstructed pumpage values based on the methodology described in Telci et al. (2013).

Chapter A–Supplement 5: Theory, Development, and Application of Linear Control Model Methodology to Reconstruct Historical Contaminant Concentrations at Selected Water-Supply Wells (Guan et al. 2013) describes the development of an alternate modeling approach using a linear state-space representation of a contaminated aquifer system, designated in this Supplement 5 report as a linear control model (LCM). The LCM is used to reconstruct historical concentrations at water-supply wells. The LCM approach is substantially less resource-intensive and requires less effort in terms of model parameter identification and calibration than traditional (numerical) groundwater-flow and contaminant fate and transport modeling approaches. The mathematical development for the LCM approach is described in detail and then verified by using synthesized data from the numerical groundwater model developed for the Tarawa Terrace study area (Faye and Green 2007; Faye and Valenzuela 2007). The LCM (TechControl) is then applied to the HPLF to reconstruct the history of chlorinated solvent contamination at water-supply well HP-651; the well was shut down in early 1985 when chlorinated solvents were detected in the well. The LCM approach utilizes the historical operating schedule of water-supply well HP-651 in conjunction with post-shutdown (1985–2004) measured contaminant concentrations in groundwater to reconstruct the history of contaminants in the water-supply well prior to 1985.

Chapter A–Supplement 6: Source Characterization and Simulation of Fate and Transport of Selected Volatile Organic Compounds in the Vicinities of the Hadnot Point Industrial Area and Landfill (Jones et al. 2013) describes reconstruction (simulation) of historical concentrations of tetrachloroethylene (PCE), trichloroethylene (TCE), and benzene in finished water in the vicinities of the HPIA and the HPLF area. A contaminant fate and transport model was used to simulate contaminant migration from source locations through the groundwater system and to estimate monthly mean contaminant concentrations in water withdrawn from production wells in the vicinity of the HPIA and the HPLF area. The monthly mean contaminant concentrations were subsequently input to a mixing model to quantify monthly mean concentrations of the contaminants in finished water that supplied the housing areas and other facilities served by the HPWTP. Review of available records indicates that the earliest production wells began operation in the early 1940s, and contaminants leaked into the subsurface as early as the late 1940s. Concentrations of the contaminants were simulated using monthly intervals for the entire period of production-well operation from January 1942 through June 2008, the date of the most recently available data. The applied and calibrated fate and transport models, described in Supplement 6, were based on the groundwater-flow models that are described in Suárez-Soto et al. (2013).

Chapter A–Supplement 7: Source Characterization and Simulation of the Migration of Light Nonaqueous Phase Liquids (LNAPLs) in the Vicinity of the Hadnot Point Industrial Area (Jang et al. 2013) describes (1) the migration potential and distribution of LNAPLs for several hypothetical scenarios, (2) the estimation of LNAPL volume based on field measurements of LNAPL thicknesses in the HPIA, and (3) the transport of dissolved contaminants within the HPIA. The analysis was carried out by using complex modeling of multiphase flow through pore spaces. The analysis of LNAPL flow delineated the migration and expansion of free-phase LNAPL plumes and the spatial variation in LNAPL saturation in the modeling domain with time. Based on available field data of LNAPL thickness from observation wells, the mass distribution and volume of LNAPLs in the subsurface at the HPIA were estimated using the TechNAPLVol model code. The computed LNAPL volume ranged from approximately 0.9 to 1.6 million gallons. The mass distribution (or saturation profile) of LNAPLs in the subsurface was used as the contaminant-source input for a fate and transport analysis of dissolved LNAPL components in groundwater at the HPIA. The TechFlowMP multiphase flow and multispecies contaminant transport model was used to simulate the dissolution and subsequent fate and transport of dissolved-phase benzene and xylenes in the HPIA.

Chapter A–Supplement 8: Field Tests, Data Analyses, 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 Systems (Sautner et al. 2013b) provides detailed information on the design of field tests conducted during 2004 to ascertain water-distribution system properties for Hadnot Point and Holcomb Boulevard. By using information and data gathered during the field tests, along with data provided by Camp Lejeune water utility staff, an extended period simulation model for water-distribution system hydraulics and water-quality dynamics was developed and calibrated using EPANET 2 (Rossman 2000). The calibrated EPANET 2 model of the Holcomb Boulevard water-distribution system was used in conjunction with Markov Chain analysis to estimate the concentrations of VOCs during the period 1972–1985. During this time, contaminated Hadnot Point finished water was intermittently provided to the Holcomb Boulevard housing areas. Within the Holcomb Boulevard housing area, except for the 8-day period of January 28–February 4, 1985, when the HBWTP was out of service, only TCE routinely exceeded its MCL during intermittent periods of connection with the Hadnot Point water-distribution system.

Chapter B: Geohydrologic Framework of the Brewster Boulevard and Castle Hayne Aquifer Systems and the Tarawa Terrace Aquifer (Faye 2012) provides detailed analyses and interpretations of well, borehole, and geophysical data used to develop the geohydrologic framework of the Brewster Boulevard and Castle Hayne aquifer systems and the Tarawa Terrace aquifer. The geometry and lithology of seven aquifers and related confining units are described in a series of sections, maps, and tables. Hydraulic characteristics, including hydraulic conductivity, transmissivity, storativity, and leakance parameters, are tabulated for several geohydrologic units. Where data density is sufficient, maps showing spatial distributions of hydraulic conductivity are included.

Chapter C: Occurrence of Selected Contaminants in Groundwater at Installation Restoration Program Sites (Faye et al. 2010) provides detailed accounting of the known occurrences of contaminants of concern (e.g., PCE and TCE) and their related degradation products in groundwater at selected Installation Restoration Program (IRP) sites within the HPWTP and HBWTB service areas at U.S. Marine Corp Base (USMCB) Camp Lejeune. These sites were identified by the Department of the Navy under the auspices of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Concentrations of these constituents in water-supply wells and in finished water of the HPWTP and HBWTP also are

described. Collectively, these data provide most of the base of information necessary to construct the fate and transport models used to reconstruct (simulate) historical concentrations of contaminants within the water-distribution systems serviced by the HPWTP and HBWTP. Additionally, this report provides a detailed summary of historical information useful to ongoing and future exposure and health studies at USMCB Camp Lejeune, including a chronology of residential housing areas served by the HPWTP and HBWTP, annual operational capacities of the WTPs, locations and construction details of water-supply wells and water-quality monitor wells, and a summary and discussion of relevant environmental investigations at 18 IRP sites within the study area where contaminated groundwater occurred or was thought to have occurred.

Chapter D: Occurrence of Selected Contaminants in Groundwater at Above-Ground and Underground Storage Tank Sites (Faye et al. 2012) provides summaries of results of investigations at 64 designated Resource Conservation and Recovery Act (RCRA) study areas and emphasizes the occurrence and distribution of benzene, toluene, ethylbenzene, and xylenes (BTEX) components within groundwater of the areas served by the HPWTP and HBWTP. The volume of BTEX mass removed from the subsurface during remediation at selected locations within the service areas also is summarized. Results of analyses of samples collected in monitor wells at several CERCLA investigation study areas co-located with RCRA areas are also included herein. Concentrations of chlorinated alkenes such as PCE and TCE are also described where plumes of BTEX and chlorinated alkenes are mixed at several locations.

Appendix H1 — Tarawa Terrace Water Treatment Plant Reconstructed (Simulated) Mean Monthly Finished Water Concentrations for Single-Specie Tetrachloroethylene (PCE) Using MT3DMS Model and for Multispecies, Multiphase PCE (Trichloroethylene [TCE], *trans*-1,2-Dichlorothylene [1,2-*t*DCE], and Vinyl Chloride [VC]) Using TechFlowMP Model

Appendix A2. Simulated tetrachloroethylene and its degradation by-products in finished water, Tarawa Terrace water treatment plant, January 1951–March 1987.[1]

[PCE, tetrachloroethylene; µg/L, microgram per liter; 1,2-tDCE, *trans*-1,2-dichloroethylene; TCE, trichloroethylene; VC, vinyl chloride; WTP, water treatment plant]

Stress period	Month and year	Single specie using MT3DMS model[2]	Multispecies, multiphase using TechFlowMP model[3]			
		[4]PCE, in µg/L	[5]PCE, in µg/L	[5]1,2-tDCE, in µg/L	[5]TCE, in µg/L	[5]VC, in µg/L
1–12	Jan–Dec 1951	WTP not operating	WTP not operating	WTP not operating	WTP not operating	WTP not operating
13	Jan 1952	0.00	0.00	0.00	0.00	0.00
14	Feb 1952	0.00	0.00	0.00	0.00	0.00
15	Mar 1952	0.00	0.00	0.00	0.00	0.00
16	Apr 1952	0.00	0.00	0.00	0.00	0.00
17	May 1952	0.00	0.00	0.00	0.00	0.00
18	June 1952	0.00	0.00	0.00	0.00	0.00
19	July 1952	0.00	0.00	0.00	0.00	0.00
20	Aug 1952	0.00	0.00	0.00	0.00	0.00
21	Sept 1952	0.00	0.00	0.00	0.00	0.00
22	Oct 1952	0.00	0.00	0.00	0.00	0.00
23	Nov 1952	0.00	0.00	0.00	0.00	0.00
24	Dec 1952	0.00	0.00	0.00	0.00	0.00
25	Jan 1953	0.00	0.00	0.00	0.00	0.00
26	Feb 1953	0.00	0.00	0.00	0.00	0.00
27	Mar 1953	0.00	0.00	0.00	0.00	0.00
28	Apr 1953	0.00	0.00	0.00	0.00	0.00
29	May 1953	0.00	0.00	0.00	0.00	0.00
30	June 1953	0.00	0.00	0.00	0.00	0.00
31	July 1953	0.00	0.00	0.00	0.00	0.00
32	Aug 1953	0.00	0.00	0.00	0.00	0.00
33	Sept 1953	0.00	0.00	0.00	0.00	0.00
34	Oct 1953	0.00	0.00	0.00	0.00	0.00
35	Nov 1953	0.00	0.00	0.00	0.00	0.00
36	Dec 1953	0.00	0.00	0.00	0.00	0.00
37	Jan 1954	0.00	0.00	0.00	0.00	0.00
38	Feb 1954	0.00	0.00	0.00	0.00	0.00
39	Mar 1954	0.00	0.00	0.00	0.00	0.00
40	Apr 1954	0.00	0.00	0.00	0.00	0.00
41	May 1954	0.00	0.00	0.00	0.00	0.00
42	June 1954	0.00	0.00	0.00	0.00	0.00
43	July 1954	0.00	0.00	0.00	0.00	0.00
44	Aug 1954	0.00	0.00	0.00	0.00	0.00
45	Sept 1954	0.00	0.00	0.00	0.00	0.00
46	Oct 1954	0.00	0.00	0.00	0.00	0.00
47	Nov 1954	0.00	0.00	0.00	0.00	0.00
48	Dec 1954	0.00	0.00	0.00	0.00	0.00

Appendix A2. Simulated tetrachloroethylene and its degradation by-products in finished water, Tarawa Terrace water treatment plant, January 1951–March 1987[1].—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; 1,2-tDCE, *trans*-1,2-dichloroethylene; TCE, trichloroethylene; VC, vinyl chloride; WTP, water treatment plant]

Stress-period	Month and year	Single specie using MT3DMS model[2]	Multispecies, multiphase using TechFlowMP model[3]			
		[4]PCE, in µg/L	[5]PCE, in µg/L	[5]1,2-tDCE, in µg/L	[5]TCE, in µg/L	[5]VC, in µg/L
49	Jan 1955	0.00	0.00	0.00	0.00	0.01
50	Feb 1955	0.00	0.00	0.01	0.00	0.01
51	Mar 1955	0.00	0.01	0.01	0.00	0.01
52	Apr 1955	0.00	0.01	0.01	0.00	0.02
53	May 1955	0.00	0.01	0.01	0.00	0.02
54	June 1955	0.01	0.01	0.02	0.00	0.03
55	July 1955	0.01	0.02	0.03	0.00	0.03
56	Aug 1955	0.01	0.03	0.03	0.00	0.04
57	Sept 1955	0.02	0.04	0.04	0.00	0.05
58	Oct 1955	0.03	0.05	0.05	0.00	0.07
59	Nov 1955	0.04	0.06	0.07	0.00	0.08
60	Dec 1955	0.06	0.08	0.08	0.01	0.10
61	Jan 1956	0.08	0.11	0.10	0.01	0.12
62	Feb 1956	0.10	0.14	0.12	0.01	0.14
63	Mar 1956	0.13	0.17	0.15	0.01	0.17
64	Apr 1956	0.17	0.22	0.18	0.01	0.20
65	May 1956	0.23	0.27	0.21	0.02	0.23
66	June 1956	0.29	0.33	0.25	0.02	0.26
67	July 1956	0.36	0.40	0.29	0.02	0.30
68	Aug 1956	0.46	0.49	0.33	0.03	0.34
69	Sept 1956	0.57	0.59	0.38	0.03	0.39
70	Oct 1956	0.70	0.70	0.44	0.04	0.44
71	Nov 1956	0.85	0.83	0.50	0.05	0.49
72	Dec 1956	1.04	0.97	0.57	0.06	0.55
73	Jan 1957	1.25	1.14	0.64	0.06	0.61
74	Feb 1957	1.47	1.33	0.72	0.07	0.68
75	Mar 1957	1.74	1.52	0.79	0.08	0.74
76	Apr 1957	2.04	1.75	0.88	0.10	0.81
77	May 1957	2.39	2.00	0.97	0.11	0.89
78	June 1957	2.77	2.28	1.08	0.12	0.97
79	July 1957	3.21	2.59	1.18	0.14	1.05
80	Aug 1957	3.69	2.93	1.29	0.16	1.13
81	Sept 1957	4.21	3.30	1.41	0.17	1.23
82	Oct 1957	4.79	3.69	1.53	0.19	1.32
83	Nov 1957	5.41	4.13	1.66	0.22	1.41
84	Dec 1957	6.10	4.59	1.80	0.24	1.51

Appendix A2. Simulated tetrachloroethylene and its degradation by-products in finished water, Tarawa Terrace water treatment plant, January 1951–March 1987[1].—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; 1,2-tDCE, *trans*-1,2-dichloroethylene; TCE, trichloroethylene; VC, vinyl chloride; WTP, water treatment plant]

Stress period	Month and year	Single specie using MT3DMS model[2]	Multispecies, multiphase using TechFlowMP model[3]			
		[4]PCE, in µg/L	[5]PCE, in µg/L	[5]1,2 tDCE, in µg/L	[5]TCE, in µg/L	[5]VC, in µg/L
85	Jan 1958	6.86	5.11	1.94	0.26	1.62
86	Feb 1958	7.60	5.65	2.09	0.29	1.72
87	Mar 1958	8.47	6.17	2.22	0.31	1.81
88	Apr 1958	9.37	6.79	2.38	0.34	1.92
89	May 1958	10.37	7.41	2.53	0.37	2.02
90	June 1958	11.39	8.10	2.70	0.41	2.13
91	July 1958	12.91	9.09	2.96	0.45	2.32
92	Aug 1958	14.12	9.88	3.14	0.49	2.44
93	Sept 1958	15.35	10.73	3.33	0.53	2.56
94	Oct 1958	16.69	11.58	3.52	0.57	2.68
95	Nov 1958	18.03	12.52	3.72	0.61	2.81
96	Dec 1958	19.49	13.46	3.92	0.66	2.94
97	Jan 1959	20.97	14.48	4.13	0.71	3.07
98	Feb 1959	22.35	15.54	4.34	0.76	3.21
99	Mar 1959	23.92	16.54	4.54	0.80	3.33
100	Apr 1959	25.49	17.70	4.77	0.85	3.48
101	May 1959	27.15	18.84	4.99	0.91	3.61
102	June 1959	28.81	20.09	5.23	0.96	3.77
103	July 1959	30.56	21.34	5.46	1.02	3.91
104	Aug 1959	32.36	22.66	5.69	1.08	4.05
105	Sept 1959	34.14	24.01	5.93	1.14	4.19
106	Oct 1959	36.01	25.35	6.16	1.20	4.32
107	Nov 1959	37.85	26.77	6.40	1.27	4.46
108	Dec 1959	39.78	28.18	6.64	1.33	4.60
109	Jan 1960	41.86	29.67	6.88	1.40	4.74
110	Feb 1960	43.85	31.17	7.12	1.46	4.86
111	Mar 1960	46.03	32.58	7.33	1.52	4.97
112	Apr 1960	48.15	34.16	7.57	1.59	5.10
113	May 1960	50.37	35.67	7.79	1.66	5.21
114	June 1960	52.51	37.24	8.03	1.73	5.33
115	July 1960	54.74	38.79	8.26	1.80	5.45
116	Aug 1960	56.96	40.45	8.51	1.87	5.59
117	Sept 1960	59.09	42.13	8.76	1.94	5.73
118	Oct 1960	61.30	43.80	9.02	2.02	5.86
119	Nov 1960	63.42	45.57	9.28	2.09	6.01
120	Dec 1960	65.61	47.31	9.54	2.17	6.15

Appendix A2. Simulated tetrachloroethylene and its degradation by-products in finished water, Tarawa Terrace water treatment plant, January 1951–March 1987[1].—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; 1,2-tDCE, *trans*-1,2-dichloroethylene; TCE, trichloroethylene; VC, vinyl chloride; WTP, water treatment plant]

Stress period	Month and year	Single specie using MT3DMS model[2]	Multispecies, multiphase using TechFlowMP model[3]			
		[4]PCE, in µg/L	[5]PCE, in µg/L	[5]1,2-tDCE, in µg/L	[5]TCE, in µg/L	[5]VC, in µg/L
121	Jan 1961	67.69	49.15	9.82	2.25	6.30
122	Feb 1961	69.54	51.03	10.10	2.33	6.46
123	Mar 1961	71.56	52.73	10.35	2.41	6.61
124	Apr 1961	73.49	54.69	10.64	2.49	6.77
125	May 1961	75.49	56.57	10.92	2.58	6.92
126	June 1961	77.39	58.53	11.20	2.66	7.07
127	July 1961	79.36	60.43	11.46	2.75	7.22
128	Aug 1961	81.32	62.42	11.74	2.83	7.36
129	Sept 1961	83.19	64.40	12.01	2.92	7.51
130	Oct 1961	85.11	66.32	12.27	3.00	7.64
131	Nov 1961	86.95	68.33	12.55	3.09	7.79
132	Dec 1961	88.84	70.28	12.80	3.17	7.92
133	Jan 1962	60.88	47.74	8.63	2.15	5.32
134	Feb 1962	62.10	49.86	9.00	2.25	5.56
135	Mar 1962	62.94	51.28	9.17	2.31	5.64
136	Apr 1962	63.59	52.37	9.25	2.36	5.67
137	May 1962	64.17	53.18	9.28	2.39	5.66
138	June 1962	64.70	53.88	9.28	2.41	5.63
139	July 1962	65.23	54.48	9.28	2.43	5.60
140	Aug 1962	65.74	55.06	9.26	2.45	5.56
141	Sept 1962	66.22	55.59	9.24	2.46	5.52
142	Oct 1962	66.71	56.07	9.22	2.48	5.47
143	Nov 1962	67.18	56.54	9.19	2.49	5.42
144	Dec 1962	67.65	56.97	9.16	2.50	5.38
145	Jan 1963	68.06	57.40	9.13	2.51	5.33
146	Feb 1963	68.39	57.78	9.09	2.52	5.28
147	Mar 1963	68.73	58.11	9.06	2.53	5.24
148	Apr 1963	69.03	58.49	9.02	2.54	5.20
149	May 1963	69.33	58.81	8.98	2.55	5.15
150	June 1963	69.62	59.14	8.94	2.56	5.11
151	July 1963	69.90	59.42	8.90	2.57	5.06
152	Aug 1963	70.17	59.70	8.86	2.57	5.02
153	Sept 1963	70.43	59.97	8.82	2.57	4.98
154	Oct 1963	70.69	60.21	8.78	2.58	4.94
155	Nov 1963	70.93	60.45	8.74	2.58	4.90
156	Dec 1963	71.17	60.67	8.70	2.59	4.86

Appendix A2. Simulated tetrachloroethylene and its degradation by-products in finished water, Tarawa Terrace water treatment plant, January 1951–March 1987[1].—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; 1,2-tDCE, *trans*-1,2-dichloroethylene; TCE, trichloroethylene; VC, vinyl chloride; WTP, water treatment plant]

Stress period	Month and year	Single specie using MT3DMS model[2]	Multispecies, multiphase using TechFlowMP model[3]			
		[4]PCE, in µg/L	[5]PCE, in µg/L	[5]1,2 tDCE, in µg/L	[5]TCE, in µg/L	[5]VC, in µg/L
157	Jan 1964	71.40	60.89	8.67	2.59	4.83
158	Feb 1964	63.77	54.39	7.69	2.31	4.27
159	Mar 1964	63.95	54.42	7.58	2.30	4.17
160	Apr 1964	64.08	54.43	7.50	2.29	4.10
161	May 1964	64.19	54.36	7.42	2.29	4.04
162	June 1964	64.27	54.29	7.35	2.28	3.98
163	July 1964	64.34	54.21	7.28	2.27	3.93
164	Aug 1964	64.39	54.14	7.22	2.26	3.88
165	Sept 1964	64.43	54.06	7.16	2.26	3.84
166	Oct 1964	64.47	53.99	7.10	2.25	3.79
167	Nov 1964	64.49	53.92	7.05	2.24	3.75
168	Dec 1964	64.50	53.85	7.00	2.24	3.72
169	Jan 1965	64.50	53.78	6.95	2.23	3.68
170	Feb 1965	64.49	53.72	6.90	2.23	3.65
171	Mar 1965	64.47	53.64	6.86	2.22	3.61
172	Apr 1965	64.45	53.59	6.82	2.22	3.58
173	May 1965	64.42	53.52	6.78	2.21	3.55
174	June 1965	64.38	53.47	6.74	2.21	3.52
175	July 1965	64.33	53.40	6.70	2.20	3.50
176	Aug 1965	64.27	53.34	6.66	2.20	3.47
177	Sept 1965	64.20	53.27	6.63	2.19	3.44
178	Oct 1965	64.13	53.20	6.59	2.19	3.42
179	Nov 1965	64.05	53.14	6.56	2.18	3.40
180	Dec 1965	63.97	53.07	6.53	2.18	3.37
181	Jan 1966	63.88	53.00	6.50	2.17	3.35
182	Feb 1966	63.79	52.93	6.47	2.17	3.33
183	Mar 1966	63.68	52.84	6.44	2.16	3.31
184	Apr 1966	63.57	52.78	6.41	2.16	3.29
185	May 1966	63.46	52.70	6.38	2.15	3.27
186	June 1966	63.34	52.63	6.35	2.15	3.25
187	July 1966	63.21	52.54	6.33	2.14	3.23
188	Aug 1966	63.08	52.46	6.30	2.14	3.21
189	Sept 1966	62.94	52.38	6.27	2.13	3.20
190	Oct 1966	62.80	52.28	6.25	2.13	3.18
191	Nov 1966	62.65	52.20	6.22	2.12	3.16
192	Dec 1966	62.50	52.11	6.19	2.12	3.14

Appendix A2. Simulated tetrachloroethylene and its degradation by-products in finished water, Tarawa Terrace water treatment plant, January 1951–March 1987[1].—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; 1,2-tDCE, *trans*-1,2-dichloroethylene; TCE, trichloroethylene; VC, vinyl chloride; WTP, water treatment plant]

Stress-period	Month and year	Single specie using MT3DMS model[2]	Multispecies, multiphase using TechFlowMP model[3]			
		[4]PCE, in µg/L	[5]PCE, in µg/L	[5]1,2-tDCE, in µg/L	[5]TCE, in µg/L	[5]VC, in µg/L
193	Jan 1967	62.25	52.02	6.17	2.11	3.13
194	Feb 1967	61.99	51.90	6.14	2.11	3.11
195	Mar 1967	61.67	51.76	6.11	2.10	3.09
196	Apr 1967	61.35	51.61	6.08	2.09	3.07
197	May 1967	61.02	51.43	6.04	2.08	3.05
198	June 1967	60.69	51.23	6.00	2.07	3.03
199	July 1967	60.37	51.02	5.96	2.06	3.00
200	Aug 1967	60.05	50.79	5.92	2.05	2.98
201	Sept 1967	59.74	50.57	5.87	2.04	2.95
202	Oct 1967	59.43	50.34	5.83	2.03	2.92
203	Nov 1967	59.13	50.11	5.79	2.02	2.90
204	Dec 1967	58.83	49.89	5.75	2.01	2.87
205	Jan 1968	58.41	49.66	5.70	2.00	2.85
206	Feb 1968	57.95	49.40	5.66	1.99	2.82
207	Mar 1968	57.43	49.10	5.60	1.97	2.79
208	Apr 1968	56.94	48.77	5.55	1.96	2.76
209	May 1968	56.45	48.43	5.49	1.94	2.73
210	June 1968	55.98	48.07	5.43	1.93	2.69
211	July 1968	55.49	47.67	5.36	1.91	2.65
212	Aug 1968	55.02	47.26	5.29	1.89	2.61
213	Sept 1968	54.58	46.84	5.23	1.87	2.57
214	Oct 1968	54.13	46.43	5.16	1.85	2.54
215	Nov 1968	53.71	46.03	5.10	1.84	2.50
216	Dec 1968	53.28	45.63	5.04	1.82	2.46
217	Jan 1969	53.07	45.24	4.98	1.80	2.43
218	Feb 1969	52.97	44.91	4.93	1.79	2.40
219	Mar 1969	52.94	44.64	4.88	1.78	2.37
220	Apr 1969	52.93	44.47	4.86	1.77	2.35
221	May 1969	52.93	44.32	4.83	1.76	2.34
222	June 1969	52.92	44.20	4.81	1.76	2.32
223	July 1969	52.90	44.09	4.79	1.75	2.31
224	Aug 1969	52.86	44.01	4.78	1.75	2.30
225	Sept 1969	52.81	43.92	4.77	1.75	2.29
226	Oct 1969	52.75	43.83	4.76	1.74	2.29
227	Nov 1969	55.19	45.75	4.97	1.82	2.38
228	Dec 1969	55.19	45.96	5.01	1.83	2.42

Appendix A2. Simulated tetrachloroethylene and its degradation by-products in finished water, Tarawa Terrace water treatment plant, January 1951–March 1987[1].—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; 1,2-tDCE, *trans*-1,2-dichloroethylene; TCE, trichloroethylene; VC, vinyl chloride; WTP, water treatment plant]

Stress period	Month and year	Single specie using MT3DMS model[2]	Multispecies, multiphase using TechFlowMP model[3]			
		[4]PCE, in µg/L	[5]PCE, in µg/L	[5]1,2 tDCE, in µg/L	[5]TCE, in µg/L	[5]VC, in µg/L
229	Jan 1970	55.01	46.05	5.03	1.84	2.43
230	Feb 1970	54.79	46.03	5.03	1.84	2.43
231	Mar 1970	54.49	45.94	5.03	1.83	2.43
232	Apr 1970	54.20	45.84	5.03	1.83	2.44
233	May 1970	53.90	45.70	5.01	1.82	2.44
234	June 1970	53.61	45.54	5.00	1.82	2.43
235	July 1970	53.32	45.37	4.98	1.81	2.43
236	Aug 1970	53.04	45.20	4.96	1.80	2.42
237	Sept 1970	52.78	45.00	4.94	1.79	2.41
238	Oct 1970	52.53	44.79	4.91	1.78	2.40
239	Nov 1970	52.29	44.58	4.89	1.78	2.39
240	Dec 1970	52.05	44.37	4.87	1.77	2.38
241	Jan 1971	51.96	44.17	4.84	1.76	2.37
242	Feb 1971	51.93	43.99	4.82	1.75	2.35
243	Mar 1971	51.95	43.86	4.80	1.74	2.34
244	Apr 1971	51.99	43.76	4.79	1.74	2.34
245	May 1971	52.03	43.66	4.78	1.74	2.33
246	June 1971	52.08	43.60	4.78	1.73	2.33
247	July 1971	52.12	43.53	4.77	1.73	2.33
248	Aug 1971	52.16	43.47	4.77	1.73	2.33
249	Sept 1971	52.20	43.41	4.77	1.73	2.33
250	Oct 1971	52.23	43.35	4.77	1.72	2.33
251	Nov 1971	52.26	43.31	4.77	1.72	2.33
252	Dec 1971	52.29	43.26	4.77	1.72	2.34
253	Jan 1972	49.34	41.02	4.53	1.63	2.22
254	Feb 1972	49.01	40.49	4.44	1.61	2.17
255	Mar 1972	48.68	40.01	4.37	1.58	2.13
256	Apr 1972	48.40	39.51	4.30	1.56	2.09
257	May 1972	48.14	39.03	4.24	1.54	2.06
258	June 1972	47.90	38.55	4.17	1.52	2.02
259	July 1972	47.67	38.11	4.11	1.50	1.98
260	Aug 1972	47.45	37.68	4.05	1.48	1.95
261	Sept 1972	47.25	37.26	3.99	1.46	1.92
262	Oct 1972	47.05	36.88	3.94	1.45	1.89
263	Nov 1972	46.87	36.51	3.89	1.43	1.86
264	Dec 1972	46.69	36.15	3.85	1.42	1.84

Appendix A2. Simulated tetrachloroethylene and its degradation by-products in finished water, Tarawa Terrace water treatment plant, January 1951–March 1987[1].—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; 1,2-tDCE, *trans*-1,2-dichloroethylene; TCE, trichloroethylene; VC, vinyl chloride; WTP, water treatment plant]

Stress-period	Month and year	Single specie using MT3DMS model[2]	Multispecies, multiphase using TechFlowMP model[3]			
		[4]PCE, in µg/L	[5]PCE, in µg/L	[5]1,2-tDCE, in µg/L	[5]TCE, in µg/L	[5]VC, in µg/L
265	Jan 1973	54.28	41.48	4.40	1.62	2.10
266	Feb 1973	54.19	42.32	4.57	1.67	2.21
267	Mar 1973	53.98	42.49	4.60	1.68	2.23
268	Apr 1973	53.76	42.42	4.60	1.68	2.24
269	May 1973	53.52	42.25	4.59	1.67	2.24
270	June 1973	53.30	42.05	4.58	1.66	2.25
271	July 1973	53.08	41.78	4.56	1.65	2.24
272	Aug 1973	52.87	41.53	4.53	1.64	2.23
273	Sept 1973	52.68	41.27	4.51	1.63	2.22
274	Oct 1973	52.51	41.01	4.48	1.62	2.21
275	Nov 1973	52.35	40.75	4.45	1.61	2.20
276	Dec 1973	52.20	40.48	4.42	1.60	2.19
277	Jan 1974	52.43	40.22	4.40	1.59	2.17
278	Feb 1974	52.82	40.13	4.39	1.59	2.17
279	Mar 1974	53.39	40.10	4.38	1.58	2.16
280	Apr 1974	53.99	40.20	4.40	1.59	2.17
281	May 1974	54.63	40.35	4.43	1.60	2.18
282	June 1974	55.25	40.59	4.48	1.61	2.21
283	July 1974	55.90	40.82	4.52	1.62	2.24
284	Aug 1974	56.53	41.08	4.57	1.63	2.27
285	Sept 1974	57.10	41.35	4.62	1.64	2.31
286	Oct 1974	57.70	41.61	4.68	1.65	2.34
287	Nov 1974	58.30	41.91	4.74	1.67	2.39
288	Dec 1974	58.92	42.19	4.81	1.68	2.43
289	Jan 1975	61.00	43.76	5.02	1.74	2.55
290	Feb 1975	61.24	43.90	5.06	1.75	2.59
291	Mar 1975	61.41	44.03	5.11	1.75	2.63
292	Apr 1975	61.57	44.18	5.16	1.76	2.68
293	May 1975	61.72	44.29	5.20	1.77	2.71
294	June 1975	61.88	44.38	5.24	1.77	2.75
295	July 1975	62.05	44.45	5.28	1.77	2.78
296	Aug 1975	62.25	44.52	5.31	1.78	2.81
297	Sept 1975	62.46	44.57	5.34	1.78	2.83
298	Oct 1975	62.69	44.62	5.36	1.78	2.85
299	Nov 1975	62.92	44.69	5.39	1.78	2.87
300	Dec 1975	63.18	44.74	5.41	1.78	2.89

Appendix A2. Simulated tetrachloroethylene and its degradation by-products in finished water, Tarawa Terrace water treatment plant, January 1951–March 1987[1].—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; 1,2-tDCE, *trans*-1,2-dichloroethylene; TCE, trichloroethylene; VC, vinyl chloride; WTP, water treatment plant]

Stress period	Month and year	Single specie using MT3DMS model[2]	Multispecies, multiphase using TechFlowMP model[3]			
		[4]PCE, in µg/L	[5]PCE, in µg/L	[5]1,2 tDCE, in µg/L	[5]TCE, in µg/L	[5]VC, in µg/L
301	Jan 1976	73.96	51.53	6.24	2.06	3.34
302	Feb 1976	74.94	53.43	6.62	2.15	3.60
303	Mar 1976	75.97	54.44	6.80	2.20	3.72
304	Apr 1976	76.97	55.38	6.99	2.24	3.85
305	May 1976	78.00	56.21	7.16	2.28	3.98
306	June 1976	79.02	57.07	7.34	2.32	4.10
307	July 1976	80.07	57.86	7.51	2.35	4.22
308	Aug 1976	81.13	58.73	7.69	2.39	4.34
309	Sept 1976	82.17	59.58	7.86	2.43	4.46
310	Oct 1976	83.25	60.41	8.02	2.46	4.57
311	Nov 1976	84.31	61.28	8.19	2.50	4.68
312	Dec 1976	85.41	62.10	8.35	2.53	4.79
313	Jan 1977	86.61	62.97	8.52	2.57	4.89
314	Feb 1977	87.70	63.98	8.71	2.62	5.01
315	Mar 1977	88.91	64.81	8.86	2.65	5.11
316	Apr 1977	90.10	65.83	9.05	2.70	5.22
317	May 1977	91.32	66.76	9.21	2.74	5.32
318	June 1977	92.53	67.76	9.38	2.78	5.43
319	July 1977	93.75	68.70	9.55	2.82	5.53
320	Aug 1977	94.99	69.70	9.72	2.86	5.63
321	Sept 1977	96.20	70.70	9.88	2.90	5.72
322	Oct 1977	97.42	71.65	10.04	2.94	5.82
323	Nov 1977	98.62	72.71	10.21	2.99	5.92
324	Dec 1977	99.84	73.68	10.36	3.03	6.00
325	Jan 1978	101.18	74.73	10.53	3.07	6.10
326	Feb 1978	102.77	76.25	10.80	3.14	6.26
327	Mar 1978	103.04	78.73	11.26	3.26	6.56
328	Apr 1978	104.31	77.97	11.02	3.21	6.37
329	May 1978	105.18	79.28	11.27	3.27	6.53
330	June 1978	106.88	79.72	11.29	3.28	6.51
331	July 1978	107.95	82.31	11.78	3.41	6.83
332	Aug 1978	108.69	83.81	12.00	3.47	6.96
333	Sept 1978	109.61	84.16	12.00	3.48	6.93
334	Oct 1978	111.18	84.92	12.09	3.51	6.97
335	Nov 1978	111.08	87.48	12.55	3.63	7.25
336	Dec 1978	111.93	85.67	12.04	3.52	6.87

Appendix A2. Simulated tetrachloroethylene and its degradation by-products in finished water, Tarawa Terrace water treatment plant, January 1951–March 1987[1].—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; 1,2-tDCE, *trans*-1,2-dichloroethylene; TCE, trichloroethylene; VC, vinyl chloride; WTP, water treatment plant]

Stress period	Month and year	Single specie using MT3DMS model[2]	Multispecies, multiphase using TechFlowMP model[3]			
		[4]PCE, in µg/L	[5]PCE, in µg/L	[5]1,2-tDCE, in µg/L	[5]TCE, in µg/L	[5]VC, in µg/L
337	Jan 1979	113.14	85.41	11.95	3.50	6.79
338	Feb 1979	114.05	86.75	12.16	3.56	6.91
339	Mar 1979	114.98	87.55	12.23	3.60	6.93
340	Apr 1979	115.82	88.43	12.32	3.63	6.97
341	May 1979	116.68	89.21	12.40	3.66	7.00
342	June 1979	117.47	90.09	12.49	3.70	7.05
343	July 1979	118.29	90.82	12.56	3.73	7.07
344	Aug 1979	119.08	91.67	12.65	3.76	7.11
345	Sept 1979	119.82	92.44	12.72	3.79	7.14
346	Oct 1979	120.59	93.22	12.81	3.82	7.18
347	Nov 1979	121.31	94.00	12.88	3.85	7.21
348	Dec 1979	122.04	94.78	12.96	3.89	7.24
349	Jan 1980	123.28	95.56	13.03	3.92	7.27
350	Feb 1980	122.98	98.20	13.49	4.04	7.56
351	Mar 1980	124.03	96.35	12.98	3.94	7.19
352	Apr 1980	123.90	97.86	13.28	4.01	7.39
353	May 1980	124.69	96.00	12.78	3.90	7.03
354	June 1980	125.83	96.23	12.80	3.91	7.03
355	July 1980	0.72	0.00	0.00	0.00	0.00
356	Aug 1980	0.75	0.00	0.00	0.00	0.00
357	Sept 1980	121.36	95.07	12.43	3.92	6.83
358	Oct 1980	121.72	91.40	11.24	3.63	5.84
359	Nov 1980	122.14	91.00	11.17	3.63	5.82
360	Dec 1980	122.95	90.64	11.14	3.62	5.81
361	Jan 1981	114.05	84.14	10.41	3.37	5.46
362	Feb 1981	114.39	84.80	10.53	3.41	5.55
363	Mar 1981	115.60	84.13	10.37	3.37	5.44
364	Apr 1981	116.55	85.90	10.74	3.46	5.69
365	May 1981	117.30	87.53	11.02	3.54	5.87
366	June 1981	118.36	88.90	11.26	3.60	6.03
367	July 1981	133.29	102.10	13.12	4.17	7.09
368	Aug 1981	134.31	105.46	13.75	4.33	7.50
369	Sept 1981	120.72	96.34	12.64	3.96	6.93
370	Oct 1981	121.04	96.29	12.60	3.95	6.90
371	Nov 1981	121.41	96.69	12.67	3.96	6.93
372	Dec 1981	121.81	97.27	12.74	3.98	6.97

Appendix A2. Simulated tetrachloroethylene and its degradation by-products in finished water, Tarawa Terrace water treatment plant, January 1951–March 1987[1].—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; 1,2-tDCE, *trans*-1,2-dichloroethylene; TCE, trichloroethylene; VC, vinyl chloride; WTP, water treatment plant]

Stress-period	Month and year	Single specie using MT3DMS model[2]	Multispecies, multiphase using TechFlowMP model[3]			
		[4]PCE, in µg/L	[5]PCE, in µg/L	[5]1,2 tDCE, in µg/L	[5]TCE, in µg/L	[5]VC, in µg/L
373	Jan 1982	103.95	81.28	10.65	3.33	5.81
374	Feb 1982	105.86	83.47	11.06	3.43	6.09
375	Mar 1982	107.52	85.42	11.40	3.51	6.31
376	Apr 1982	108.83	87.32	11.75	3.60	6.55
377	May 1982	148.50	120.45	16.30	4.98	9.13
378	June 1982	110.78	92.65	12.81	3.86	7.26
379	July 1982	111.98	92.98	12.77	3.86	7.21
380	Aug 1982	113.07	94.09	12.97	3.91	7.34
381	Sept 1982	114.04	95.33	13.18	3.96	7.46
382	Oct 1982	114.60	96.51	13.37	4.01	7.57
383	Nov 1982	113.87	96.63	13.31	4.00	7.51
384	Dec 1982	115.16	93.14	12.43	3.80	6.88
385	Jan 1983	1.25	0.10	0.04	0.00	0.05
386	Feb 1983	1.29	0.12	0.05	0.01	0.07
387	Mar 1983	111.76	88.43	11.55	3.65	6.37
388	Apr 1983	112.66	86.39	10.85	3.43	5.77
389	May 1983	113.97	87.67	11.04	3.52	5.88
390	June 1983	106.10	82.26	10.54	3.33	5.70
391	July 1983	116.70	92.03	11.95	3.75	6.52
392	Aug 1983	117.72	94.46	12.45	3.87	6.87
393	Sept 1983	117.83	96.92	12.94	3.99	7.21
394	Oct 1983	117.97	96.60	12.82	3.96	7.12
395	Nov 1983	118.63	95.49	12.58	3.89	6.95
396	Dec 1983	120.78	95.52	12.60	3.89	6.96
397	Jan 1984	132.87	111.52	15.09	4.61	8.43
398	Feb 1984	180.39	145.48	19.20	5.94	10.56
399	Mar 1984	183.02	155.54	21.34	6.47	11.97
400	Apr 1984	151.46	132.07	18.23	5.52	10.26
401	May 1984	153.42	132.19	18.09	5.49	10.13
402	June 1984	182.13	158.14	21.85	6.60	12.28
403	July 1984	156.39	140.96	19.72	5.92	11.14
404	Aug 1984	170.47	118.88	16.05	4.81	8.94
405	Sept 1984	181.22	149.36	19.60	6.17	11.20
406	Oct 1984	173.73	136.04	17.33	5.56	9.39
407	Nov 1984	173.77	131.63	16.46	5.34	8.87
408	Dec 1984	173.18	128.47	15.83	5.18	8.46

Appendix A2. Simulated tetrachloroethylene and its degradation by-products in finished water, Tarawa Terrace water treatment plant, January 1951–March 1987[1].—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; 1,2-tDCE, *trans*-1,2-dichloroethylene; TCE, trichloroethylene; VC, vinyl chloride; WTP, water treatment plant]

Stress period	Month and year	Single specie using MT3DMS model[2]	Multispecies, multiphase using TechFlowMP model[3]			
		[4]PCE, in µg/L	[5]PCE, in µg/L	[5]1,2-tDCE, in µg/L	[5]TCE, in µg/L	[5]VC, in µg/L
409	Jan 1985	176.12	127.80	15.48	5.13	8.20
410	Feb 1985	3.64	1.10	0.29	0.05	0.22
411	Mar 1985	8.71	3.88	0.68	0.17	0.47
412	Apr 1985	8.09	3.70	0.68	0.16	0.49
413	May 1985	4.76	1.65	0.44	0.07	0.35
414	June 1985	5.14	1.88	0.50	0.08	0.41
415	July 1985	5.54	2.10	0.56	0.09	0.47
416	Aug 1985	6.01	2.34	0.63	0.10	0.52
417	Sept 1985	6.50	2.62	0.71	0.12	0.59
418	Oct 1985	7.06	2.91	0.79	0.13	0.65
419	Nov 1985	7.64	3.24	0.87	0.15	0.71
420	Dec 1985	8.27	3.58	0.95	0.16	0.76
421	Jan 1986	8.85	3.95	1.04	0.18	0.82
422	Feb 1986	9.42	4.24	1.08	0.19	0.83
423	Mar 1986	12.14	5.40	1.34	0.24	1.01
424	Apr 1986	10.83	4.93	1.20	0.22	0.89
425	May 1986	11.56	5.25	1.25	0.23	0.91
426	June 1986	12.28	5.61	1.30	0.25	0.92
427	July 1986	13.06	5.97	1.35	0.26	0.94
428	Aug 1986	13.84	6.36	1.39	0.28	0.96
429	Sept 1986	14.61	6.75	1.44	0.30	0.97
430	Oct 1986	15.42	7.12	1.48	0.31	0.99
431	Nov 1986	16.21	7.52	1.52	0.33	1.00
432	Dec 1986	17.03	7.89	1.56	0.34	1.01
433	Jan 1987	17.85	8.28	1.59	0.36	1.01
434	Feb 1987	18.49	8.71	1.64	0.38	1.03
435	Mar 1987	**WTP closed**	**WTP closed**	**WTP closed**	**WTP closed**	**WTP closed**

[1]Current maximum contaminant levels (MCLs) are: tetrachloroethylene (PCE) and trichloroethylene (TCE), 5 µg/L; *trans*-1,2-dichloroethylene (1,2-tDCE), 100 µg/L; and vinyl chloride (VC), 2 µg/L (USEPA, 2003); effective dates for MCLs are as follows: TCE and VC, January 9, 1989; PCE and 1,2-tDCE, July 6, 1992 (40 CFR, Section 141.60, Effective Dates, July 1, 2002, ed.)

[2]MT3DMS: A three-dimensional mass transport, multispecies model developed by C. Zheng and P. Wang (1999) on behalf of the U.S. Army Engineer Research and Development Center in Vicksburg, Mississippi (*http://hydro.geo.ua.edu/mt3d/*)

[3]TechFlowMP: A three-dimensional multispecies, multiphase mass transport model developed by the Multimedia Environmental Simulations Laboratory (Jang and Aral 2007) at the Georgia Institute of Technology, Atlanta, Georgia (*http://mesl.ce.gatech.edu*)

[4]Results from Chapter F report (Faye In press 2007b)

[5]Results from Chapter G report (Jang and Aral In press 2007)

Appendix H2 — Tarawa Terrace Water Treatment Plant Reconstructed (Simulated) Mean Monthly Finished Water Concentration of Single-Specie Tetrachloroethylene (PCE) and Range of Concentrations Derived from Monte Carlo Simulation

Appendix I5. Simulated concentrations of tetrachloroethylene in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[PCE, tetrachloroethylene; µg/L, microgram per liter; $P_{2.5}$, Monte Carlo simulation results for the 2.5 percentile; P_{50}, Monte Carlo simulation results for the 50 percentile; $P_{97.5}$, Monte Carlo simulation results for the 97.5 percentile; WTP, water treatment plant; Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Dec, December]

Stress period	Month and year	Calibrated PCE concentration, in µg/L[1]	Range of concentrations derived from Monte Carlo simulations[2]					
			Monte Carlo simulation (Scenario 1)[3]			Monte Carlo simulation (Scenario 2)[4]		
			$P_{2.5}$, in µg/L	P_{50}, in µg/L	$P_{97.5}$, in µg/L	$P_{2.5}$, in µg/L	P_{50}, in µg/L	$P_{97.5}$, in µg/L
1-12	Jan–Dec 1951				WTP not operating			
13	Jan 1952	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	Feb 1952	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	Mar 1952	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	Apr 1952	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	May 1952	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	June 1952	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	July 1952	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	Aug 1952	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21	Sept 1952	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22	Oct 1952	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23	Nov 1952	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24	Dec 1952	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25	Jan 1953	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26	Feb 1953	0.00	0.00	0.00	0.00	0.00	0.00	0.00
27	Mar 1953	0.00	0.00	0.00	0.00	0.00	0.00	0.00
28	Apr 1953	0.00	0.00	0.00	0.00	0.00	0.00	0.00
29	May 1953	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	June 1953	0.00	0.00	0.00	0.00	0.00	0.00	0.00
31	July 1953	0.00	0.00	0.00	0.00	0.00	0.00	0.00
32	Aug 1953	0.00	0.00	0.00	0.00	0.00	0.00	0.00
33	Sept 1953	0.00	0.00	0.00	0.00	0.00	0.00	0.00
34	Oct 1953	0.00	0.00	0.00	0.00	0.00	0.00	0.00
35	Nov 1953	0.00	0.00	0.00	0.00	0.00	0.00	0.00
36	Dec 1953	0.00	0.00	0.00	0.00	0.00	0.00	0.00
37	Jan 1954	0.00	0.00	0.00	0.00	0.00	0.00	0.00
38	Feb 1954	0.00	0.00	0.00	0.00	0.00	0.00	0.00
39	Mar 1954	0.00	0.00	0.00	0.00	0.00	0.00	0.00
40	Apr 1954	0.00	0.00	0.00	0.00	0.00	0.00	0.00
41	May 1954	0.00	0.00	0.00	0.00	0.00	0.00	0.00
42	June 1954	0.00	0.00	0.00	0.00	0.00	0.00	0.00
43	July 1954	0.00	0.00	0.00	0.00	0.00	0.00	0.00
44	Aug 1954	0.00	0.00	0.00	0.00	0.00	0.00	0.00
45	Sept 1954	0.00	0.00	0.00	0.00	0.00	0.00	0.00
46	Oct 1954	0.00	0.00	0.00	0.00	0.00	0.00	0.00
47	Nov 1954	0.00	0.00	0.00	0.00	0.00	0.00	0.00
48	Dec 1954	0.00	0.00	0.00	0.00	0.00	0.00	0.00
49	Jan 1955	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50	Feb 1955	0.00	0.00	0.00	0.00	0.00	0.00	0.00
51	Mar 1955	0.00	0.00	0.00	0.00	0.00	0.00	0.00
52	Apr 1955	0.00	0.00	0.00	0.01	0.00	0.00	0.01
53	May 1955	0.00	0.00	0.00	0.01	0.00	0.00	0.01
54	June 1955	0.01	0.00	0.00	0.01	0.00	0.00	0.01
55	July 1955	0.01	0.00	0.01	0.02	0.00	0.01	0.02
56	Aug 1955	0.01	0.00	0.01	0.03	0.00	0.01	0.02
57	Sept 1955	0.02	0.00	0.01	0.04	0.00	0.01	0.03
58	Oct 1955	0.03	0.01	0.02	0.05	0.01	0.02	0.04
59	Nov 1955	0.04	0.01	0.03	0.07	0.01	0.03	0.07
60	Dec 1955	0.06	0.01	0.04	0.09	0.01	0.03	0.09

Appendix I5. Simulated concentrations of tetrachloroethylene in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; $P_{2.5}$, Monte Carlo simulation results for the 2.5 percentile; P_{50}, Monte Carlo simulation results for the 50 percentile; $P_{97.5}$, Monte Carlo simulation results for the 97.5 percentile; WTP, water treatment plant; Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Dec, December]

Stress period	Month and year	Calibrated PCE concentration, in µg/L[1]	Range of concentrations derived from Monte Carlo simulations[2]					
			Monte Carlo simulation (Scenario 1)[3]			Monte Carlo simulation (Scenario 2)[4]		
			$P_{2.5}$, in µg/L	P_{50}, in µg/L	$P_{97.5}$, in µg/L	$P_{2.5}$, in µg/L	P_{50}, in µg/L	$P_{97.5}$, in µg/L
61	Jan 1956	0.08	0.02	0.05	0.12	0.02	0.04	0.12
62	Feb 1956	0.10	0.02	0.07	0.16	0.02	0.06	0.15
63	Mar 1956	0.13	0.03	0.09	0.21	0.03	0.08	0.18
64	Apr 1956	0.17	0.04	0.12	0.26	0.04	0.10	0.24
65	May 1956	0.23	0.05	0.15	0.33	0.05	0.12	0.29
66	June 1956	0.29	0.07	0.20	0.42	0.06	0.15	0.34
67	July 1956	0.36	0.09	0.25	0.52	0.08	0.18	0.41
68	Aug 1956	0.46	0.12	0.31	0.65	0.10	0.23	0.51
69	Sept 1956	0.57	0.15	0.38	0.79	0.13	0.29	0.65
70	Oct 1956	0.70	0.18	0.47	0.96	0.16	0.35	0.78
71	Nov 1956	0.85	0.23	0.57	1.16	0.22	0.47	1.03
72	Dec 1956	1.04	0.28	0.69	1.38	0.24	0.54	1.14
73	Jan 1957	1.25	0.35	0.83	1.63	0.31	0.63	1.38
74	Feb 1957	1.47	0.41	0.97	1.89	0.37	0.77	1.69
75	Mar 1957	1.74	0.49	1.16	2.21	0.43	0.88	1.84
76	Apr 1957	2.04	0.59	1.36	2.57	0.53	1.09	2.08
77	May 1957	2.39	0.70	1.59	2.97	0.60	1.20	2.40
78	June 1957	2.77	0.83	1.84	3.40	0.64	1.31	2.51
79	July 1957	3.21	0.98	2.12	3.87	0.74	1.50	3.08
80	Aug 1957	3.69	1.15	2.45	4.42	0.87	1.73	3.38
81	Sept 1957	4.21	1.33	2.80	4.99	1.07	2.11	3.83
82	Oct 1957	4.79	1.54	3.20	5.64	1.20	2.31	4.48
83	Nov 1957	5.41	1.77	3.61	6.32	1.46	2.95	5.33
84	Dec 1957	6.10	2.02	4.08	7.07	1.61	3.08	5.81
85	Jan 1958	6.86	2.29	4.60	7.87	1.81	3.43	6.42
86	Feb 1958	7.60	2.57	5.11	8.67	2.04	3.97	7.10
87	Mar 1958	8.47	2.88	5.71	9.58	2.36	4.36	7.74
88	Apr 1958	9.37	3.22	6.33	10.56	2.68	5.04	8.73
89	May 1958	10.37	3.61	7.02	11.61	2.99	5.37	9.15
90	June 1958	11.39	4.00	7.73	12.67	2.98	5.43	9.32
91	July 1958	12.91	4.59	8.78	14.26	4.03	6.88	11.46
92	Aug 1958	14.12	5.09	9.61	15.49	4.55	7.67	12.57
93	Sept 1958	15.35	5.62	10.47	16.74	4.62	8.07	13.12
94	Oct 1958	16.69	6.19	11.39	18.13	5.24	8.98	14.89
95	Nov 1958	18.03	6.79	12.32	19.54	5.71	9.88	16.33
96	Dec 1958	19.49	7.45	13.33	21.07	6.32	10.83	17.27
97	Jan 1959	20.97	8.11	14.36	22.62	6.84	11.56	18.53
98	Feb 1959	22.35	8.77	15.34	23.97	7.74	12.87	20.40
99	Mar 1959	23.92	9.53	16.47	25.59	7.80	13.07	20.81
100	Apr 1959	25.49	10.24	17.59	27.22	8.26	14.30	23.52
101	May 1959	27.15	11.08	18.81	29.01	8.82	15.02	23.60
102	June 1959	28.81	11.94	20.01	30.78	10.46	16.86	25.74
103	July 1959	30.56	12.79	21.37	32.69	11.14	17.71	27.35
104	Aug 1959	32.36	13.70	22.77	34.63	12.06	18.88	28.65
105	Sept 1959	34.14	14.62	24.11	36.56	12.39	19.29	28.82
106	Oct 1959	36.01	15.60	25.59	38.60	13.35	20.99	31.36
107	Nov 1959	37.85	16.60	27.04	40.57	13.30	22.66	35.03
108	Dec 1959	39.78	17.68	28.50	42.59	14.48	23.99	36.02

Appendix I5. Simulated concentrations of tetrachloroethylene in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; $P_{2.5}$, Monte Carlo simulation results for the 2.5 percentile; P_{50}, Monte Carlo simulation results for the 50 percentile; $P_{97.5}$, Monte Carlo simulation results for the 97.5 percentile; WTP, water treatment plant; Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Dec, December]

Stress period	Month and year	Calibrated PCE concentration, in µg/L[1]	Range of concentrations derived from Monte Carlo simulations[2]					
			Monte Carlo simulation (Scenario 1)[3]			Monte Carlo simulation (Scenario 2)[4]		
			$P_{2.5}$, in µg/L	P_{50}, in µg/L	$P_{97.5}$, in µg/L	$P_{2.5}$, in µg/L	P_{50}, in µg/L	$P_{97.5}$, in µg/L
109	Jan 1960	41.86	18.82	30.15	44.74	15.99	24.99	38.89
110	Feb 1960	43.85	19.92	31.62	46.80	16.98	27.00	41.00
111	Mar 1960	46.03	21.13	33.16	49.07	17.85	26.94	41.01
112	Apr 1960	48.15	22.35	34.81	51.31	18.45	29.03	43.84
113	May 1960	50.37	23.59	36.60	53.65	19.84	30.13	44.48
114	June 1960	52.51	24.80	38.35	55.92	22.20	33.22	47.21
115	July 1960	54.74	26.08	40.12	58.27	23.30	34.55	50.18
116	Aug 1960	56.96	27.37	42.13	60.60	24.49	36.32	51.82
117	Sept 1960	59.09	28.64	43.80	62.82	24.27	35.66	51.64
118	Oct 1960	61.30	29.98	45.51	65.09	26.27	38.51	55.86
119	Nov 1960	63.42	31.31	47.25	67.22	26.43	40.46	59.79
120	Dec 1960	65.61	32.81	48.96	69.64	26.91	43.02	60.66
121	Jan 1961	67.69	34.22	50.74	71.88	28.21	43.30	63.65
122	Feb 1961	69.54	35.52	52.42	73.96	30.97	45.69	70.43
123	Mar 1961	71.56	36.93	54.16	76.28	31.47	45.72	66.14
124	Apr 1961	73.49	38.31	55.82	78.51	32.33	47.92	70.86
125	May 1961	75.49	39.76	57.54	80.74	32.37	49.12	70.32
126	June 1961	77.39	41.04	59.14	82.99	38.28	53.02	73.49
127	July 1961	79.36	42.45	60.87	84.92	36.88	54.13	75.55
128	Aug 1961	81.32	43.86	62.61	86.79	38.78	56.07	77.30
129	Sept 1961	83.19	45.25	64.23	88.82	38.62	54.74	76.56
130	Oct 1961	85.11	46.69	65.85	90.84	40.37	58.11	80.91
131	Nov 1961	86.95	48.10	67.44	92.75	39.55	59.92	87.09
132	Dec 1961	88.84	49.61	69.03	94.71	42.20	62.63	86.40
133	Jan 1962	60.88	34.23	47.47	64.96	27.60	42.46	62.20
134	Feb 1962	62.10	35.17	48.52	66.43	30.36	45.91	68.03
135	Mar 1962	62.94	35.84	49.35	67.26	31.00	45.13	66.06
136	Apr 1962	63.59	36.33	50.10	68.07	32.57	48.08	68.30
137	May 1962	64.17	36.80	50.73	68.98	31.10	46.57	66.06
138	June 1962	64.70	37.21	51.33	69.81	29.45	43.47	61.90
139	July 1962	65.23	37.65	51.82	70.45	28.63	44.36	62.01
140	Aug 1962	65.74	38.07	52.41	71.23	29.87	45.14	64.88
141	Sept 1962	66.22	38.47	52.91	71.97	32.00	47.51	67.91
142	Oct 1962	66.71	38.89	53.53	72.74	30.29	47.30	68.59
143	Nov 1962	67.18	39.30	54.16	73.38	35.13	53.53	77.51
144	Dec 1962	67.65	39.72	54.77	74.05	33.21	50.53	75.06
145	Jan 1963	68.06	40.19	55.24	74.67	32.41	49.74	74.10
146	Feb 1963	68.39	40.63	55.56	75.17	34.46	52.70	77.58
147	Mar 1963	68.73	41.15	56.03	75.76	35.61	52.41	73.73
148	Apr 1963	69.03	41.66	56.47	76.32	36.91	55.39	79.81
149	May 1963	69.33	42.03	56.98	77.17	34.47	53.02	77.36
150	June 1963	69.62	42.25	57.46	77.94	34.18	49.23	70.00
151	July 1963	69.90	42.45	57.98	78.48	32.75	49.62	71.03
152	Aug 1963	70.17	42.67	58.43	79.00	34.06	51.05	73.06
153	Sept 1963	70.43	42.87	58.82	79.47	36.62	52.90	76.53
154	Oct 1963	70.69	43.17	59.15	79.90	36.26	52.47	77.15
155	Nov 1963	70.93	43.60	59.49	80.31	38.46	59.09	84.58
156	Dec 1963	71.17	43.90	59.88	80.88	36.71	56.06	80.60

Appendix I5. Simulated concentrations of tetrachloroethylene in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; $P_{2.5}$, Monte Carlo simulation results for the 2.5 percentile; P_{50}, Monte Carlo simulation results for the 50 percentile; $P_{97.5}$, Monte Carlo simulation results for the 97.5 percentile; WTP, water treatment plant; Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Dec, December]

Stress period	Month and year	Calibrated PCE concentration, in µg/L[1]	Range of concentrations derived from Monte Carlo simulations[2]					
			Monte Carlo simulation (Scenario 1)[3]			Monte Carlo simulation (Scenario 2)[4]		
			$P_{2.5}$, in µg/L	P_{50}, in µg/L	$P_{97.5}$, in µg/L	$P_{2.5}$, in µg/L	P_{50}, in µg/L	$P_{97.5}$, in µg/L
157	Jan 1964	71.40	44.18	60.32	81.34	35.81	55.22	80.71
158	Feb 1964	63.77	39.66	54.00	72.84	37.51	58.47	83.80
159	Mar 1964	63.95	39.92	54.36	73.38	37.37	57.84	81.58
160	Apr 1964	64.08	40.09	54.68	73.85	40.30	60.39	85.06
161	May 1964	64.19	40.31	54.98	74.28	39.56	57.23	84.15
162	June 1964	64.27	40.51	55.23	74.64	37.14	53.54	75.21
163	July 1964	64.34	40.61	55.45	74.98	35.59	54.24	76.87
164	Aug 1964	64.39	40.68	55.64	75.27	37.29	55.12	77.08
165	Sept 1964	64.43	40.75	55.82	75.62	39.55	57.96	80.84
166	Oct 1964	64.47	40.81	56.00	75.94	38.57	56.64	78.51
167	Nov 1964	64.49	40.88	56.18	76.19	42.49	63.10	91.13
168	Dec 1964	64.50	40.96	56.36	76.45	39.06	59.01	88.36
169	Jan 1965	64.50	41.10	56.58	76.70	37.87	59.05	88.52
170	Feb 1965	64.49	41.12	56.70	76.94	39.46	61.35	94.71
171	Mar 1965	64.47	41.14	56.78	77.17	41.20	60.99	89.98
172	Apr 1965	64.45	41.16	56.92	77.24	42.66	64.07	93.10
173	May 1965	64.42	41.20	57.06	77.13	41.03	61.17	87.07
174	June 1965	64.38	41.23	57.20	77.34	36.64	56.23	81.33
175	July 1965	64.33	41.26	57.22	77.80	38.15	57.32	81.83
176	Aug 1965	64.27	41.14	57.22	77.91	38.93	57.04	84.04
177	Sept 1965	64.20	41.03	57.22	77.92	41.40	60.36	84.29
178	Oct 1965	64.13	40.92	57.30	78.03	38.84	59.61	87.79
179	Nov 1965	64.05	40.85	57.34	78.10	44.47	66.00	95.45
180	Dec 1965	63.97	40.78	57.39	78.10	39.95	61.88	91.31
181	Jan 1966	63.88	40.81	57.48	78.26	39.34	61.61	91.59
182	Feb 1966	63.79	40.88	57.54	78.38	42.06	64.63	99.81
183	Mar 1966	63.68	41.01	57.62	78.45	41.44	63.87	94.47
184	Apr 1966	63.57	41.20	57.61	78.33	43.72	66.91	97.21
185	May 1966	63.46	41.28	57.64	78.43	42.05	64.21	91.37
186	June 1966	63.34	41.40	57.70	78.44	38.28	58.86	86.56
187	July 1966	63.21	41.54	57.70	78.65	39.70	58.20	87.29
188	Aug 1966	63.08	41.69	57.74	78.94	39.57	60.11	87.73
189	Sept 1966	62.94	41.79	57.79	78.91	41.82	62.94	91.60
190	Oct 1966	62.80	41.73	57.82	78.87	40.67	60.35	90.52
191	Nov 1966	62.65	41.67	57.78	78.78	44.43	68.76	99.82
192	Dec 1966	62.50	41.60	57.82	78.70	40.92	63.19	97.26
193	Jan 1967	62.25	41.42	57.70	78.67	40.95	62.45	96.88
194	Feb 1967	61.99	41.20	57.61	78.56	41.00	66.51	98.39
195	Mar 1967	61.67	40.98	57.36	78.37	43.47	64.42	95.01
196	Apr 1967	61.35	40.74	57.12	78.11	44.75	66.63	97.65
197	May 1967	61.02	40.52	56.84	77.78	42.71	64.23	95.11
198	June 1967	60.69	40.22	56.65	77.54	38.89	58.53	86.55
199	July 1967	60.37	40.03	56.43	77.45	38.46	59.64	87.57
200	Aug 1967	60.05	39.87	56.26	77.39	39.01	59.72	89.18
201	Sept 1967	59.74	39.69	56.04	77.26	40.93	61.91	90.19
202	Oct 1967	59.43	39.49	55.86	77.12	40.30	60.56	90.27
203	Nov 1967	59.13	39.31	55.71	76.98	44.01	68.01	99.90
204	Dec 1967	58.83	39.12	55.50	76.83	41.94	63.60	97.99

Appendix I5. Simulated concentrations of tetrachloroethylene in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; $P_{2.5}$, Monte Carlo simulation results for the 2.5 percentile; P_{50}, Monte Carlo simulation results for the 50 percentile; $P_{97.5}$, Monte Carlo simulation results for the 97.5 percentile; WTP, water treatment plant; Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Dec, December]

Stress period	Month and year	Calibrated PCE concentration, in µg/L[1]	Range of concentrations derived from Monte Carlo simulations[2]					
			Monte Carlo simulation (Scenario 1)[3]			Monte Carlo simulation (Scenario 2)[4]		
			$P_{2.5}$, in µg/L	P_{50}, in µg/L	$P_{97.5}$, in µg/L	$P_{2.5}$, in µg/L	P_{50}, in µg/L	$P_{97.5}$, in µg/L
205	Jan 1968	58.41	38.91	55.32	76.43	40.60	63.04	98.22
206	Feb 1968	57.95	38.69	55.12	75.94	39.51	63.91	98.67
207	Mar 1968	57.43	38.44	54.74	75.51	41.62	63.54	94.21
208	Apr 1968	56.94	38.22	54.56	75.12	42.61	65.79	99.98
209	May 1968	56.45	37.99	54.20	74.61	39.39	62.35	92.79
210	June 1968	55.98	37.72	53.86	74.13	37.49	57.23	84.15
211	July 1968	55.49	37.46	53.50	73.63	37.51	56.92	83.56
212	Aug 1968	55.02	37.31	53.27	73.27	37.52	58.08	84.83
213	Sept 1968	54.58	37.16	53.00	73.05	40.06	60.24	89.84
214	Oct 1968	54.13	36.94	52.72	72.83	37.61	59.46	87.96
215	Nov 1968	53.71	36.71	52.49	72.61	42.84	64.11	96.77
216	Dec 1968	53.28	36.45	52.16	72.34	39.36	60.93	93.74
217	Jan 1969	53.07	36.40	52.03	72.40	37.42	60.60	90.38
218	Feb 1969	52.97	36.41	52.07	72.32	38.68	63.83	100.33
219	Mar 1969	52.94	36.41	52.21	72.23	40.85	62.20	90.15
220	Apr 1969	52.93	36.50	52.33	72.58	41.71	63.74	95.37
221	May 1969	52.93	36.55	52.41	72.94	40.51	60.54	94.64
222	June 1969	52.92	36.59	52.49	73.24	37.99	56.86	82.85
223	July 1969	52.90	36.61	52.54	73.52	35.02	57.32	85.75
224	Aug 1969	52.86	36.63	52.71	73.77	36.90	57.85	85.34
225	Sept 1969	52.81	36.64	52.74	73.98	39.74	59.97	89.19
226	Oct 1969	52.75	36.64	52.75	74.13	37.64	59.44	92.22
227	Nov 1969	55.19	38.34	55.24	77.72	36.74	55.89	84.87
228	Dec 1969	55.19	38.30	55.23	77.70	32.94	51.96	81.13
229	Jan 1970	55.01	38.10	55.14	77.54	32.78	50.97	81.62
230	Feb 1970	54.79	37.97	55.03	77.34	33.13	52.80	83.08
231	Mar 1970	54.49	37.71	54.76	77.08	32.85	52.72	79.35
232	Apr 1970	54.20	37.46	54.48	76.72	34.85	54.22	82.26
233	May 1970	53.90	37.21	54.17	76.27	33.91	51.26	78.11
234	June 1970	53.61	37.01	53.91	75.89	29.54	47.08	71.71
235	July 1970	53.32	36.82	53.59	75.68	28.77	46.80	72.48
236	Aug 1970	53.04	36.64	53.32	75.44	29.60	47.37	70.90
237	Sept 1970	52.78	36.47	53.06	75.25	31.55	49.00	74.82
238	Oct 1970	52.53	36.31	52.78	75.02	30.14	48.10	73.55
239	Nov 1970	52.29	36.19	52.67	74.93	32.50	53.01	81.51
240	Dec 1970	52.05	36.05	52.54	74.88	32.47	48.94	76.35
241	Jan 1971	51.96	35.96	52.53	75.02	30.00	48.86	77.29
242	Feb 1971	51.93	35.90	52.50	75.19	32.51	50.78	80.73
243	Mar 1971	51.95	35.87	52.60	75.42	32.25	49.82	78.27
244	Apr 1971	51.99	35.86	52.73	75.65	32.74	52.65	81.01
245	May 1971	52.03	35.86	52.88	75.88	30.15	49.32	76.96
246	June 1971	52.08	35.85	52.86	76.11	29.02	45.87	72.87
247	July 1971	52.12	35.92	52.88	76.35	29.03	45.64	72.37
248	Aug 1971	52.16	35.93	52.97	76.52	29.30	46.61	71.75
249	Sept 1971	52.20	35.93	53.07	76.72	30.33	48.38	74.56
250	Oct 1971	52.23	35.95	53.13	76.91	29.27	46.98	73.25
251	Nov 1971	52.26	35.98	53.25	77.05	32.40	52.55	82.47
252	Dec 1971	52.29	35.91	53.28	77.28	30.91	49.57	76.35

Appendix I5. Simulated concentrations of tetrachloroethylene in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; $P_{2.5}$, Monte Carlo simulation results for the 2.5 percentile; P_{50}, Monte Carlo simulation results for the 50 percentile; $P_{97.5}$, Monte Carlo simulation results for the 97.5 percentile; WTP, water treatment plant; Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Dec, December]

Stress period	Month and year	Calibrated PCE concentration, in µg/L[1]	Range of concentrations derived from Monte Carlo simulations[2]					
			Monte Carlo simulation (Scenario 1)[3]			Monte Carlo simulation (Scenario 2)[4]		
			$P_{2.5}$, in µg/L	P_{50}, in µg/L	$P_{97.5}$, in µg/L	$P_{2.5}$, in µg/L	P_{50}, in µg/L	$P_{97.5}$, in µg/L
253	Jan 1972	49.34	33.93	50.30	73.12	29.17	48.14	77.82
254	Feb 1972	49.01	33.72	50.06	72.93	30.19	50.33	81.13
255	Mar 1972	48.68	33.47	49.71	72.72	31.69	48.44	75.80
256	Apr 1972	48.40	33.25	49.54	72.47	30.79	50.77	79.48
257	May 1972	48.14	33.10	49.27	72.26	30.44	48.53	73.97
258	June 1972	47.90	32.98	49.08	72.17	27.68	44.98	68.87
259	July 1972	47.67	32.85	48.97	72.02	27.13	43.58	66.62
260	Aug 1972	47.45	32.72	48.78	71.78	26.91	43.63	68.46
261	Sept 1972	47.25	32.60	48.69	71.47	28.10	46.38	72.80
262	Oct 1972	47.05	32.49	48.58	71.34	28.15	44.90	70.07
263	Nov 1972	46.87	32.41	48.43	71.26	30.68	49.80	78.83
264	Dec 1972	46.69	32.29	48.21	71.16	28.36	46.21	76.56
265	Jan 1973	54.28	37.52	56.04	82.79	27.54	44.70	72.51
266	Feb 1973	54.19	37.39	55.96	82.69	29.05	47.31	78.50
267	Mar 1973	53.98	37.15	55.78	82.35	28.09	46.20	73.11
268	Apr 1973	53.76	36.91	55.44	81.94	28.95	46.73	77.52
269	May 1973	53.52	36.68	55.24	81.51	26.12	45.17	70.36
270	June 1973	53.30	36.46	55.22	81.10	25.61	40.75	66.70
271	July 1973	53.08	36.24	55.12	80.74	25.25	40.82	63.84
272	Aug 1973	52.87	36.03	54.99	80.59	25.02	41.47	64.39
273	Sept 1973	52.68	35.84	54.88	80.46	26.43	43.33	68.68
274	Oct 1973	52.51	35.66	54.87	80.34	26.17	41.28	65.28
275	Nov 1973	52.35	35.49	54.80	80.25	27.77	45.41	72.92
276	Dec 1973	52.20	35.33	54.72	80.17	25.66	42.21	68.89
277	Jan 1974	52.43	35.41	54.97	80.49	25.72	42.62	69.65
278	Feb 1974	52.82	35.59	55.42	80.98	26.19	43.80	72.53
279	Mar 1974	53.39	35.86	55.92	81.66	25.08	42.86	68.49
280	Apr 1974	53.99	36.16	56.60	82.41	28.14	45.59	71.28
281	May 1974	54.63	36.49	57.21	83.20	25.84	42.70	72.49
282	June 1974	55.25	36.80	57.69	84.15	25.00	40.00	64.50
283	July 1974	55.90	37.13	58.15	85.07	24.17	40.57	65.57
284	Aug 1974	56.53	37.50	58.85	85.98	24.29	40.75	65.98
285	Sept 1974	57.10	37.85	59.43	86.86	27.22	43.16	69.98
286	Oct 1974	57.70	38.22	60.00	87.74	25.22	42.68	67.27
287	Nov 1974	58.30	38.56	60.59	88.58	28.99	47.52	76.53
288	Dec 1974	58.92	38.98	61.11	89.45	25.07	44.15	72.46
289	Jan 1975	61.00	40.30	63.17	92.62	27.61	45.83	75.73
290	Feb 1975	61.24	40.39	63.33	92.97	28.46	48.17	80.43
291	Mar 1975	61.41	40.51	63.43	93.20	28.98	46.39	77.50
292	Apr 1975	61.57	40.61	63.45	93.38	29.37	48.59	82.56
293	May 1975	61.72	40.78	63.62	93.32	28.00	46.55	76.49
294	June 1975	61.88	40.92	63.77	93.48	24.95	42.93	67.44
295	July 1975	62.05	41.05	64.04	93.91	25.59	42.20	68.93
296	Aug 1975	62.25	41.13	64.22	94.27	26.21	42.72	68.78
297	Sept 1975	62.46	41.20	64.36	94.54	25.88	44.92	73.09
298	Oct 1975	62.69	41.18	64.65	94.84	26.24	43.56	70.58
299	Nov 1975	62.92	41.12	64.91	95.15	27.40	49.02	80.06
300	Dec 1975	63.18	41.12	65.11	95.44	26.23	45.41	76.07

Appendix I5. Simulated concentrations of tetrachloroethylene in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; $P_{2.5}$, Monte Carlo simulation results for the 2.5 percentile; P_{50}, Monte Carlo simulation results for the 50 percentile; $P_{97.5}$, Monte Carlo simulation results for the 97.5 percentile; WTP, water treatment plant; Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Dec, December]

Stress period	Month and year	Calibrated PCE concentration, in µg/L[1]	Range of concentrations derived from Monte Carlo simulations[2]					
			Monte Carlo simulation (Scenario 1)[3]			Monte Carlo simulation (Scenario 2)[4]		
			$P_{2.5}$, in µg/L	P_{50}, in µg/L	$P_{97.5}$, in µg/L	$P_{2.5}$, in µg/L	P_{50}, in µg/L	$P_{97.5}$, in µg/L
301	Jan 1976	73.96	48.06	76.13	111.62	27.44	47.37	78.75
302	Feb 1976	74.94	48.64	77.01	112.96	28.08	50.08	82.73
303	Mar 1976	75.97	49.28	77.88	114.29	30.00	49.48	77.65
304	Apr 1976	76.97	49.90	78.87	115.66	29.89	51.83	83.45
305	May 1976	78.00	50.66	79.94	117.25	28.96	49.32	81.75
306	June 1976	79.02	51.42	80.86	118.78	27.37	44.69	74.98
307	July 1976	80.07	52.20	81.82	120.35	28.29	45.16	75.62
308	Aug 1976	81.13	52.86	82.70	121.82	27.95	46.57	76.48
309	Sept 1976	82.17	53.51	83.71	123.46	29.17	49.14	79.62
310	Oct 1976	83.25	54.25	84.81	124.74	28.92	48.10	80.30
311	Nov 1976	84.31	55.09	85.76	126.00	31.09	53.61	90.47
312	Dec 1976	85.41	55.90	86.67	127.61	28.21	50.51	82.95
313	Jan 1977	86.61	56.70	87.66	129.36	28.88	49.71	81.57
314	Feb 1977	87.70	57.45	88.70	131.09	30.18	52.13	85.43
315	Mar 1977	88.91	58.14	89.80	133.02	29.18	51.65	83.61
316	Apr 1977	90.10	58.86	90.90	134.30	32.23	54.40	88.91
317	May 1977	91.32	59.61	91.86	135.48	30.43	50.86	86.19
318	June 1977	92.53	60.38	93.08	136.61	28.97	47.43	78.24
319	July 1977	93.75	61.24	94.29	137.80	29.03	47.45	77.48
320	Aug 1977	94.99	62.11	95.48	139.43	28.20	48.28	81.51
321	Sept 1977	96.20	62.97	96.44	140.89	30.24	50.29	85.19
322	Oct 1977	97.42	63.86	97.49	142.51	28.33	51.14	82.53
323	Nov 1977	98.62	64.58	98.62	144.08	32.33	56.02	92.86
324	Dec 1977	99.84	65.31	99.65	145.59	29.86	53.22	90.47
325	Jan 1978	101.18	66.16	101.09	147.13	44.02	75.70	120.92
326	Feb 1978	102.77	67.25	102.62	148.91	39.93	67.26	112.31
327	Mar 1978	103.04	67.39	103.04	149.08	52.50	84.64	133.87
328	Apr 1978	104.31	68.24	104.52	150.32	46.79	76.94	126.94
329	May 1978	105.19	68.81	105.34	151.12	50.49	85.95	136.76
330	June 1978	106.88	70.00	107.10	153.19	42.45	73.13	119.19
331	July 1978	107.95	70.77	108.05	154.56	45.08	75.24	121.43
332	Aug 1978	108.69	71.12	108.58	155.63	48.54	80.46	135.92
333	Sept 1978	109.61	71.68	109.40	156.91	48.81	83.51	139.85
334	Oct 1978	111.18	72.89	110.78	158.60	44.55	75.04	121.83
335	Nov 1978	111.08	72.99	110.76	158.33	59.23	100.40	162.58
336	Dec 1978	111.93	73.52	111.71	159.48	58.45	100.01	162.64
337	Jan 1979	113.14	74.30	112.93	161.01	57.81	95.20	164.77
338	Feb 1979	114.05	74.80	113.75	162.04	58.23	99.50	166.62
339	Mar 1979	114.98	75.32	114.60	163.14	59.21	101.26	162.26
340	Apr 1979	115.82	76.01	115.14	164.14	64.03	105.77	169.77
341	May 1979	116.68	76.83	115.85	165.22	60.49	104.49	166.33
342	June 1979	117.47	77.56	116.62	166.12	57.29	95.08	158.63
343	July 1979	118.29	78.22	117.32	166.52	60.76	97.83	159.43
344	Aug 1979	119.08	78.87	117.95	167.11	60.40	101.30	162.28
345	Sept 1979	119.83	79.50	118.62	167.82	67.04	105.09	167.67
346	Oct 1979	120.59	80.14	119.49	168.59	63.07	104.48	172.01
347	Nov 1979	121.31	80.74	120.12	169.34	74.24	119.14	191.45
348	Dec 1979	122.04	81.35	120.77	170.09	68.90	113.89	186.42

Appendix I5. Simulated concentrations of tetrachloroethylene in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; $P_{2.5}$, Monte Carlo simulation results for the 2.5 percentile; P_{50}, Monte Carlo simulation results for the 50 percentile; $P_{97.5}$, Monte Carlo simulation results for the 97.5 percentile; WTP, water treatment plant; Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Dec, December]

Stress period	Month and year	Calibrated PCE concentration, in µg/L[1]	Range of concentrations derived from Monte Carlo simulations[2]					
			Monte Carlo simulation (Scenario 1)[3]			Monte Carlo simulation (Scenario 2)[4]		
			$P_{2.5}$, in µg/L	P_{50}, in µg/L	$P_{97.5}$, in µg/L	$P_{2.5}$, in µg/L	P_{50}, in µg/L	$P_{97.5}$, in µg/L
349	Jan 1980	123.28	82.20	122.09	171.34	61.30	101.54	159.81
350	Feb 1980	122.98	81.93	121.80	171.45	77.70	131.23	206.13
351	Mar 1980	124.03	82.63	122.99	172.63	67.73	114.94	183.21
352	Apr 1980	123.90	82.42	123.27	172.41	86.02	143.61	229.05
353	May 1980	124.69	82.89	123.73	173.81	85.23	138.95	220.28
354	June 1980	125.83	83.92	124.67	175.54	80.14	128.55	203.28
355	July 1980	0.72	0.10	0.43	1.67	0.06	0.32	1.22
356	Aug 1980	0.75	0.11	0.45	1.73	0.07	0.34	1.28
357	Sept 1980	121.36	80.64	120.61	170.25	74.54	128.20	195.86
358	Oct 1980	121.72	80.95	121.00	170.55	82.88	137.09	215.09
359	Nov 1980	122.14	81.32	121.73	171.07	89.83	145.35	231.15
360	Dec 1980	122.95	81.96	122.56	171.97	87.97	143.51	226.80
361	Jan 1981	114.05	76.20	113.83	159.33	81.35	131.65	210.19
362	Feb 1981	114.39	76.42	114.22	159.76	71.73	120.32	185.47
363	Mar 1981	115.60	77.32	115.10	161.62	65.38	104.23	164.75
364	Apr 1981	116.55	78.07	116.07	163.34	61.89	101.55	158.35
365	May 1981	117.30	78.64	116.91	164.52	63.14	99.62	156.29
366	June 1981	118.36	79.53	117.92	165.37	54.95	86.73	140.98
367	July 1981	133.29	89.77	132.96	186.08	58.22	92.47	142.21
368	Aug 1981	134.31	90.57	133.94	187.73	59.68	95.47	151.17
369	Sept 1981	120.72	81.40	120.32	168.91	58.90	98.56	150.82
370	Oct 1981	121.04	81.71	120.86	169.57	61.42	99.80	157.59
371	Nov 1981	121.41	82.04	121.17	170.30	60.76	101.36	158.08
372	Dec 1981	121.81	82.41	121.56	171.08	63.30	102.27	160.36
373	Jan 1982	103.95	70.61	103.86	145.41	55.35	91.05	141.55
374	Feb 1982	105.86	71.96	105.76	147.68	56.60	92.63	140.40
375	Mar 1982	107.52	73.05	107.51	149.67	59.57	93.91	147.10
376	Apr 1982	108.83	74.01	108.79	151.25	58.43	97.00	147.50
377	May 1982	148.50	101.45	147.91	206.23	66.65	107.89	166.05
378	June 1982	110.78	75.70	110.41	153.60	61.01	99.03	151.27
379	July 1982	111.98	76.77	111.69	154.90	62.24	97.91	154.37
380	Aug 1982	113.07	77.74	112.66	156.03	63.70	99.09	152.90
381	Sept 1982	114.04	78.49	113.60	157.00	65.21	100.91	153.98
382	Oct 1982	114.60	79.03	114.14	157.69	67.41	108.99	165.07
383	Nov 1982	113.87	78.41	113.67	157.37	88.82	142.12	223.75
384	Dec 1982	115.16	79.21	114.95	158.89	79.98	128.05	193.75
385	Jan 1983	1.25	0.25	0.75	2.48	0.17	0.61	1.90
386	Feb 1983	1.29	0.27	0.78	2.56	0.18	0.63	1.94
387	Mar 1983	111.76	77.09	112.19	156.29	78.57	123.82	194.41
388	Apr 1983	112.66	77.92	112.99	157.31	74.18	119.77	182.63
389	May 1983	113.97	79.21	114.10	158.82	70.85	117.76	174.86
390	June 1983	106.10	74.18	106.03	147.67	68.30	103.53	162.13
391	July 1983	116.70	81.48	116.62	162.17	66.41	108.10	166.88
392	Aug 1983	117.72	82.09	117.54	163.39	67.97	107.12	161.29
393	Sept 1983	117.83	82.03	117.63	163.40	76.74	120.27	183.16
394	Oct 1983	117.97	82.03	117.88	163.53	84.95	133.04	207.24
395	Nov 1983	118.63	82.60	118.70	164.81	89.04	142.71	224.56
396	Dec 1983	120.78	84.23	120.74	167.35	72.65	113.38	171.38

Appendix I5. Simulated concentrations of tetrachloroethylene in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; $P_{2.5}$, Monte Carlo simulation results for the 2.5 percentile; P_{50}, Monte Carlo simulation results for the 50 percentile; $P_{97.5}$, Monte Carlo simulation results for the 97.5 percentile; WTP, water treatment plant; Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Dec, December]

Stress period	Month and year	Calibrated PCE concentration, in µg/L[1]	Range of concentrations derived from Monte Carlo simulations[2]					
			Monte Carlo simulation (Scenario 1)[3]			Monte Carlo simulation (Scenario 2)[4]		
			$P_{2.5}$, in µg/L	P_{50}, in µg/L	$P_{97.5}$, in µg/L	$P_{2.5}$, in µg/L	P_{50}, in µg/L	$P_{97.5}$, in µg/L
397	Jan 1984	132.87	92.63	133.27	185.03	103.04	159.84	247.01
398	Feb 1984	180.39	126.52	180.97	249.43	94.25	150.35	230.69
399	Mar 1984	183.02	128.61	183.55	252.50	99.38	159.70	240.42
400	Apr 1984	151.46	106.37	151.54	208.97	97.90	155.71	236.45
401	May 1984	153.42	107.63	153.20	211.58	92.85	146.63	220.85
402	June 1984	182.13	127.45	181.99	250.57	94.11	152.75	228.36
403	July 1984	156.39	109.41	156.40	214.58	101.95	160.97	234.39
404	Aug 1984	170.47	106.73	158.25	238.65	108.76	168.54	261.54
405	Sept 1984	181.22	113.28	168.51	253.93	117.53	184.30	295.64
406	Oct 1984	173.73	108.42	161.84	245.02	120.12	182.33	281.84
407	Nov 1984	173.77	108.41	161.92	245.70	124.18	187.60	287.36
408	Dec 1984	173.18	107.82	161.69	246.06	127.85	193.50	301.23
409	Jan 1985	176.12	109.98	164.71	251.48	122.98	187.00	293.19
410	Feb 1985	3.64	1.13	2.67	6.57	0.47	1.41	3.74
411	Mar 1985	8.71	3.21	6.58	14.79	8.83	20.01	41.59
412	Apr 1985	8.09	2.99	6.16	13.70	9.00	20.41	42.30
413	May 1985	4.76	1.50	3.46	8.36	0.58	1.68	4.47
414	June 1985	5.14	1.65	3.80	9.21	0.64	1.81	4.78
415	July 1985	5.54	1.80	4.12	10.04	0.69	1.96	5.12
416	Aug 1985	6.01	1.98	4.50	10.97	0.76	2.14	5.56
417	Sept 1985	6.50	2.19	4.88	11.89	0.83	2.30	6.03
418	Oct 1985	7.06	2.43	5.33	12.88	0.92	2.53	6.53
419	Nov 1985	7.64	2.68	5.78	13.90	1.02	2.76	7.07
420	Dec 1985	8.27	2.93	6.32	14.99	1.13	3.00	7.59
421	Jan 1986	8.85	3.18	6.82	15.87	1.24	3.22	8.14
422	Feb 1986	9.42	3.45	7.30	16.67	1.35	3.46	8.69
423	Mar 1986	12.14	4.55	9.43	21.18	1.85	4.67	11.50
424	Apr 1986	10.83	4.09	8.44	18.71	1.64	4.08	9.90
425	May 1986	11.56	4.42	9.06	19.63	1.79	4.41	10.49
426	June 1986	12.28	4.77	9.70	20.59	1.94	4.76	11.08
427	July 1986	13.06	5.14	10.35	21.75	2.11	5.12	11.77
428	Aug 1986	13.84	5.54	11.01	23.04	2.29	5.51	12.50
429	Sept 1986	14.61	5.90	11.70	24.30	2.49	5.89	13.19
430	Oct 1986	15.42	6.28	12.41	25.59	2.71	6.33	13.94
431	Nov 1986	16.21	6.66	13.11	26.70	2.93	6.73	14.77
432	Dec 1986	17.03	7.06	13.77	27.86	3.17	7.20	15.65
433	Jan 1987	17.85	7.47	14.46	29.04	3.41	7.66	16.46
434	Feb 1987	18.49	7.82	15.02	29.91	3.62	8.04	17.16
435	Mar 1987				WTP closed			

[1]Results from Faye (2008) and reported in Maslia et al. (2007, Appendix A2)

[2]$P_{97.5}$ and $P_{2.5}$ represent the upper and lower bound, respectively, of 95 percent of Monte Carlo simulations; for a Gaussian (normal) distribution, the median (P_{50}) should equal the mean value

[3]Scenario 1 Monte Carlo simulation is for pumping uncertainty excluded

[4]Scenario 2 Monte Carlo simulation is for pumping uncertainty included

Appendix I —Reconstructed (Simulated) Mean Monthly Concentrations of Selected Water-Supply Wells, for Tetrachloroethylene (PCE), Trichloroethylene (TCE), *trans*-1,2-Dichloroethylene (1,2-tDCE), Vinyl Chloride (VC), and Benzene, Hadnot Point-Holcomb Boulevard Study Area

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
1–6	Jan. 1942–June 1942	—	—	—	—	—	—	—	—	—	—	—	—
7–114	July 1942–June 1951	—	—	0	0	0	—	—	—	—	0	0	0
115	July 1951	—	—	0	1	0	—	—	—	—	0	0	0
116	Aug. 1951	—	—	0	2	0	—	—	—	—	0	0	0
117	Sept. 1951	—	—	0	4	0	—	—	—	—	0	0	0
118	Oct. 1951	—	—	0	5	0	—	—	—	—	0	0	0
119	Nov. 1951	—	—	0	9	0	—	—	—	—	0	0	0
120	Dec. 1951	—	—	0	12	0	—	—	—	—	0	0	0
121	Jan. 1952	—	—	0	18	0	—	—	—	—	0	0	0
122	Feb. 1952	—	—	0	23	0	—	—	—	—	0	0	0
123	Mar. 1952	—	—	0	27	0	—	—	—	—	0	0	0
124	Apr. 1952	—	—	0	34	0	—	—	—	—	0	0	0
125	May 1952	—	—	0	42	0	—	—	—	—	0	0	0
126	June 1952	—	—	0	49	0	—	—	—	—	0	0	0
127	July 1952	—	—	0	58	0	—	—	—	—	0	0	0
128	Aug. 1952	—	—	0	71	0	—	—	—	—	0	0	0
129	Sept. 1952	—	—	0	81	0	—	—	—	—	0	0	0
130	Oct. 1952	—	—	0	92	0	—	—	—	—	0	0	0
131	Nov. 1952	—	—	0	106	0	—	—	—	—	0	0	0
132	Dec. 1952	—	—	0	120	0	—	—	—	—	0	0	0
133	Jan. 1953	—	—	0	136	0	—	—	—	—	0	0	0
134	Feb. 1953	—	—	0	148	0	—	—	—	—	0	0	0
135	Mar. 1953	—	—	0	157	0	—	—	—	—	0	0	0
136	Apr. 1953	—	—	0	170	0	—	—	—	—	0	0	0
137	May 1953	—	—	0	181	0	—	—	—	—	0	0	0
138	June 1953	—	—	0	191	0	—	—	—	—	0	0	0
139	July 1953	—	—	0	201	0	—	—	—	—	0	0	0
140	Aug. 1953	—	—	0	218	0	—	—	—	—	0	0	0
141	Sept. 1953	—	—	0	229	0	—	—	—	—	0	0	0
142	Oct. 1953	—	—	0	238	0	—	—	—	—	0	0	0
143	Nov. 1953	—	—	0	252	0	—	—	—	—	0	0	0
144	Dec. 1953	—	—	0	264	0	—	—	—	—	0	0	0
145	Jan. 1954	—	—	0	275	0	—	—	—	—	0	0	0
146	Feb. 1954	—	—	0	283	0	—	—	—	—	0	0	0
147	Mar. 1954	—	—	0	287	0	—	—	—	—	0	0	0
148	Apr. 1954	—	—	0	296	0	—	—	—	—	0	0	0
149	May 1954	—	—	0	303	0	—	—	—	—	0	0	0
150	June 1954	—	—	0	311	0	—	—	—	—	0	0	0

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2- dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Handot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
151	July 1954	—	—	0	320	0	—	—	—	—	0	0	0
152	Aug. 1954	—	—	0	334	0	—	—	—	—	0	0	0
153	Sept. 1954	—	—	0	346	—	—	—	—	—	0	0	—
154	Oct. 1954	—	—	0	356	—	—	—	—	—	0	0	—
155	Nov. 1954	—	—	0	375	—	—	—	—	—	0	0	—
156	Dec. 1954	—	—	0	388	—	—	—	—	—	0	0	—
157	Jan. 1955	—	—	0	403	—	—	—	—	—	0	0	—
158	Feb. 1955	—	—	0	413	—	—	—	—	—	0	—	—
159	Mar. 1955	—	—	0	419	—	—	—	—	—	0	—	—
160	Apr. 1955	—	—	0	433	—	—	—	—	—	0	—	—
161	May 1955	—	—	0	443	—	—	—	—	—	1	—	—
162	June 1955	—	—	0	453	—	—	—	—	—	1	—	—
163	July 1955	—	—	0	464	0	—	—	—	—	1	0	0
164	Aug. 1955	—	—	0	484	0	—	—	—	—	1	0	0
165	Sept. 1955	—	—	0	514	0	—	—	—	—	1	0	0
166	Oct. 1955	—	—	0	524	0	—	—	—	—	1	0	0
167	Nov. 1955	—	—	0	532	1	—	—	—	—	1	0	0
168	Dec. 1955	—	—	0	537	1	—	—	—	—	1	0	0
169	Jan. 1956	—	—	0	543	1	—	—	—	—	1	0	0
170	Feb. 1956	—	—	0	547	1	—	—	—	—	1	0	0
171	Mar. 1956	—	—	1	547	1	—	—	—	—	1	0	0
172	Apr. 1956	—	—	1	548	1	—	—	—	—	1	0	0
173	May 1956	—	—	1	552	1	—	—	—	—	1	0	0
174	June 1956	—	—	1	554	1	—	—	—	—	1	0	0
175	July 1956	—	—	1	557	2	—	—	—	—	2	—	0
176	Aug. 1956	—	—	1	565	2	—	—	—	—	2	—	0
177	Sept. 1956	—	—	1	571	2	—	—	—	—	2	—	1
178	Oct. 1956	—	—	1	576	2	—	—	—	—	2	—	1
179	Nov. 1956	—	—	1	584	2	—	—	—	—	2	—	1
180	Dec. 1956	—	—	1	588	3	—	—	—	—	2	—	1
181	Jan. 1957	—	—	1	596	3	—	—	—	—	2	—	1
182	Feb. 1957	—	—	1	598	3	—	—	—	—	2	—	1
183	Mar. 1957	—	—	1	598	4	—	—	—	—	2	—	1
184	Apr. 1957	—	—	1	602	4	—	—	—	—	3	—	1
185	May 1957	—	—	1	605	4	—	—	—	—	3	0	1
186	June 1957	—	—	1	608	5	—	—	—	—	3	0	1
187	July 1957	—	—	1	609	5	—	—	—	—	3	0	1
188	Aug. 1957	—	—	2	613	5	—	—	—	—	3	0	1
189	Sept. 1957	—	—	2	619	6	—	—	—	—	3	0	1
190	Oct. 1957	—	—	2	619	6	—	—	—	—	3	0	1
191	Nov. 1957	—	—	2	627	7	—	—	—	—	4	0	1
192	Dec. 1957	—	—	2	631	7	—	—	—	—	4	0	1

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2- dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Handot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
193	Jan. 1958	—	—	2	637	7	—	—	—	—	4	0	1
194	Feb. 1958	—	—	2	639	8	—	—	—	—	4	0	1
195	Mar. 1958	—	—	2	638	8	—	—	—	—	4	0	2
196	Apr. 1958	—	—	2	640	9	—	—	—	—	5	0	2
197	May 1958	—	—	2	642	10	—	—	—	—	5	0	2
198	June 1958	—	—	2	643	10	—	—	—	—	5	0	2
199	July 1958	—	—	3	644	11	—	—	—	—	5	0	2
200	Aug. 1958	—	—	3	646	11	—	—	—	—	5	0	2
201	Sept. 1958	—	—	3	650	12	—	—	—	—	6	0	2
202	Oct. 1958	—	—	3	651	13	—	—	—	—	6	0	2
203	Nov. 1958	—	—	3	656	14	—	—	—	—	6	0	2
204	Dec. 1958	—	—	3	657	14	—	—	—	—	6	0	2
205	Jan. 1959	—	—	3	658	15	—	—	—	—	7	0	2
206	Feb. 1959	—	—	3	658	15	—	—	—	—	7	0	2
207	Mar. 1959	—	—	3	655	16	—	—	—	—	7	0	2
208	Apr. 1959	—	—	3	654	17	—	—	—	—	7	0	2
209	May 1959	—	—	4	653	18	—	—	—	—	8	0	2
210	June 1959	—	—	4	650	18	—	—	—	—	8	0	2
211	July 1959	—	—	4	649	19	—	—	—	—	8	0	2
212	Aug. 1959	—	—	4	650	20	—	—	—	—	8	0	2
213	Sept. 1959	—	—	4	651	21	—	—	—	—	9	0	2
214	Oct. 1959	—	—	4	648	22	—	—	—	—	9	0	2
215	Nov. 1959	—	—	4	652	23	—	—	—	—	9	0	2
216	Dec. 1959	—	—	4	652	24	—	—	—	—	10	0	2
217	Jan. 1960	—	—	4	654	25	0	—	—	—	10	0	3
218	Feb. 1960	—	—	4	652	26	0	—	—	—	10	0	3
219	Mar. 1960	—	—	5	647	27	0	—	—	—	10	0	3
220	Apr. 1960	—	—	5	645	27	0	—	—	—	11	0	3
221	May 1960	—	—	5	643	28	1	—	—	—	11	0	3
222	June 1960	—	—	5	639	29	2	—	—	—	11	0	3
223	July 1960	—	—	5	640	30	3	—	—	—	11	0	3
224	Aug. 1960	—	—	5	638	31	6	—	—	—	12	0	3
225	Sept. 1960	—	—	5	637	32	9	—	—	—	12	0	3
226	Oct. 1960	—	—	5	632	33	14	—	—	—	12	0	3
227	Nov. 1960	—	—	5	632	33	19	—	—	—	13	0	3
228	Dec. 1960	—	—	5	630	34	25	—	—	—	13	0	3

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2- dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Handot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
229	Jan. 1961	—	—	5	629	34	32	—	—	—	14	0	3
230	Feb. 1961	—	—	5	626	35	41	—	—	—	14	0	3
231	Mar. 1961	—	—	5	621	35	51	—	—	—	14	0	3
232	Apr. 1961	—	—	5	621	36	63	—	—	—	15	0	3
233	May 1961	—	—	6	621	37	74	—	—	—	15	0	3
234	June 1961	—	—	6	622	38	88	—	—	—	15	0	3
235	July 1961	—	—	6	620	39	102	—	—	—	16	0	3
236	Aug. 1961	—	—	6	620	40	120	—	—	—	16	0	3
237	Sept. 1961	—	—	6	620	40	133	—	—	—	16	0	3
238	Oct. 1961	—	—	6	615	41	149	—	—	—	17	0	3
239	Nov. 1961	—	—	6	614	41	161	—	—	—	17	0	3
240	Dec. 1961	—	—	6	610	41	175	—	—	—	17	0	3
241	Jan. 1962	—	—	6	607	41	188	—	—	—	18	0	3
242	Feb. 1962	—	—	6	602	41	209	—	—	—	18	0	3
243	Mar. 1962	—	—	6	594	41	226	—	—	—	18	0	3
244	Apr. 1962	—	—	6	590	41	245	—	—	—	19	0	3
245	May 1962	—	—	6	588	41	258	—	—	—	19	0	3
246	June 1962	—	—	6	587	42	279	—	—	—	19	0	4
247	July 1962	—	—	7	585	43	300	—	—	—	20	0	4
248	Aug. 1962	—	—	7	584	44	325	—	—	—	20	0	4
249	Sept. 1962	—	—	7	583	45	339	—	—	—	20	0	4
250	Oct. 1962	—	—	7	577	45	357	—	—	—	21	0	4
251	Nov. 1962	—	—	7	574	45	370	—	—	—	21	0	4
252	Dec. 1962	—	—	7	571	45	382	—	—	—	22	0	4
253	Jan. 1963	—	—	7	569	45	395	—	—	—	22	0	4
254	Feb. 1963	—	—	7	566	45	412	—	—	—	22	0	4
255	Mar. 1963	—	—	7	559	45	424	—	—	—	22	0	4
256	Apr. 1963	—	—	7	553	45	438	—	—	—	23	0	4
257	May 1963	—	—	7	550	45	448	—	—	—	23	0	4
258	June 1963	—	—	7	545	45	457	—	—	—	24	0	4
259	July 1963	—	—	7	540	45	466	—	—	—	24	0	4
260	Aug. 1963	—	—	8	538	45	483	—	—	—	25	0	4
261	Sept. 1963	—	—	8	536	45	492	—	—	—	25	0	4
262	Oct. 1963	—	—	8	532	45	504	—	—	—	25	0	4
263	Nov. 1963	—	—	8	531	45	511	—	—	—	26	0	4
264	Dec. 1963	—	—	8	529	45	517	—	—	—	26	0	4

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2- dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Handot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
265	Jan. 1964	—	—	8	529	45	524	—	—	—	27	0	4
266	Feb. 1964	—	—	8	527	45	534	—	—	—	27	0	4
267	Mar. 1964	—	—	8	522	45	539	—	—	—	27	0	4
268	Apr. 1964	—	—	8	518	45	547	—	—	—	28	0	4
269	May 1964	—	—	8	516	45	552	—	—	—	28	0	4
270	June 1964	—	—	8	512	45	556	—	—	—	28	0	4
271	July 1964	—	—	8	510	46	563	—	—	—	29	0	4
272	Aug. 1964	—	—	8	508	46	573	—	—	—	29	0	4
273	Sept. 1964	—	—	8	507	46	580	—	—	—	30	0	5
274	Oct. 1964	—	—	8	505	47	589	—	—	—	30	0	5
275	Nov. 1964	—	—	9	503	47	589	—	—	—	31	0	5
276	Dec. 1964	—	—	9	501	46	591	—	—	—	31	0	5
277	Jan. 1965	—	—	9	499	46	588	—	—	—	31	0	5
278	Feb. 1965	—	—	9	497	46	592	—	—	—	32	0	5
279	Mar. 1965	—	—	9	492	46	594	—	—	—	32	0	5
280	Apr. 1965	—	—	9	487	45	595	—	—	—	32	0	5
281	May 1965	—	—	9	484	45	594	—	—	—	33	0	5
282	June 1965	—	—	9	483	46	597	—	—	—	33	0	5
283	July 1965	—	—	9	481	46	600	—	—	—	33	0	5
284	Aug. 1965	—	—	9	478	46	604	—	—	—	34	0	5
285	Sept. 1965	—	—	9	475	46	601	—	—	—	34	1	5
286	Oct. 1965	—	—	9	470	45	600	—	—	—	35	1	5
287	Nov. 1965	—	—	9	468	45	594	—	—	—	35	1	5
288	Dec. 1965	—	—	9	465	44	588	—	—	—	36	1	5
289	Jan. 1966	—	—	9	464	43	586	—	—	—	36	1	5
290	Feb. 1966	—	—	9	462	43	589	—	—	—	36	1	5
291	Mar. 1966	—	—	9	458	43	590	—	—	—	36	2	5
292	Apr. 1966	—	—	9	455	42	591	—	—	—	37	2	5
293	May 1966	—	—	9	454	43	591	—	—	—	37	2	5
294	June 1966	—	—	9	452	42	593	—	—	—	38	2	5
295	July 1966	—	—	9	452	43	598	—	—	—	38	3	5
296	Aug. 1966	—	—	9	453	43	610	—	—	—	39	3	5
297	Sept. 1966	—	—	10	454	44	613	—	—	—	39	3	5
298	Oct. 1966	—	—	10	450	44	615	—	—	—	39	4	5
299	Nov. 1966	—	—	10	450	43	612	—	—	—	40	4	5
300	Dec. 1966	—	—	10	451	43	613	—	—	—	41	4	5

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2- dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Handot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
301	Jan. 1967	—	—	10	452	43	613	—	—	—	42	4	5
302	Feb. 1967	—	—	10	453	43	619	—	—	—	42	4	5
303	Mar. 1967	—	—	10	449	43	619	—	—	—	42	4	5
304	Apr. 1967	—	—	10	449	42	623	—	—	—	43	5	5
305	May 1967	—	—	10	448	42	622	—	—	—	43	5	5
306	June 1967	—	—	10	447	42	623	—	—	—	43	5	5
307	July 1967	—	—	10	448	43	630	—	—	—	44	5	5
308	Aug. 1967	—	—	11	452	43	642	—	—	—	45	5	5
309	Sept. 1967	—	—	11	454	43	646	—	—	—	45	5	6
310	Oct. 1967	—	—	11	453	43	651	—	—	—	46	5	6
311	Nov. 1967	—	—	11	457	44	652	—	—	—	47	6	6
312	Dec. 1967	—	—	11	461	44	657	—	—	—	47	6	6
313	Jan. 1968	—	—	11	463	44	656	—	—	—	48	6	6
314	Feb. 1968	—	—	11	463	44	657	—	—	—	48	6	6
315	Mar. 1968	—	—	11	459	44	654	—	—	—	48	6	6
316	Apr. 1968	—	—	11	459	44	654	—	—	—	49	6	6
317	May 1968	—	—	11	458	44	648	—	—	—	49	6	6
318	June 1968	—	—	11	456	44	646	—	—	—	49	7	6
319	July 1968	—	—	11	457	44	649	—	—	—	50	7	6
320	Aug. 1968	—	—	11	459	44	655	—	—	—	51	7	6
321	Sept. 1968	—	—	11	460	45	655	—	—	—	51	7	6
322	Oct. 1968	—	—	11	460	45	659	—	—	—	51	7	6
323	Nov. 1968	—	—	12	465	45	658	—	—	—	52	8	6
324	Dec. 1968	—	—	12	467	45	658	—	—	—	53	8	6
325	Jan. 1969	—	—	12	469	45	653	—	—	—	53	8	6
326	Feb. 1969	—	—	12	469	45	654	—	—	—	53	8	6
327	Mar. 1969	—	—	12	466	45	651	—	—	—	53	8	6
328	Apr. 1969	—	—	12	466	46	652	—	—	—	54	8	6
329	May 1969	—	—	12	466	46	647	—	—	—	55	9	6
330	June 1969	—	—	12	466	46	648	—	—	—	55	8	6
331	July 1969	—	—	12	467	47	647	—	—	—	56	8	6
332	Aug. 1969	—	—	12	467	47	636	—	—	—	56	10	6
333	Sept. 1969	—	—	12	466	48	609	—	—	—	56	11	6
334	Oct. 1969	—	—	12	459	48	582	—	—	—	55	12	6
335	Nov. 1969	—	—	12	452	48	581	—	—	—	57	13	6
336	Dec. 1969	—	—	12	452	48	576	—	—	—	58	14	6

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2- dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Handot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
337	Jan. 1970	—	—	12	453	48	566	—	—	—	59	15	6
338	Feb. 1970	—	—	12	454	48	563	—	—	—	59	16	6
339	Mar. 1970	—	—	12	452	48	556	—	—	—	59	17	6
340	Apr. 1970	—	—	12	451	47	550	—	—	—	60	18	6
341	May 1970	—	—	12	452	47	540	—	—	—	61	18	6
342	June 1970	—	—	11	451	47	533	—	—	—	61	19	6
343	July 1970	—	—	11	453	47	529	—	—	—	62	20	6
344	Aug. 1970	—	—	12	457	48	529	—	—	—	63	20	6
345	Sept. 1970	—	—	11	459	49	524	—	—	—	64	21	6
346	Oct. 1970	—	—	11	459	48	519	—	—	—	64	22	6
347	Nov. 1970	—	—	11	461	48	509	—	—	—	65	23	6
348	Dec. 1970	—	—	11	463	48	502	—	—	—	66	24	6
349	Jan. 1971	—	—	11	466	48	493	—	—	—	67	25	6
350	Feb. 1971	—	—	11	468	48	490	—	—	—	67	26	6
351	Mar. 1971	—	—	11	467	48	485	—	—	—	67	26	6
352	Apr. 1971	—	—	11	466	48	481	—	—	—	68	27	6
353	May 1971	—	—	11	468	48	474	—	—	—	69	28	6
354	June 1971	—	—	11	470	48	470	—	—	—	70	29	6
355	July 1971	—	—	11	472	48	468	—	—	—	70	29	7
356	Aug. 1971	—	—	11	474	49	468	—	—	—	71	30	7
357	Sept. 1971	—	—	11	477	49	464	—	—	—	72	31	7
358	Oct. 1971	—	—	11	482	50	466	—	—	—	73	31	7
359	Nov. 1971	—	—	11	484	50	461	—	—	—	74	32	7
360	Dec. 1971	—	—	11	488	50	454	—	—	—	75	33	7
361	Jan. 1972	—	—	11	491	50	447	—	—	—	76	34	7
362	Feb. 1972	—	—	11	493	50	446	—	—	—	76	35	7
363	Mar. 1972	—	—	11	492	50	441	—	—	—	77	36	7
364	Apr. 1972	—	—	11	489	50	437	—	—	—	78	37	7
365	May 1972	—	—	10	490	50	430	—	—	—	79	38	7
366	June 1972	—	—	10	490	50	426	—	—	—	79	38	7
367	July 1972	0	1	10	490	50	422	—	69	8	80	39	7
368	Aug. 1972	0	9	10	490	50	420	—	634	16	81	40	7
369	Sept. 1972	0	27	10	490	50	415	—	1102	25	82	41	7
370	Oct. 1972	0	31	10	487	50	410	—	1491	33	82	42	7
371	Nov. 1972	1	94	10	487	50	404	—	1815	41	83	42	7
372	Dec. 1972	2	215	10	487	50	398	—	2083	49	84	43	7

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[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
373	Jan. 1973	2	283	10	487	50	392	—	2,306	57	85	44	7
374	Feb. 1973	3	391	10	486	49	389	—	2,492	64	85	45	7
375	Mar. 1973	5	538	9	483	49	383	—	2,646	72	85	46	7
376	Apr. 1973	6	636	9	479	49	381	—	2,773	80	87	46	7
377	May 1973	8	771	9	477	49	374	—	2,880	87	87	48	7
378	June 1973	10	954	9	477	49	372	—	2,968	95	88	48	7
379	July 1973	13	1,187	9	474	49	367	—	3,041	102	88	49	7
380	Aug. 1973	18	1,530	9	472	49	366	—	3,102	110	89	50	8
381	Sept. 1973	22	1,761	9	471	49	362	—	3,152	117	90	51	8
382	Oct. 1973	22	1,738	9	467	48	358	—	3,194	124	91	52	8
383	Nov. 1973	31	2,209	9	465	47	348	—	3,229	131	92	52	7
384	Dec. 1973	39	2,637	9	465	47	344	—	3,258	139	92	52	8
385	Jan. 1974	43	2,776	8	465	47	339	—	3,282	146	93	52	8
386	Feb. 1974	48	2,998	8	463	46	337	—	3,302	152	93	53	8
387	Mar. 1974	54	3,234	8	461	46	332	—	3,318	159	93	53	8
388	Apr. 1974	57	3,344	8	456	46	330	—	3,332	166	95	54	8
389	May 1974	62	3,501	8	457	46	326	—	3,344	173	95	53	8
390	June 1974	68	3,711	8	455	47	324	—	3,353	179	96	54	8
391	July 1974	75	3,947	8	453	47	321	—	3,361	186	97	55	8
392	Aug. 1974	84	4,255	8	453	47	322	—	3,368	192	98	55	8
393	Sept. 1974	91	4,406	8	452	47	318	—	3,373	199	98	55	8
394	Oct. 1974	90	4,256	8	449	47	315	—	3,377	205	99	57	8
395	Nov. 1974	103	4,749	8	446	46	308	—	3,381	211	100	57	8
396	Dec. 1974	114	5,039	8	444	46	304	—	3,384	217	101	58	8
397	Jan. 1975	119	5,061	8	444	46	300	—	3,387	223	102	58	8
398	Feb. 1975	126	5,205	7	443	45	298	—	3,389	229	102	59	8
399	Mar. 1975	133	5,338	7	438	45	293	—	3,391	235	102	60	8
400	Apr. 1975	136	5,372	7	434	45	292	—	3,392	241	103	60	8
402	May 1975	141	5,425	7	433	45	288	—	3,394	247	104	60	8
402	June 1975	147	5,550	7	431	45	286	—	3,395	253	104	61	8
403	July 1975	154	5,677	7	431	45	285	—	3,395	258	105	60	9
404	Aug. 1975	163	5,840	7	429	45	285	—	3,396	264	106	61	9
405	Sept. 1975	168	5,899	7	432	46	285	—	3,397	270	107	60	9
406	Oct. 1975	165	5,647	7	430	46	283	—	3,397	275	108	62	9
407	Nov. 1975	178	6,061	7	428	46	278	—	3,398	280	109	62	9
408	Dec. 1975	188	6,208	7	427	46	274	—	3,398	286	110	63	9

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2- dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Handot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
409	Jan. 1976	193	6,211	7	425	45	271	—	3,398	291	111	64	9
410	Feb. 1976	199	6,297	7	423	44	269	—	3,398	296	111	65	9
411	Mar. 1976	206	6,390	7	418	44	267	—	3,399	301	111	66	9
412	Apr. 1976	209	6,374	7	415	43	265	—	3,399	306	113	67	9
413	May 1976	213	6,411	6	415	43	263	—	3,399	311	113	67	9
414	June 1976	220	6,490	6	416	43	263	—	3,399	316	113	67	9
415	July 1976	226	6,574	6	415	43	263	—	3,399	321	114	67	9
416	Aug. 1976	234	6,700	6	417	43	265	—	3,399	326	116	68	9
417	Sept. 1976	239	6,724	6	419	44	265	—	3,399	331	117	68	9
418	Oct. 1976	234	6,484	6	418	44	266	—	3,399	335	117	69	9
419	Nov. 1976	247	6,792	6	419	44	263	—	3,400	340	119	70	9
420	Dec. 1976	256	6,915	6	421	43	262	—	3,400	345	120	70	9
421	Jan. 1977	258	6,860	6	422	43	259	—	3,400	349	121	71	9
422	Feb. 1977	262	6,906	6	420	43	260	—	3,400	354	121	72	9
423	Mar. 1977	267	6,933	6	418	43	258	—	3,400	358	121	72	9
424	Apr. 1977	267	6,881	6	417	42	258	—	3,399	363	122	73	9
425	May 1977	270	6,885	6	418	42	257	—	3,367	368	123	73	9
426	June 1977	274	6,917	6	417	42	257	—	3,341	372	124	74	9
427	July 1977	278	6,957	6	416	42	256	—	3,320	377	124	74	9
428	Aug. 1977	283	7,032	6	417	42	258	—	3,302	382	126	75	9
429	Sept. 1977	286	7,027	6	418	42	258	—	3,287	386	126	76	9
430	Oct. 1977	279	6,771	6	419	42	260	—	3,274	390	127	76	9
431	Nov. 1977	291	7,042	6	421	42	259	—	3,264	395	129	76	9
432	Dec. 1977	297	7,107	6	423	42	258	—	3,255	399	129	77	9
433	Jan. 1978	297	7,039	6	427	—	259	—	3,248	404	131	78	—
434	Feb. 1978	300	7,055	6	427	—	261	—	3,242	408	131	80	—
435	Mar. 1978	303	7,062	6	425	—	261	—	3,238	412	131	81	—
436	Apr. 1978	302	6,998	6	427	—	264	—	3,233	416	133	81	—
437	May 1978	303	6,982	6	428	—	264	—	3,230	420	134	82	—
438	June 1978	306	6,998	6	427	—	263	—	3,227	424	135	83	—
439	July 1978	310	7,039	6	427	—	264	—	3,225	428	136	84	—
440	Aug. 1978	314	7,095	6	430	—	268	—	3,223	432	137	85	—
441	Sept. 1978	316	7,086	6	431	—	268	—	3,222	436	138	86	—
442	Oct. 1978	308	6,849	6	431	—	270	—	3,220	440	138	87	—
443	Nov. 1978	318	7,072	6	434	—	269	—	3,219	443	140	88	—
444	Dec. 1978	323	7,135	—	438	—	269	—	3,218	447	143	90	—

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2- dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Handot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
445	Jan. 1979	322	7,062	—	444	—	—	—	3,218	449	145	91	—
446	Feb. 1979	324	7,068	—	448	—	—	—	3,173	451	146	93	—
447	Mar. 1979	325	7,066	—	449	—	—	—	3,118	452	148	95	—
448	Apr. 1979	324	6,995	—	—	—	—	—	3,073	453	—	97	—
449	May 1979	324	6,968	—	—	—	—	—	3,035	454	—	98	—
450	June 1979	324	6,958	—	—	—	—	—	3,004	455	—	99	—
451	July 1979	326	6,969	—	—	—	212	—	2,978	456	—	100	—
452	Aug. 1979	329	7,015	—	—	—	219	—	2,956	457	—	—	—
453	Sept. 1979	330	6,989	—	—	30	224	—	2,938	459	—	100	11
454	Oct. 1979	322	6,756	—	—	29	230	—	2,923	460	—	101	10
455	Nov. 1979	329	6,934	—	357	29	229	—	2,911	461	141	102	10
456	Dec. 1979	332	6,977	—	359	29	230	—	2,901	462	145	102	10
457	Jan. 1980	331	6,915	—	363	29	231	—	2,892	463	148	103	10
458	Feb. 1980	333	6,943	—	365	28	237	—	2,885	464	150	104	10
459	Mar. 1980	335	6,964	—	366	29	243	—	2,898	466	151	104	10
460	Apr. 1980	334	6,912	—	369	28	249	—	2,921	467	154	106	10
461	May 1980	333	6,879	—	374	29	252	—	2,940	469	156	105	10
462	June 1980	334	6,888	—	376	29	255	—	2,956	471	158	106	10
463	July 1980	336	6,911	—	378	29	260	—	2,969	472	160	107	10
464	Aug. 1980	337	6,926	—	379	29	264	—	2,980	474	161	108	10
465	Sept. 1980	337	6,912	—	381	29	266	—	2,989	475	163	108	10
466	Oct. 1980	328	6,652	—	382	29	271	—	2,997	477	165	109	10
467	Nov. 1980	336	6,870	—	384	29	272	—	3,003	478	167	110	10
468	Dec. 1980	340	6,926	—	387	29	274	—	3,008	480	168	110	10
469	Jan. 1981	339	6,882	—	390	29	277	—	3,013	481	170	111	10
470	Feb. 1981	339	6,880	—	391	29	281	—	3,016	483	171	112	10
471	Mar. 1981	340	6,888	—	390	29	284	—	3,019	484	173	113	10
472	Apr. 1981	339	6,844	—	390	28	289	—	3,022	486	174	114	9
473	May 1981	339	6,844	—	393	28	294	—	3,024	487	175	114	9
474	June 1981	340	6,849	—	394	29	298	—	3,025	488	176	114	9
475	July 1981	342	6,879	—	397	29	305	—	3,027	490	178	114	10
476	Aug. 1981	344	6,930	—	403	30	314	—	3,058	495	180	113	10
477	Sept. 1981	345	6,928	—	405	30	318	—	3,206	499	182	115	10
478	Oct. 1981	337	6,730	—	—	30	327	—	3,329	504	—	116	10
479	Nov. 1981	345	6,921	—	393	30	326	—	3,431	508	182	117	10
480	Dec. 1981	348	6,984	—	394	29	327	—	3,516	513	184	117	10

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2- dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Handot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
481	Jan. 1982	349	6,975	—	400	29	336	—	3,587	517	185	117	10
482	Feb. 1982	350	6,996	—	405	30	346	—	3,646	521	187	118	10
483	Mar. 1982	351	7,008	—	405	30	350	—	3,694	526	189	118	10
484	Apr. 1982	350	6,970	—	406	30	356	—	3,735	530	190	119	10
485	May 1982	350	6,958	—	408	30	358	—	3,769	534	191	120	10
486	June 1982	350	6,964	—	409	30	362	—	3,796	538	193	120	10
487	July 1982	351	6,975	—	410	30	364	—	3,820	542	194	120	10
488	Aug. 1982	353	7,011	—	411	30	370	—	3,839	546	196	121	10
489	Sept. 1982	353	7,017	—	414	30	376	—	3,855	550	197	121	10
490	Oct. 1982	347	6,852	—	415	31	382	—	3,868	555	199	121	10
491	Nov. 1982	352	6,976	—	419	31	384	—	3,877	559	199	121	10
492	Dec. 1982	353	7,012	—	424	31	387	—	3,884	564	201	121	10
493	Jan. 1983	352	6,975	—	427	31	387	—	3,891	568	203	121	10
494	Feb. 1983	352	6,971	—	432	32	391	—	3,896	573	205	120	10
495	Mar. 1983	352	6,972	—	435	33	396	—	3,900	577	208	120	10
496	Apr. 1983	350	6,920	—	434	33	400	—	3,904	581	208	121	10
497	May 1983	350	6,903	—	435	33	399	—	3,907	585	210	121	10
498	June 1983	350	6,923	—	435	33	399	—	3,909	590	212	122	10
499	July 1983	352	6,958	—	434	34	400	—	3,911	594	213	122	10
500	Aug. 1983	353	6,985	—	435	34	402	—	3,913	598	214	123	10
501	Sept. 1983	353	6,976	—	438	34	399	—	3,915	602	215	123	10
502	Oct. 1983	346	6,809	—	441	34	403	—	3,927	606	216	123	10
503	Nov. 1983	352	6,963	—	447	35	—	—	3,945	611	217	123	10
504	Dec. 1983	353	7,004	—	454	35	—	—	3,961	615	219	123	10
505	Jan. 1984	353	6,988	—	464	—	—	—	3,973	620	220	125	—
506	Feb. 1984	353	6,992	—	472	35	370	—	3,984	624	222	124	10
507	Mar. 1984	353	6,998	—	477	35	383	—	3,993	628	226	124	10
508	Apr. 1984	352	6,969	—	481	35	403	—	4,000	632	225	124	10
509	May 1984	352	6,975	—	490	36	420	—	4,006	637	227	124	10
510	June 1984	352	6,975	—	494	37	433	—	4,011	641	230	124	10
511	July 1984	352	6,978	—	496	38	444	1	4,015	645	231	124	10
512	Aug. 1984	352	6,983	—	495	38	456	1	4,019	649	232	124	10
513	Sept. 1984	351	6,966	—	499	40	469	1	4,022	653	233	123	10
514	Oct. 1984	342	6,721	—	495	40	480	1	4,024	656	235	124	10
515	Nov. 1984	348	6,895	—	493	41	478	1	4,027	660	236	123	10
516	Dec. 1984	337	6,583	—	—	—	—	—	4,037	653	—	125	—

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2- dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Handot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
517	Jan. 1985	343	6,772	—	—	—	—	—	3,400	652	—	128	—
518	Feb. 1985	—	—	—	—	—	—	—	—	—	—	129	—
519	Mar. 1985	—	—	—	—	—	—	—	—	—	—	130	—
520	Apr. 1985	—	—	—	—	—	—	—	—	—	—	131	—
521	May 1985	—	—	—	—	—	—	—	—	—	—	132	—
522	June 1985	—	—	—	—	—	—	—	—	—	—	133	—
523	July 1985	—	—	—	—	—	—	—	—	—	—	133	—
524	Aug. 1985	—	—	—	—	—	—	—	—	—	—	133	—
525	Sept. 1985	—	—	—	—	—	—	—	—	—	—	133	—
526	Oct. 1985	—	—	—	—	—	—	—	—	—	—	133	—
527	Nov. 1985	—	—	—	—	—	—	—	—	—	—	133	—
528	Dec. 1985	—	—	—	—	—	—	—	—	—	—	134	—
529	Jan. 1986	—	—	—	—	—	—	—	—	—	—	135	—
530	Feb. 1986	—	—	—	—	—	—	—	—	—	—	136	—
531	Mar. 1986	—	—	—	—	—	—	—	—	—	—	136	—
532	Apr. 1986	—	—	—	—	—	—	—	—	—	—	137	—
533	May 1986	—	—	—	—	—	—	—	—	—	—	138	—
534	June 1986	—	—	—	—	—	—	—	—	—	—	138	—
535	July 1986	—	—	—	—	—	—	—	—	—	—	137	—
536	Aug. 1986	—	—	—	—	—	—	—	—	—	—	137	—
537	Sept. 1986	—	—	—	—	—	—	—	—	—	—	138	—
538	Oct. 1986	—	—	—	—	—	—	—	—	—	—	139	—
539	Nov. 1986	—	—	—	—	—	—	—	—	—	—	139	—
540	Dec. 1986	—	—	—	—	—	—	—	—	—	—	140	—
541	Jan. 1987	—	—	—	—	—	—	—	—	—	—	139	—
542	Feb. 1987	—	—	—	—	—	—	—	—	—	—	141	—
543	Mar. 1987	—	—	—	—	—	—	—	—	—	—	141	—
544	Apr. 1987	—	—	—	—	—	—	—	—	—	—	142	—
545	May 1987	—	—	—	—	—	—	—	—	—	—	142	—
546	June 1987	—	—	—	—	—	—	—	—	—	—	142	—
547	July 1987	—	—	—	—	—	—	—	—	—	—	142	—
548	Aug. 1987	—	—	—	—	—	—	—	—	—	—	143	—
549	Sept. 1987	—	—	—	—	—	—	—	—	—	—	143	—
550	Oct. 1987	—	—	—	—	—	—	—	—	—	—	145	—
551	Nov. 1987	—	—	—	—	—	—	—	—	—	—	145	—
552	Dec. 1987	—	—	—	—	—	—	—	—	—	—	146	—

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2- dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Handot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
553	Jan. 1988	—	—	—	—	—	—	—	—	—	—	146	—
554	Feb. 1988	—	—	—	—	—	—	—	—	—	—	147	—
555	Mar. 1988	—	—	—	—	—	—	—	—	—	—	147	—
556	Apr. 1988	—	—	—	—	—	—	—	—	—	—	148	—
557	May 1988	—	—	—	—	—	—	—	—	—	—	148	—
558	June 1988	—	—	—	—	—	—	—	—	—	—	148	—
559	July 1988	—	—	—	—	—	—	—	—	—	—	148	—
560	Aug. 1988	—	—	—	—	—	—	—	—	—	—	148	—
561	Sept. 1988	—	—	—	—	—	—	—	—	—	—	149	—
562	Oct. 1988	—	—	—	—	—	—	—	—	—	—	150	—
563	Nov. 1988	—	—	—	—	—	—	—	—	—	—	150	—
564	Dec. 1988	—	—	—	—	—	—	—	—	—	—	151	—
565	Jan. 1989	—	—	—	—	—	—	—	—	—	—	151	—
566	Feb. 1989	—	—	—	—	—	—	—	—	—	—	151	—
567	Mar. 1989	—	—	—	—	—	—	—	—	—	—	152	—
568	Apr. 1989	—	—	—	—	—	—	—	—	—	—	151	—
569	May 1989	—	—	—	—	—	—	—	—	—	—	152	—
570	June 1989	—	—	—	—	—	—	—	—	—	—	152	—
571	July 1989	—	—	—	—	—	—	—	—	—	—	152	—
572	Aug. 1989	—	—	—	—	—	—	—	—	—	—	151	—
573	Sept. 1989	—	—	—	—	—	—	—	—	—	—	151	—
574	Oct. 1989	—	—	—	—	—	—	—	—	—	—	152	—
575	Nov. 1989	—	—	—	—	—	—	—	—	—	—	153	—
576	Dec. 1989	—	—	—	—	—	—	—	—	—	—	153	—
577	Jan. 1990	—	—	—	—	—	—	—	—	—	—	154	—
578	Feb. 1990	—	—	—	—	—	—	—	—	—	—	155	—
579	Mar. 1990	—	—	—	—	—	—	—	—	—	—	155	—
580	Apr. 1990	—	—	—	—	—	—	—	—	—	—	156	—
581	May 1990	—	—	—	—	—	—	—	—	—	—	156	—
582	June 1990	—	—	—	—	—	—	—	—	—	—	157	—
583	July 1990	—	—	—	—	—	—	—	—	—	—	157	—
584	Aug. 1990	—	—	—	—	—	—	—	—	—	—	157	—
585	Sept. 1990	—	—	—	—	—	—	—	—	—	—	158	—
586	Oct. 1990	—	—	—	—	—	—	—	—	—	—	159	—
587	Nov. 1990	—	—	—	—	—	—	—	—	—	—	159	—
588	Dec. 1990	—	—	—	—	—	—	—	—	—	—	160	—

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2- dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Handot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
589	Jan. 1991	—	—	—	—	—	—	—	—	—	—	159	—
590	Feb. 1991	—	—	—	—	—	—	—	—	—	—	160	—
591	Mar. 1991	—	—	—	—	—	—	—	—	—	—	160	—
592	Apr. 1991	—	—	—	—	—	—	—	—	—	—	160	—
593	May 1991	—	—	—	—	—	—	—	—	—	—	161	—
594	June 1991	—	—	—	—	—	—	—	—	—	—	160	—
595	July 1991	—	—	—	—	—	—	—	—	—	—	159	—
596	Aug. 1991	—	—	—	—	—	—	—	—	—	—	160	—
597	Sept. 1991	—	—	—	—	—	—	—	—	—	—	160	—
598	Oct. 1991	—	—	—	—	—	—	—	—	—	—	161	—
599	Nov. 1991	—	—	—	—	—	—	—	—	—	—	162	—
600	Dec. 1991	—	—	—	—	—	—	—	—	—	—	162	—
601	Jan. 1992	—	—	—	—	—	—	—	—	—	—	162	—
602	Feb. 1992	—	—	—	—	—	—	—	—	—	—	164	—
603	Mar. 1992	—	—	—	—	—	—	—	—	—	—	164	—
604	Apr. 1992	—	—	—	—	—	—	—	—	—	—	165	—
605	May 1992	—	—	—	—	—	—	—	—	—	—	164	—
606	June 1992	—	—	—	—	—	—	—	—	—	—	165	—
607	July 1992	—	—	—	—	—	—	—	—	—	—	165	—
608	Aug. 1992	—	—	—	—	—	—	—	—	—	—	164	—
609	Sept. 1992	—	—	—	—	—	—	—	—	—	—	165	—
610	Oct. 1992	—	—	—	—	—	—	—	—	—	—	166	—
611	Nov. 1992	—	—	—	—	—	—	—	—	—	—	166	—
612	Dec. 1992	—	—	—	—	—	—	—	—	—	—	167	—
613	Jan. 1993	—	—	—	—	—	—	—	—	—	—	167	—
614	Feb. 1993	—	—	—	—	—	—	—	—	—	—	168	—
615	Mar. 1993	—	—	—	—	—	—	—	—	—	—	168	—
616	Apr. 1993	—	—	—	—	—	—	—	—	—	—	169	—
617	May 1993	—	—	—	—	—	—	—	—	—	—	169	—
618	June 1993	—	—	—	—	—	—	—	—	—	—	170	—
619	July 1993	—	—	—	—	—	—	—	—	—	—	170	—
620	Aug. 1993	—	—	—	—	—	—	—	—	—	—	171	—
621	Sept. 1993	—	—	—	—	—	—	—	—	—	—	170	—
622	Oct. 1993	—	—	—	—	—	—	—	—	—	—	170	—
623	Nov. 1993	—	—	—	—	—	—	—	—	—	—	171	—
624	Dec. 1993	—	—	—	—	—	—	—	—	—	—	172	—

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2- dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Handot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
625	Jan. 1994	—	—	—	—	—	—	—	—	—	—	172	—
626	Feb. 1994	—	—	—	—	—	—	—	—	—	—	172	—
627	Mar. 1994	—	—	—	—	—	—	—	—	—	—	172	—
628	Apr. 1994	—	—	—	—	—	—	—	—	—	—	173	—
629	May 1994	—	—	—	—	—	—	—	—	—	—	173	—
630	June 1994	—	—	—	—	—	—	—	—	—	—	174	—
631	July 1994	—	—	—	—	—	—	—	—	—	—	173	—
632	Aug. 1994	—	—	—	—	—	—	—	—	—	—	174	—
633	Sept. 1994	—	—	—	—	—	—	—	—	—	—	174	—
634	Oct. 1994	—	—	—	—	—	—	—	—	—	—	174	—
635	Nov. 1994	—	—	—	—	—	—	—	—	—	—	174	—
636	Dec. 1994	—	—	—	—	—	—	—	—	—	—	174	—
637	Jan. 1995	—	—	—	—	—	—	—	—	—	—	174	—
638	Feb. 1995	—	—	—	—	—	—	—	—	—	—	175	—
639	Mar. 1995	—	—	—	—	—	—	—	—	—	—	175	—
640	Apr. 1995	—	—	—	—	—	—	—	—	—	—	176	—
641	May 1995	—	—	—	—	—	—	—	—	—	—	176	—
642	June 1995	—	—	—	—	—	—	—	—	—	—	175	—
643	July 1995	—	—	—	—	—	—	—	—	—	—	176	—
644	Aug. 1995	—	—	—	—	—	—	—	—	—	—	176	—
645	Sept. 1995	—	—	—	—	—	—	—	—	—	—	177	—
646	Oct. 1995	—	—	—	—	—	—	—	—	—	—	177	—
647	Nov. 1995	—	—	—	—	—	—	—	—	—	—	177	—
648	Dec. 1995	—	—	—	—	—	—	—	—	—	—	178	—
649	Jan. 1996	—	—	—	—	—	—	—	—	—	—	177	—
650	Feb. 1996	—	—	—	—	—	—	—	—	—	—	178	—
651	Mar. 1996	—	—	—	—	—	—	—	—	—	—	178	—
652	Apr. 1996	—	—	—	—	—	—	—	—	—	—	179	—
653	May 1996	—	—	—	—	—	—	—	—	—	—	179	—
654–798	June 1996–June 2008	—	—	—	—	—	—	—	—	—	—	—	—

[1] Results obtained using MT3DMS model (Jones et al. 2013)

[2] Results obtained using linear control model, TechControl (Guan et al. 2013)

[3] Results obtained using LNAPL model, TechFlowMP (Jang et al. 2013)

Appendix J — Hadnot Point Water Treatment Plant Reconstructed (Simulated) Mean Monthly Finished Water Concentrations

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
1–6	Jan.–June 1942	—	—	—	—	—
7–12	July–Dec. 1942	0	0	*	*	0
13–120	Jan. 1943–Dec. 1951	0	0	0	0	0
121	Jan. 1952	0	1	0	0	0
122	Feb. 1952	0	0	0	0	0
123	Mar. 1952	0	0	0	0	0
124	Apr. 1952	0	1	0	0	0
125	May 1952	0	1	0	0	0
126	June 1952	0	1	0	0	0
127	July 1952	0	1	0	0	0
128	Aug. 1952	0	2	0	0	0
129	Sept. 1952	0	2	0	0	0
130	Oct. 1952	0	2	0	0	0
131	Nov. 1952	0	3	0	0	0
132	Dec. 1952	0	3	0	0	0
133	Jan. 1953	0	4	0	0	0
134	Feb. 1953	0	3	0	0	0
135	Mar. 1953	0	3	0	0	0
136	Apr. 1953	0	5	0	0	0
137	May 1953	0	4	0	0	0
138	June 1953	0	3	0	0	0
139	July 1953	0	4	0	0	0
140	Aug. 1953	0	6	0	0	0
141	Sept. 1953	0	5	0	0	0
142	Oct. 1953	0	4	0	0	0
143	Nov. 1953	0	7	0	0	0
144	Dec. 1953	0	6	0	0	0
145	Jan. 1954	0	6	0	0	0
146	Feb. 1954	0	5	0	0	0
147	Mar. 1954	0	4	0	0	0
148	Apr. 1954	0	7	0	0	0
149	May 1954	0	5	0	0	0
150	June 1954	0	7	0	0	0
151	July 1954	0	7	0	0	0
152	Aug. 1954	0	10	0	0	0
153	Sept. 1954	0	9	0	0	0
154	Oct. 1954	0	8	0	0	0
155	Nov. 1954	0	14	0	0	0
156	Dec. 1954	0	11	0	0	0

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.— Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
157	Jan. 1955	0	12	0	0	0
158	Feb. 1955	0	9	0	0	0
159	Mar. 1955	0	7	0	0	0
160	Apr. 1955	0	14	0	0	0
161	May 1955	0	11	0	0	0
162	June 1955	0	10	0	0	0
163	July 1955	0	10	0	0	0
164	Aug. 1955	0	14	0	0	0
165	Sept. 1955	0	13	0	0	0
166	Oct. 1955	0	11	0	0	0
167	Nov. 1955	0	19	0	0	0
168	Dec. 1955	0	14	0	0	0
169	Jan. 1956	0	15	0	0	0
170	Feb. 1956	0	11	0	0	0
171	Mar. 1956	0	8	0	0	0
172	Apr. 1956	0	17	0	0	0
173	May 1956	0	13	0	0	0
174	June 1956	0	11	0	0	0
175	July 1956	0	12	0	0	0
176	Aug. 1956	0	16	0	0	0
177	Sept. 1956	0	14	0	0	0
178	Oct. 1956	0	13	0	0	0
179	Nov. 1956	0	21	0	0	0
180	Dec. 1956	0	17	0	0	0
181	Jan. 1957	0	17	0	0	0
182	Feb. 1957	0	12	0	0	0
183	Mar. 1957	0	9	0	0	0
184	Apr. 1957	0	19	0	0	0
185	May 1957	0	14	0	0	0
186	June 1957	0	12	0	0	0
187	July 1957	0	12	0	0	0
188	Aug. 1957	0	16	0	0	0
189	Sept. 1957	0	14	0	0	0
190	Oct. 1957	0	12	0	0	0
191	Nov. 1957	0	20	0	0	0
192	Dec. 1957	0	16	0	0	0

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.— Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
193	Jan. 1958	0	17	0	0	0
194	Feb. 1958	0	12	0	0	0
195	Mar. 1958	0	9	0	0	0
196	Apr. 1958	0	18	0	0	0
197	May 1958	0	14	0	0	0
198	June 1958	0	12	0	0	0
199	July 1958	0	13	0	0	0
200	Aug. 1958	0	18	0	0	0
201	Sept. 1958	0	15	0	0	0
202	Oct. 1958	0	13	0	0	0
203	Nov. 1958	0	22	0	0	0
204	Dec. 1958	0	17	0	0	0
205	Jan. 1959	0	18	0	0	0
206	Feb. 1959	0	13	0	0	0
207	Mar. 1959	0	9	0	0	0
208	Apr. 1959	0	19	0	0	0
209	May 1959	0	14	0	0	0
210	June 1959	0	13	0	0	0
211	July 1959	0	13	0	0	0
212	Aug. 1959	0	18	0	0	0
213	Sept. 1959	0	15	0	0	0
214	Oct. 1959	0	14	0	0	0
215	Nov. 1959	0	22	0	0	0
216	Dec. 1959	0	17	0	0	0
217	Jan. 1960	0	16	0	0	0
218	Feb. 1960	0	11	0	0	0
219	Mar. 1960	0	9	0	0	0
220	Apr. 1960	0	16	0	0	0
221	May 1960	0	13	0	0	0
222	June 1960	0	12	0	0	0
223	July 1960	0	12	0	0	0
224	Aug. 1960	0	15	0	0	0
225	Sept. 1960	0	14	0	0	0
226	Oct. 1960	0	13	0	0	0
227	Nov. 1960	0	18	0	0	0
228	Dec. 1960	0	14	0	0	0

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.— Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
229	Jan. 1961	0	16	0	0	0
230	Feb. 1961	0	12	0	0	0
231	Mar. 1961	0	10	0	0	0
232	Apr. 1961	0	18	0	0	0
233	May 1961	0	15	0	0	0
234	June 1961	0	14	0	0	0
235	July 1961	0	14	0	0	0
236	Aug. 1961	0	19	0	0	0
237	Sept. 1961	0	17	0	0	0
238	Oct. 1961	0	17	0	0	0
239	Nov. 1961	0	19	0	0	0
240	Dec. 1961	0	15	0	0	0
241	Jan. 1962	0	16	0	0	0
242	Feb. 1962	0	14	0	0	0
243	Mar. 1962	0	12	0	0	0
244	Apr. 1962	0	19	0	0	0
245	May 1962	0	16	0	0	0
246	June 1962	0	15	0	0	0
247	July 1962	0	16	0	0	0
248	Aug. 1962	0	21	0	0	0
249	Sept. 1962	0	18	0	0	0
250	Oct. 1962	0	19	0	0	0
251	Nov. 1962	0	22	0	0	1
252	Dec. 1962	0	20	0	0	0
253	Jan. 1963	0	20	0	0	0
254	Feb. 1963	0	20	0	0	0
255	Mar. 1963	0	17	0	0	0
256	Apr. 1963	0	24	0	0	1
257	May 1963	0	19	0	0	0
258	June 1963	0	19	0	0	0
259	July 1963	0	19	0	0	0
260	Aug. 1963	0	24	0	0	1
261	Sept. 1963	0	21	0	0	0
262	Oct. 1963	0	22	0	0	0
263	Nov. 1963	0	24	0	0	1
264	Dec. 1963	0	21	0	0	1

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
265	Jan. 1964	0	22	0	0	1
266	Feb. 1964	0	21	0	0	0
267	Mar. 1964	0	18	0	0	0
268	Apr. 1964	0	25	0	0	1
269	May 1964	0	21	0	0	1
270	June 1964	0	20	0	0	0
271	July 1964	0	21	0	0	0
272	Aug. 1964	0	25	0	0	1
273	Sept. 1964	0	22	0	0	1
274	Oct. 1964	0	24	0	0	1
275	Nov. 1964	0	25	0	0	1
276	Dec. 1964	0	23	0	0	1
277	Jan. 1965	0	22	0	0	1
278	Feb. 1965	0	23	0	0	1
279	Mar. 1965	0	19	0	0	0
280	Apr. 1965	0	26	0	0	1
281	May 1965	0	21	0	0	1
282	June 1965	0	21	0	0	1
283	July 1965	0	21	0	0	1
284	Aug. 1965	0	25	0	0	1
285	Sept. 1965	0	22	0	0	1
286	Oct. 1965	0	23	0	0	1
287	Nov. 1965	0	23	0	0	1
288	Dec. 1965	0	21	0	0	1
289	Jan. 1966	0	21	0	0	1
290	Feb. 1966	0	22	0	0	1
291	Mar. 1966	0	19	0	0	0
292	Apr. 1966	0	26	0	0	1
293	May 1966	0	21	0	0	1
294	June 1966	0	21	0	0	1
295	July 1966	0	21	0	0	1
296	Aug. 1966	0	26	0	0	1
297	Sept. 1966	0	23	0	0	1
298	Oct. 1966	0	25	0	0	1
299	Nov. 1966	0	26	0	0	1
300	Dec. 1966	0	26	0	0	1

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
301	Jan. 1967	0	25	0	0	1
302	Feb. 1967	0	26	0	0	1
303	Mar. 1967	0	23	0	0	1
304	Apr. 1967	0	30	0	0	1
305	May 1967	0	24	0	0	1
306	June 1967	0	24	0	0	1
307	July 1967	0	25	0	0	1
308	Aug. 1967	0	31	0	0	1
309	Sept. 1967	0	26	0	0	1
310	Oct. 1967	0	29	0	0	1
311	Nov. 1967	0	29	0	0	1
312	Dec. 1967	0	28	0	0	1
313	Jan. 1968	0	27	0	0	1
314	Feb. 1968	0	26	0	0	1
315	Mar. 1968	0	23	0	0	1
316	Apr. 1968	0	30	0	0	1
317	May 1968	0	24	0	0	1
318	June 1968	0	24	0	0	1
319	July 1968	0	25	0	0	1
320	Aug. 1968	0	32	0	0	1
321	Sept. 1968	0	28	0	0	1
322	Oct. 1968	0	31	0	0	1
323	Nov. 1968	0	31	0	0	2
324	Dec. 1968	0	29	0	0	1
325	Jan. 1969	0	28	0	0	1
326	Feb. 1969	0	28	0	0	1
327	Mar. 1969	0	23	0	0	1
328	Apr. 1969	0	32	0	0	2
329	May 1969	0	26	0	0	1
330	June 1969	0	26	0	0	1
331	July 1969	0	24	0	0	1
332	Aug. 1969	0	18	0	0	1
333	Sept. 1969	0	8	0	0	1
334	Oct. 1969	0	8	0	0	1
335	Nov. 1969	0	24	0	0	2
336	Dec. 1969	0	24	0	0	2

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
337	Jan. 1970	0	23	0	0	2
338	Feb. 1970	0	23	0	0	2
339	Mar. 1970	0	19	0	0	1
340	Apr. 1970	0	26	0	0	2
341	May 1970	0	20	0	0	2
342	June 1970	0	20	0	0	2
343	July 1970	0	20	0	0	2
344	Aug. 1970	0	24	0	0	2
345	Sept. 1970	0	21	0	0	2
346	Oct. 1970	0	23	0	0	2
347	Nov. 1970	0	25	0	0	3
348	Dec. 1970	0	22	0	0	2
349	Jan. 1971	0	22	0	0	2
350	Feb. 1971	0	21	0	0	2
351	Mar. 1971	0	17	0	0	2
352	Apr. 1971	0	24	0	0	3
353	May 1971	0	19	0	0	2
354	June 1971	0	19	0	0	2
355	July 1971	0	19	0	0	2
356	Aug. 1971	0	24	0	0	3
357	Sept. 1971	0	21	0	0	2
358	Oct. 1971	0	22	0	0	2
359	Nov. 1971	0	25	0	0	3
360	Dec. 1971	0	22	0	0	3
361	Jan. 1972	0	22	0	0	3
362	Feb. 1972	0	21	0	0	2
363	Mar. 1972	0	17	0	0	2
364	Apr. 1972	0	24	0	0	3
365	May 1972	0	19	0	0	3
366	June 1972	0	19	0	0	3
367	July 1972	0	16	3	0	2
368	Aug. 1972	0	20	38	1	3
369	Sept. 1972	0	18	50	1	2
370	Oct. 1972	0	18	12	0	3
371	Nov. 1972	0	25	133	3	3
372	Dec. 1972	0	32	146	3	2

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
373	Jan. 1973	0	27	74	2	3
374	Feb. 1973	0	34	113	3	2
375	Mar. 1973	0	38	123	3	2
376	Apr. 1973	0	38	80	2	3
377	May 1973	0	43	104	3	3
378	June 1973	0	57	131	4	3
379	July 1973	1	73	149	5	3
380	Aug. 1973	1	109	184	7	3
381	Sept. 1973	1	96	143	5	3
382	Oct. 1973	0	31	26	1	3
383	Nov. 1973	2	187	249	10	3
384	Dec. 1973	3	201	230	10	2
385	Jan. 1974	1	106	106	5	3
386	Feb. 1974	2	152	151	7	2
387	Mar. 1974	3	163	155	7	2
388	Apr. 1974	2	116	97	5	3
389	May 1974	2	142	122	6	2
390	June 1974	3	179	149	8	2
391	July 1974	4	209	166	9	2
392	Aug. 1974	5	274	203	12	3
393	Sept. 1974	4	217	155	9	3
394	Oct. 1974	1	50	28	2	3
395	Nov. 1974	8	399	273	17	3
396	Dec. 1974	8	369	239	15	3
397	Jan. 1975	4	179	109	7	3
398	Feb. 1975	6	252	155	11	3
399	Mar. 1975	6	261	159	11	2
400	Apr. 1975	4	174	99	7	3
401	May 1975	5	211	124	9	3
402	June 1975	7	260	151	11	2
403	July 1975	8	294	168	13	3
404	Aug. 1975	10	368	205	16	3
405	Sept. 1975	8	285	156	12	3
406	Oct. 1975	1	61	28	2	3
407	Nov. 1975	14	503	274	23	3
408	Dec. 1975	13	451	240	20	3

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.— Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
409	Jan. 1976	7	227	116	10	3
410	Feb. 1976	10	317	164	14	3
411	Mar. 1976	10	323	166	15	2
412	Apr. 1976	6	212	104	9	4
413	May 1976	8	257	130	12	3
414	June 1976	10	314	158	15	3
415	July 1976	12	348	174	16	3
416	Aug. 1976	15	436	214	20	4
417	Sept. 1976	11	336	163	16	3
418	Oct. 1976	2	70	29	3	3
419	Nov. 1976	19	543	264	26	4
420	Dec. 1976	19	520	249	25	3
421	Jan. 1977	9	249	116	12	4
422	Feb. 1977	13	346	164	17	3
423	Mar. 1977	13	342	162	17	2
424	Apr. 1977	8	218	99	11	4
425	May 1977	10	264	123	13	3
426	June 1977	12	320	149	17	3
427	July 1977	14	355	164	19	3
428	Aug. 1977	17	440	199	23	4
429	Sept. 1977	13	338	152	18	4
430	Oct. 1977	2	69	27	3	4
431	Nov. 1977	22	544	245	30	4
432	Dec. 1977	21	513	229	28	4
433	Jan. 1978	10	250	109	14	4
434	Feb. 1978	14	348	154	19	3
435	Mar. 1978	15	352	157	20	3
436	Apr. 1978	9	231	99	13	5
437	May 1978	12	278	123	16	4
438	June 1978	14	333	148	19	3
439	July 1978	17	388	172	23	3
440	Aug. 1978	20	475	209	28	4
441	Sept. 1978	16	364	159	22	4
442	Oct. 1978	3	74	28	4	4
443	Nov. 1978	24	544	240	33	5
444	Dec. 1978	24	546	240	33	4

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
445	Jan. 1979	12	268	117	16	6
446	Feb. 1979	17	370	163	23	5
447	Mar. 1979	17	378	165	24	5
448	Apr. 1979	11	230	101	15	4
449	May 1979	13	274	119	18	3
450	June 1979	15	320	138	21	3
451	July 1979	17	361	152	23	3
452	Aug. 1979	22	483	201	31	0
453	Sept. 1979	17	358	148	23	3
454	Oct. 1979	3	71	27	4	4
455	Nov. 1979	23	507	207	33	6
456	Dec. 1979	23	504	205	33	6
457	Jan. 1980	12	264	104	17	7
458	Feb. 1980	17	378	152	24	6
459	Mar. 1980	20	433	175	28	6
460	Apr. 1980	12	273	108	17	8
461	May 1980	15	322	131	21	6
462	June 1980	18	394	163	26	6
463	July 1980	20	415	173	27	6
464	Aug. 1980	23	496	206	33	7
465	Sept. 1980	18	388	162	26	7
466	Oct. 1980	3	88	32	5	8
467	Nov. 1980	25	524	222	35	7
468	Dec. 1980	26	541	229	37	6
469	Jan. 1981	14	295	122	19	8
470	Feb. 1981	18	387	163	26	7
471	Mar. 1981	19	397	169	27	6
472	Apr. 1981	12	266	109	17	9
473	May 1981	15	322	135	22	7
474	June 1981	18	380	161	26	7
475	July 1981	21	436	185	30	6
476	Aug. 1981	30	631	270	44	8
477	Sept. 1981	25	516	231	36	7
478	Oct. 1981	5	115	50	8	5
479	Nov. 1981	36	748	362	54	8
480	Dec. 1981	37	753	370	54	8

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
481	Jan. 1982	19	406	199	29	9
482	Feb. 1982	26	529	266	38	7
483	Mar. 1982	27	556	285	41	6
484	Apr. 1982	18	376	189	27	10
485	May 1982	21	438	227	32	8
486	June 1982	25	505	266	38	7
487	July 1982	27	551	293	42	7
488	Aug. 1982	33	670	355	51	9
489	Sept. 1982	29	588	311	44	9
490	Oct. 1982	6	138	64	9	9
491	Nov. 1982	34	706	379	55	10
492	Dec. 1982	35	721	388	56	8
493	Jan. 1983	19	389	206	30	8
494	Feb. 1983	26	526	284	42	7
495	Mar. 1983	29	588	319	47	6
496	Apr. 1983	18	372	196	29	10
497	May 1983	22	449	243	36	8
498	June 1983	27	546	298	45	7
499	July 1983	30	618	337	51	7
500	Aug. 1983	32	659	357	54	9
501	Sept. 1983	26	543	292	45	9
502	Oct. 1983	5	134	61	9	10
503	Nov. 1983	39	783	435	67	10
504	Dec. 1983	34	688	381	59	9
505	Jan. 1984	21	427	233	36	11
506	Feb. 1984	27	560	303	47	8
507	Mar. 1984	28	587	320	50	7
508	Apr. 1984	18	400	206	33	12
509	May 1984	23	491	262	42	10
510	June 1984	22	471	256	41	7
511	July 1984	24	507	278	45	7
512	Aug. 1984	26	539	295	48	8
513	Sept. 1984	21	443	241	39	8
514	Oct. 1984	3	94	40	6	8
515	Nov. 1984	31	639	358	59	8
516	Dec. 1984	2	43	26	4	2

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
517	Jan. 1985	16	324	163	31	4
518	Feb. 1985	0	0	0	0	3
519	Mar. 1985	0	0	0	0	3
520	Apr. 1985	0	0	0	0	4
521	May 1985	0	0	0	0	3
522	June 1985	0	0	0	0	3
523	July 1985	0	0	0	0	3
524	Aug. 1985	0	0	0	0	3
525	Sept. 1985	0	0	0	0	3
526	Oct. 1985	0	0	0	0	3
527	Nov. 1985	0	0	0	0	3
528	Dec. 1985	0	0	0	0	3
529	Jan. 1986	0	0	0	0	3
530	Feb. 1986	0	0	0	0	3
531	Mar. 1986	0	0	0	0	3
532	Apr. 1986	0	0	0	0	4
533	May 1986	0	0	0	0	3
534	June 1986	0	0	0	0	3
535	July 1986	0	0	0	0	3
536	Aug. 1986	0	0	0	0	3
537	Sept. 1986	0	0	0	0	3
538	Oct. 1986	0	0	0	0	3
539	Nov. 1986	0	0	0	0	3
540	Dec. 1986	0	0	0	0	3
541	Jan. 1987	0	0	0	0	2
542	Feb. 1987	0	0	0	0	3
543	Mar. 1987	0	0	0	0	2
544	Apr. 1987	0	0	0	0	3
545	May 1987	0	0	0	0	2
546	June 1987	0	0	0	0	2
547	July 1987	0	0	0	0	3
548	Aug. 1987	0	0	0	0	3
549	Sept. 1987	0	0	0	0	3
550	Oct. 1987	0	0	0	0	3
551	Nov. 1987	0	0	0	0	2
552	Dec. 1987	0	0	0	0	2

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
553	Jan. 1988	0	0	0	0	3
554	Feb. 1988	0	0	0	0	3
555	Mar. 1988	0	0	0	0	3
556	Apr. 1988	0	0	0	0	4
557	May 1988	0	0	0	0	3
558	June 1988	0	0	0	0	3
559	July 1988	0	0	0	0	3
560	Aug. 1988	0	0	0	0	3
561	Sept. 1988	0	0	0	0	3
562	Oct. 1988	0	0	0	0	3
563	Nov. 1988	0	0	0	0	3
564	Dec. 1988	0	0	0	0	3
565	Jan. 1989	0	0	0	0	3
566	Feb. 1989	0	0	0	0	3
567	Mar. 1989	0	0	0	0	3
568	Apr. 1989	0	0	0	0	3
569	May 1989	0	0	0	0	3
570	June 1989	0	0	0	0	3
571	July 1989	0	0	0	0	3
572	Aug. 1989	0	0	0	0	3
573	Sept. 1989	0	0	0	0	3
574	Oct. 1989	0	0	0	0	3
575	Nov. 1989	0	0	0	0	3
576	Dec. 1989	0	0	0	0	3
577	Jan. 1990	0	0	0	0	3
578	Feb. 1990	0	0	0	0	3
579	Mar. 1990	0	0	0	0	3
580	Apr. 1990	0	0	0	0	3
581	May 1990	0	0	0	0	3
582	June 1990	0	0	0	0	3
583	July 1990	0	0	0	0	3
584	Aug. 1990	0	0	0	0	3
585	Sept. 1990	0	0	0	0	3
586	Oct. 1990	0	0	0	0	3
587	Nov. 1990	0	0	0	0	2
588	Dec. 1990	0	0	0	0	3

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
589	Jan. 1991	0	0	0	0	2
590	Feb. 1991	0	0	0	0	3
591	Mar. 1991	0	0	0	0	3
592	Apr. 1991	0	0	0	0	3
593	May 1991	0	0	0	0	3
594	June 1991	0	0	0	0	3
595	July 1991	0	0	0	0	3
596	Aug. 1991	0	0	0	0	3
597	Sept. 1991	0	0	0	0	3
598	Oct. 1991	0	0	0	0	3
599	Nov. 1991	0	0	0	0	2
600	Dec. 1991	0	0	0	0	3
601	Jan. 1992	0	0	*	0	2
602	Feb. 1992	0	0	*	0	3
603	Mar. 1992	0	0	*	0	3
604	Apr. 1992	0	0	*	0	3
605	May 1992	0	0	*	0	3
606	June 1992	0	0	*	0	3
607	July 1992	0	0	*	0	3
608	Aug. 1992	0	0	*	0	3
609	Sept. 1992	0	0	*	0	3
610	Oct. 1992	0	0	*	0	3
611	Nov. 1992	0	0	*	0	3
612	Dec. 1992	0	0	*	0	3
613	Jan. 1993	0	0	*	0	3
614	Feb. 1993	0	0	*	0	3
615	Mar. 1993	0	0	*	0	3
616	Apr. 1993	0	0	*	0	4
617	May 1993	0	0	*	0	3
618	June 1993	0	0	*	0	3
619	July 1993	0	0	*	0	3
620	Aug. 1993	0	0	*	0	4
621	Sept. 1993	0	0	*	0	3
622	Oct. 1993	0	0	*	0	4
623	Nov. 1993	0	0	*	0	3
624	Dec. 1993	0	0	*	0	3

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
625	Jan. 1994	0	0	*	0	3
626	Feb. 1994	0	0	*	0	4
627	Mar. 1994	0	0	*	0	3
628	Apr. 1994	0	0	*	0	4
629	May 1994	0	0	*	0	3
630	June 1994	0	0	*	0	4
631	July 1994	0	0	*	0	4
632	Aug. 1994	0	0	*	0	4
633	Sept. 1994	0	0	*	0	4
634	Oct. 1994	0	0	*	0	4
635	Nov. 1994	0	0	*	0	3
636	Dec. 1994	0	0	*	0	4
637	Jan. 1995	0	0	*	0	3
638	Feb. 1995	0	0	*	0	4
639	Mar. 1995	0	0	*	0	4
640	Apr. 1995	0	0	*	0	4
641	May 1995	0	0	*	0	3
642	June 1995	0	0	*	0	4
643	July 1995	0	0	*	0	4
644	Aug. 1995	0	0	*	0	4
645	Sept. 1995	0	0	*	0	4
646	Oct. 1995	0	0	*	0	4
647	Nov. 1995	0	0	*	0	3
648	Dec. 1995	0	0	*	0	3
649	Jan. 1996	0	0	*	0	3
650	Feb. 1996	0	0	*	0	4
651	Mar. 1996	0	0	*	0	3
652	Apr. 1996	0	0	*	0	4
653	May 1996	0	0	*	0	3
654–798	June 1996–June 2008	0	0	*	0	0

Appendix K — Holcomb Boulevard Water-Distribution System Reconstructed (Simulated) Mean Monthly Finished Water Concentrations

Table A8.1. Reconstructed (simulated) monthly mean tetrachloroethylene (PCE) concentrations in finished water distributed to Holcomb Boulevard family housing areas for interconnection events, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, 1972–1985.[1]

[PP, Paradise Point; MP, Midway Park; BM, Berkeley Manor; WV, Watkins Village; —, not applicable; concentration in micrograms per liter (µg/L)]

Month	[2]1972			[3]WV	1973			[3]WV	1974			[3]WV	1975			[3]WV	1976			[3]WV
	PP	MP	BM		PP	MP	BM		PP	MP	BM		PP	MP	BM		PP	MP	BM	
Jan.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Feb.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Mar.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Apr.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
May	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
June	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
July	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Aug.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Sept.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Oct.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Nov.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Dec.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—

Month	1977			[3]WV	1978			[3]WV	1979			WV	1980			WV	1981			WV
	PP	MP	BM		PP	MP	BM		PP	MP	BM		PP	MP	BM		PP	MP	BM	
Jan.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Feb.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mar.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Apr.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1
May	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
June	0	0	0	—	0	1	2	2	0	0	0	0	0	0	1	1	0	0	0	0
July	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aug.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sept.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oct.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nov.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dec.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Month	1982				1983				1984				[4]1985				1986			
	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV
Jan.	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2				
Feb.	0	0	0	0	0	0	0	0	0	0	0	0	3	3	3	3				
Mar.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Apr.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
May	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0				
June	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0				
July	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0				
Aug.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Sept.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Oct.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Nov.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Dec.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				

[1] Derived from multiplying monthly mean concentrations in finished water from the Hadnot Point water treatment plant (Appendix A7) by average percentage (unrounded) of Hadnot Point water distributed through Booster Pump 742 (Table A20); current maximum contaminant level (MCL) for PCE is 5 µg/L

[2] Prior to June 1972 when Holcomb Boulevard water treatment plant came online, 100 percent of Hadnot Point water was delivered to Holcomb Boulevard family housing areas (see Appendix A7 for January–May 1972)

[3] Watkins Village housing was not built and occupied until about 1978 (Faye et al. 2010), and the first documented interconnection occurs during May 1978 (U.S. Marine Corps Camp Lejeune Water Documents CLW #7023, #7031, and #7033)

[4] For period of January 28–February 4, 1985, booster pump 742 operated continuously due to shutdown of Holcomb Boulevard water treatment plant; this continuous event is not included in the Markov Chain analysis

Table A8.2. Reconstructed (simulated) monthly mean trichloroethylene (TCE) concentrations in finished water distributed to Holcomb Boulevard family housing areas for interconnection events, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, 1972–1985.[1]

[PP, Paradise Point; MP, Midway Park; BM, Berkeley Manor; WV, Watkins Village; —, not applicable; concentration in micrograms per liter (µg/L)]

Month	[2]1972				1973				1974				1975				1976			
	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV
Jan.	22	22	22	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Feb.	21	21	21	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Mar.	17	17	17	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Apr.	24	24	24	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
May	19	19	19	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
June	19	19	19	—	0	0	1	—	0	0	0	—	0	0	0	—	1	2	3	—
July	1	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Aug.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Sept.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Oct.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Nov.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Dec.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—

Month	1977				1978				1979				1980				1981			
	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV
Jan.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Feb.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mar.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Apr.	0	1	2	—	0	0	0	0	0	1	2	1	0	0	0	0	0	4	39	28
May	1	1	3	—	0	2	6	4	0	1	3	2	0	0	0	0	0	4	13	10
June	1	2	3	—	3	23	51	38	0	2	6	4	2	8	17	13	0	4	10	7
July	1	2	3	—	0	0	1	1	0	1	4	2	0	0	0	0	0	2	4	3
Aug.	1	2	4	—	0	0	0	0	0	2	5	3	0	0	0	0	0	2	6	4
Sept.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oct.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nov.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dec.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Month	1982				1983				1984				[4]1985				1986			
	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV
Jan.	0	0	0	0	0	0	0	0	0	0	0	0	34	31	32	34				
Feb.	0	0	0	0	0	0	0	0	0	0	0	0	66	53	54	56				
Mar.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Apr.	0	3	9	7	0	0	0	0	0	2	5	3	0	0	0	0				
May	1	6	20	13	1	5	14	10	0	0	0	0	0	0	0	0				
June	0	4	10	7	0	0	2	2	0	0	0	0	0	0	0	0				
July	0	4	12	8	0	0	3	2	0	0	0	0	0	0	0	0				
Aug.	1	3	6	4	0	2	5	3	0	0	0	0	0	0	0	0				
Sept.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Oct.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Nov.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Dec.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				

[1] Derived from multiplying monthly mean concentrations in finished water from the Hadnot Point water treatment plant (Appendix A7) by average percentage (unrounded) of Hadnot Point water distributed through Booster Pump 742 (Table A20); current maximum contaminant level (MCL) for PCE is 5 µg/L

[2] Prior to June 1972 when Holcomb Boulevard water treatment plant came online, 100 percent of Hadnot Point water was delivered to Holcomb Boulevard family housing areas (see Appendix A7 for January–May 1972)

[3] Watkins Village housing was not built and occupied until about 1978 (Faye et al. 2010), and the first documented interconnection occurs during May 1978 (U.S. Marine Corps Camp Lejeune Water Documents CLW #7023, #7031, and #7033)

[4] For period of January 28–February 4, 1985, booster pump 742 operated continuously due to shutdown of Holcomb Boulevard water treatment plant; this continuous event is not included in the Markov Chain analysis

Table A8.3. Reconstructed (simulated) monthly mean *trans*-1,2-dichloroethylene (1,2-tDCE) concentrations in finished water distributed to Holcomb Boulevard family housing areas for interconnection events, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, 1972–1985.[1]

[PP, Paradise Point; MP, Midway Park; BM, Berkeley Manor; WV, Watkins Village; —, not applicable; concentration in micrograms per liter (µg/L)]

Month	[2]1972				1973				1974				1975				1976			
	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV
Jan.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Feb.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Mar.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Apr.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
May	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
June	0	0	0	—	0	1	1	—	0	0	0	—	0	0	0	—	0	1	2	—
July	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Aug.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Sept.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Oct.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Nov.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Dec.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—

Month	1977				1978				1979				1980				1981			
	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV
Jan.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Feb.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mar.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Apr.	0	1	1	—	0	0	0	0	0	1	1	1	0	0	0	0	0	2	16	12
May	0	1	1	—	0	1	3	2	0	0	1	1	0	0	0	0	0	2	6	4
June	0	1	1	—	2	10	22	17	0	1	3	2	1	3	7	5	0	2	4	3
July	0	1	2	—	0	0	0	0	0	0	1	1	0	0	0	0	0	1	2	1
Aug.	0	1	2	—	0	0	0	0	0	1	2	1	0	0	0	0	0	1	3	2
Sept.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oct.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nov.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dec.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Month	1982				1983				1984				[4]1985				1986			
	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV
Jan.	0	0	0	0	0	0	0	0	0	0	0	0	17	16	16	17				
Feb.	0	0	0	0	0	0	0	0	0	0	0	0	33	27	27	28				
Mar.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Apr.	0	2	4	3	0	0	0	0	0	1	2	2	0	0	0	0				
May	0	3	10	7	0	3	8	5	0	0	0	0	0	0	0	0				
June	0	2	6	4	0	0	1	1	0	0	0	0	0	0	0	0				
July	0	2	6	4	0	0	2	1	0	0	0	0	0	0	0	0				
Aug.	0	2	3	2	0	1	3	2	0	0	0	0	0	0	0	0				
Sept.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Oct.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Nov.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Dec.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				

[1]Derived from multiplying monthly mean concentrations in finished water from the Hadnot Point water treatment plant (Appendix A7) by average percentage (unrounded) of Hadnot Point water distributed through Booster Pump 742 (Table A20); current maximum contaminant level (MCL) for PCE is 5 µg/L

[2]Prior to June 1972 when Holcomb Boulevard water treatment plant came online, 100 percent of Hadnot Point water was delivered to Holcomb Boulevard family housing areas (see Appendix A7 for January–May 1972)

[3]Watkins Village housing was not built and occupied until about 1978 (Faye et al. 2010), and the first documented interconnection occurs during May 1978 (U.S. Marine Corps Camp Lejeune Water Documents CLW #7023, #7031, and #7033)

[4]For period of January 28–February 4, 1985, booster pump 742 operated continuously due to shutdown of Holcomb Boulevard water treatment plant; this continuous event is not included in the Markov Chain analysis

Table A8.4. Reconstructed (simulated) monthly mean vinyl chloride (VC) concentrations in finished water distributed to Holcomb Boulevard family housing areas for interconnection events, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, 1972–1985.[1]

[PP, Paradise Point; MP, Midway Park; BM, Berkeley Manor; WV, Watkins Village; —, not applicable; concentration in micrograms per liter (µg/L)]

Month	[2]1972			[3]WV	1973			[3]WV	1974			[3]WV	1975			[3]WV	1976			[3]WV
	PP	MP	BM		PP	MP	BM		PP	MP	BM		PP	MP	BM		PP	MP	BM	
Jan.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Feb.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Mar.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Apr.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
May	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
June	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
July	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Aug.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Sept.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Oct.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Nov.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Dec.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—

Month	1977			[3]WV	1978			[3]WV	1979			WV	1980			WV	1981			WV
	PP	MP	BM		PP	MP	BM		PP	MP	BM		PP	MP	BM		PP	MP	BM	
Jan.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Feb.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mar.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Apr.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2
May	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
June	0	0	0	—	0	1	3	2	0	0	0	0	0	1	1	1	0	0	1	0
July	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aug.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sept.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oct.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nov.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dec.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Month	1982			WV	1983			WV	1984			WV	[4]1985			WV	1986			WV
	PP	MP	BM		PP	MP	BM		PP	MP	BM		PP	MP	BM		PP	MP	BM	
Jan.	0	0	0	0	0	0	0	0	0	0	0	0	3	3	3	3				
Feb.	0	0	0	0	0	0	0	0	0	0	0	0	6	5	5	5				
Mar.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Apr.	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0				
May	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0				
June	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0				
July	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0				
Aug.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Sept.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Oct.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Nov.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Dec.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				

[1]Derived from multiplying monthly mean concentrations in finished water from the Hadnot Point water treatment plant (Appendix A7) by average percentage (unrounded) of Hadnot Point water distributed through Booster Pump 742 (Table A20); current maximum contaminant level (MCL) for PCE is 5 µg/L

[2]Prior to June 1972 when Holcomb Boulevard water treatment plant came online, 100 percent of Hadnot Point water was delivered to Holcomb Boulevard family housing areas (see Appendix A7 for January–May 1972)

[3]Watkins Village housing was not built and occupied until about 1978 (Faye et al. 2010), and the first documented interconnection occurs during May 1978 (U.S. Marine Corps Camp Lejeune Water Documents CLW #7023, #7031, and #7033)

[4]For period of January 28–February 4, 1985, booster pump 742 operated continuously due to shutdown of Holcomb Boulevard water treatment plant; this continuous event is not included in the Markov Chain analysis

Table A8.5. Reconstructed (simulated) monthly mean benzene concentrations in finished water distributed to Holcomb Boulevard family housing areas for interconnection events, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, 1972–1985.[1]

[PP, Paradise Point; MP, Midway Park; BM, Berkeley Manor; WV, Watkins Village; —, not applicable; concentration in micrograms per liter (µg/L)]

Month	[2]1972				1973				1974				1975				1976			
	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV
Jan.	3	3	3	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Feb.	3	3	3	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Mar.	2	2	2	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Apr.	3	3	3	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
May	3	3	3	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
June	3	3	3	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
July	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Aug.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Sept.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Oct.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Nov.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Dec.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—

Month	1977				1978				1979				1980				1981			
	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV
Jan.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Feb.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mar.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Apr.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
May	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
June	0	0	0	—	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
July	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aug.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sept.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oct.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nov.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dec.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Month	1982				1983				1984				[4]1985				1986			
	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV
Jan.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Feb.	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1				
Mar.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Apr.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
June	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
July	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Aug.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Sept.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Oct.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Nov.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Dec.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				

[1] Derived from multiplying monthly mean concentrations in finished water from the Hadnot Point water treatment plant (Appendix A7) by average percentage (unrounded) of Hadnot Point water distributed through Booster Pump 742 (Table A20); current maximum contaminant level (MCL) for PCE is 5 µg/L

[2] Prior to June 1972 when Holcomb Boulevard water treatment plant came online, 100 percent of Hadnot Point water was delivered to Holcomb Boulevard family housing areas (see Appendix A7 for January–May 1972)

[3] Watkins Village housing was not built and occupied until about 1978 (Faye et al. 2010), and the first documented interconnection occurs during May 1978 (U.S. Marine Corps Camp Lejeune Water Documents CLW #7023, #7031, and #7033)

[4] For period of January 28–February 4, 1985, booster pump 742 operated continuously due to shutdown of Holcomb Boulevard water treatment plant; this continuous event is not included in the Markov Chain analysis

Appendix L — ATSDR Response to Department of the Navy's Letter on: Assessment of ATSDTR Water Modeling for Tarawa Terrace (ATSDR 2009)

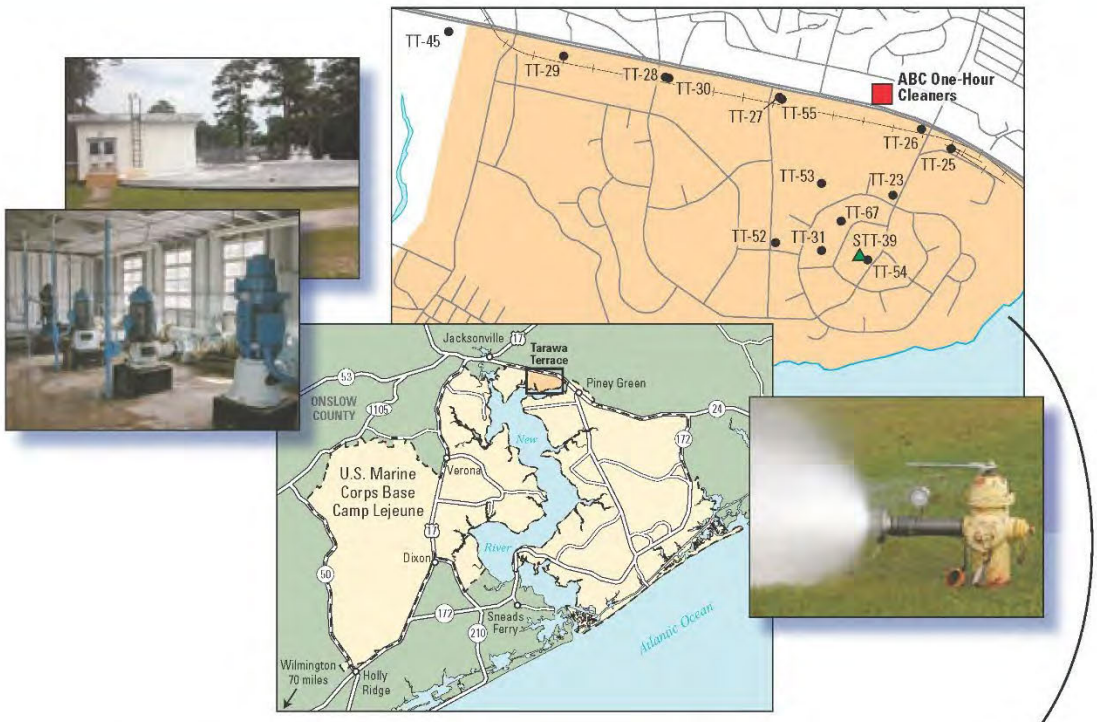
The ATSDR Response to Department of Navy's Letter is publicly available on the ATSDR website at:

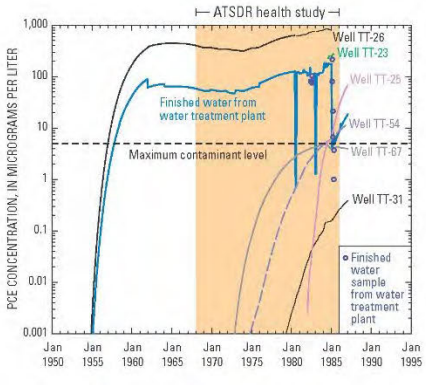
ATSDR_Response2DON_10Mar09.pdf (cdc.gov)

References to "Attachment 2 – Attachment 8" in the text portion of the response included with this Appendix K are found in the publicly available report on ATSDR's website. Attachment 1 is included with this Appendix

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

Response to the Department of the Navy's Letter on: Assessment of ATSDR Water Modeling for Tarawa Terrace







ATSDR
AGENCY FOR TOXIC SUBSTANCES AND DISEASE REGISTRY

Atlanta, Georgia–March 2009

March 10, 2009

Brian P. Harrison, M.P.A., P.E.
Department of the Navy
Naval Facilities Engineering Command
1322 Patterson Avenue, SE
Suite 1000
Washington Navy Yard, D.C. 20374-5065

Dear Mr. Harrison:

I am writing this letter in response to the Department of Navy's (DON) letter dated June 19, 2008. In that letter you reiterated the DON's continued support for working with the Agency for Toxic Substances and Disease Registry (ATSDR) and brought to my attention issues of concern to the DON regarding ATSDR's current health study. This health study uses results of water-modeling analyses to reconstruct historical levels of contaminants in base housing drinking-water supplies during the health study period of 1968–1985.

I have requested ATSDR technical staff working on the current health study at Camp Lejeune to compile responses to the scientific and technical issues you describe in your letter. These responses are enclosed. As a particular response warrants, the response is supported with additional technical and scientific documentation. Technical points of contact for responses to the DON letter are listed below:

Health study/epidemiology, Dr. Frank J. Bove, (770) 488-3809,
Historical reconstruction/modeling, Mr. Morris L. Maslia, (770) 488-3842,

ATSDR appreciates the DON's support and commitment to working with us on this scientifically complex and technically challenging project. One of the benefits to the public from a complex project of this type is a demonstration of how two independent Federal Government agencies can work together for the betterment of public health.

Sincerely,

Thomas H. Sinks, Ph.D.
Deputy Director
National Center for Environmental Health/
Agency for Toxic Substances and Disease Registry

Page 2 – Mr. Brian P. Harrison

Enclosure

cc:
H. Frumkin, NCEH/ATSDR/OD
C. Aloisio, NCEH/ATSDR/OFAS
M. Campbell, NCEH/ATSDR/OFAS
J. Masone, NCEH/ATSDR/OFAS
G. David Williamson, ATSDR/DHS
Bill Cibulas, ATSDR/DHAC
Susan Moore, ATSDR/DHAC
F. J. Bove, ATSDR/DHS
P. Z. Ruckart, ATSDR/DHS
M. L. Maslia, ATSDR/DHAC
R. Mach, DON/ASN(E)
K. Brown, DON/NAVFACHQ
D. Waddill, DON/NAVFAC ATLANTIC
M. Simmons, DON/NMCPHC
C. Rennix, DON/NMCPHC
C. Sakai, USMCHQ
S. Williams, USMCHQ

RESPONSE TO THE DEPARTMENT OF THE NAVY'S LETTER ON ASSESSMENT OF ATSDR WATER MODELING FOR TARAWA TERRACE

INTRODUCTION

The Agency for Toxic Substances and Disease Registry (ATSDR) has used the following referencing format in responding to the Department of the Navy (DON) comments contained in their letter of June 19, 2008. A comment is identified in the DON letter by a number (e.g., 1.1, 2.1, 3.1, etc.), and the ATSDR response to that particular comment is identified with a sequential number (e.g., 1.2, 2.2, 3.2, etc.). To facilitate comparison of DON comments with ATSDR responses, DON comment identifiers (e.g., 1.1, 2.1, 3.1, etc.) have been placed in the margins of the DON letter. This "marked up" letter is provided as a reference and is identified herein as Attachment 1.

BACKGROUND

This ATSDR response and related attachments are part of a continuing effort on the part of ATSDR to maintain a high level of communication between ATSDR and other agencies responsible for the current health study at Camp Lejeune. To reiterate those efforts, Attachment 2 presents information pertinent to previous meetings, presentations, and conversations between ATSDR and the Department of Defense (DOD), the DON, and the U.S. Marine Corps (USMC). Since ATSDR proposed using the historical reconstruction approach as part of the current health study during October 2003, ATSDR staff have kept the DOD, DON, and USMC fully informed, at the highest levels of command, regarding ATSDR's work plans, activities, progress, and results. Attachment 2 provides a complete chronology of meetings, presentations, and publications related to the historical reconstruction of contaminated drinking water at Tarawa Terrace and vicinity. Three examples, we believe, are noteworthy:

(1) On October 8, 2003, ATSDR presented its proposed modeling approach to support the current health study—historical reconstruction—during a meeting at ATSDR headquarters. Attending the meeting were representatives from the DOD, DON, and USMC (headquarters and Camp Lejeune). A copy of the meeting sign-in sheet and sample presentation slides also are provided in Attachment 2.

(2) On August 26, 2005, ATSDR health study and water-modeling staff met with Lt. General Kelly and his staff at USMC headquarters and presented initial water-modeling results indicating tetrachloroethylene (PCE) had reached Tarawa Terrace water-supply wells as early as 1960.

(3) On June 11, 2007, ATSDR health study and water-modeling staff met with Lt. General Kramlich and his staff at USMC headquarters and presented final water-modeling results. These results indicated that PCE dissolved in groundwater had reached Tarawa Terrace water-supply wells as early as November 1957. ATSDR also presented Lt. General Kramlich and his staff with printed copies of the Executive Summary report (Maslia et al. 2007a) that would be publicly released the following day (June 12, 2007).

RESPONSE TO SPECIFIC COMMENTS

1.1 DON Comment/Statement

During a Technical Information Meeting with the Marine Corps and Navy on March 26, 2008, the ATSDR presented their water modeling efforts in a summary report entitled "Exposure to Volatile Organic Compounds in Drinking Water and Specific Birth Defects and Childhood Cancer at U.S. Marine Corps Base Camp Lejeune, North Carolina."

1.2 ATSDR Response

During the aforementioned meeting on March 26, 2008, in Atlanta, ATSDR presented water-modeling results for Tarawa Terrace and vicinity. Staff and technical representatives from ATSDR, DON, and USMC headquarters attended the meeting. ATSDR presented a summary of published results and a list of Tarawa Terrace chapter reports to be completed. Attendees were provided with a copy of the ATSDR PowerPoint® presentation that was used during the meeting.

Note that all reports of technical analyses and water-modeling results pertinent to historical reconstruction of exposure to volatile organic compounds (VOCs) at Tarawa Terrace and vicinity published to date by ATSDR have been available on the agency's Camp Lejeune Web site (http://www.atsdr.cdc.gov/sites/lejeune/watermodeling.html) since June 2007. For example, the Executive Summary (Maslia et al. 2007a) and Chapter A (Maslia et al. 2007b) reports were released publicly during June and July 2007, respectively. As agreed upon with USMC headquarters staff, ATSDR provided Camp Lejeune and USMC headquarters staff with advanced electronic copies (508-compliant PDF® files) of the aforementioned reports 24 hours prior to their public release.

2.1 DON Comment/Statement

Monthly PCE concentrations are required for the ATSDR health study, which will examine births that occurred from 1968 (when North Carolina computerized its birth certificates) to 1985 (when the contaminated water supply wells were removed from service).

2. 2 ATSDR Response

In general, ATSDR is in agreement with this statement. Specifically, however, historical and water treatment plant (WTP) operations records indicate that only the most contaminated wells were removed from continuous service during 1985. For example, water-supply wells TT-26 and TT-23 were removed from continuous service during February and May 1985, respectively. Remaining Tarawa Terrace water-supply wells continued to operate continuously and intermittently until the Tarawa Terrace WTP was permanently shut down during March 1987 (Maslia et al. 2007b, Table A6). Thus, ATSDR is not in agreement with the DON statement in parentheses that incorrectly describes the schedule for the removal of water-supply wells from service at Tarawa Terrace.

Case 7:23-cv-00897-RJ Document 462-1 Filed 08/24/25 Page 252 of 400

3.1 DON Comment/Statement

Due to lack of measured concentrations, the ATSDR used groundwater flow and contaminant transport modeling in a historical reconstruction process to simulate PCE concentrations in the drinking water on a monthly basis from 1952 to 1987.

3.2 ATSDR Response

To reconstruct monthly concentrations of PCE in drinking water, ATSDR used three types of models: (1) groundwater flow, (2) contaminant fate and transport, and (3) simple mixing based on the concepts of continuity and mass balance. The mixing model was necessary to account for the mixing of uncontaminated and contaminated water-supply wells contributing to the water supply at the Tarawa Terrace WTP. The mixing model provided the final "mixed" drinking- water concentrations on a monthly basis, and these are the values that are available on the ATSDR Web site and published in the Chapter A report (Maslia et al. 2007b).

4.1 DON Comment/Statement

Figure 1 shows the simulated concentrations of PCE versus measured concentrations in finished water from the WTP. Significantly, measured concentrations of PCE are available only in 1982 and 1985, near the end of the overall time period. Thus, the majority of the simulated concentrations cannot be compared to measured data.

4.2 ATSDR Response

ATSDR agrees that there is a lack of historical contaminant concentration data. That is why ATSDR applied the historical reconstruction process to reconstruct (or synthesize) water levels, groundwater concentrations, and drinking-water concentrations of PCE for historical periods (months) when data were not available. Note that data used to calibrate the model(s) in the historical reconstruction process can either be historical data (as was the situation for Tarawa Terrace), or present-day data obtained through a field-test program—as was the case for the water-distribution system model developed by ATSDR for the Dover Township (Toms River), New Jersey, childhood cancer cluster investigation (Maslia et al. 2000).

5.1 DON Comment/Statement

Furthermore, all of the measured concentrations were used during model calibration, leaving no data available for model validation. As a result, the Tarawa Terrace model was not validated.

5.2 ATSDR Response

A number of terms have been used throughout the published literature that reference the adequacy of model simulation to reliably reproduce real-world conditions based on the fidelity of the model and its intended use. Many groundwater modelers and hydrologists have abandoned the use of terms such as model verification and validation for the terms of history matching and post audits (Bredehoeft and Konikow 1993, Oreskes et al. 1994). However, ATSDR understands that the DON comment was intended to express the DON's concern that the calibrated Tarawa Terrace models were not compared to multiple independent sets of measured data (water levels

and concentrations) as part of ATSDR's model calibration process and strategy. To address this concern, definitions of terms such as "verification" and "validation" should be agreed upon, and the consequences of undertaking a useful "validation" program for Tarawa Terrace should be completely understood by ATSDR and the DON. Model verification requires that multiple sets of field data be available for model calibration. These sets of field data should be sufficiently large in quantity and distribution and of sufficient quality to provide at least two equally useful calibration data sets. Each data set also should be sufficiently separated in time so as to represent significantly different water-level and contaminant conditions within the model domain. The field data set at Tarawa Terrace used for model calibration was not of sufficient quantity and was too compressed in time to implement a verification procedure. To appropriately calibrate the Tarawa Terrace models, all available field data were required for a single calibration data set and effort. This is consistent with and follows ASTM D5981-96, Standard Guide for Calibrating a Ground-Water Flow Model Application (1996, Note 4), that states: *"When only one data set is available, it is inadvisable to artificially split it into separate 'calibration' and 'verification' data sets. It is usually more important to calibrate to data spanning as much of the modeled domain as possible."*

To meaningfully validate the Tarawa Terrace models (or more appropriately, to conduct a post audit), sufficient time should elapse between individual sets of field data to ensure that significant changes in field conditions have occurred compared to calibrated conditions. At Tarawa Terrace, such changes, by necessity, would require the migration of the contaminant mass to a completely new location and for contaminant concentrations to change significantly when compared to calibrated conditions. Additionally, at Tarawa Terrace, validation (a post audit) would require the collection and analyses of substantial quantities of additional field data, similar to Weston's Operational Units 1 and 2 (Roy F. Weston, Inc. 1992, 1994).

Note, once an acceptable calibration was achieved (using a four-stage calibration strategy described in Maslia et al. [2007a], Faye and Valenzuela [2007], and Faye [2008]), the calibrated models were used to reconstruct historical monthly PCE and PCE degradation by-product concentrations in groundwater and drinking water (Jang and Aral 2008). This is standard practice in the modeling community—using a calibrated model to "predict" (in ATSDR's situation, "reconstruct") results for a period of time when data are not available or cannot be obtained. An example using this same approach is the application of fate and transport modeling to chlorinated organic compounds at Operable Unit 1, U.S. Naval Air Station, Jacksonville, Florida (NASJF), conducted by Davis (2007, Figures 28–31). At this site, the earliest water-quality data that are available were collected during 1992, but the fate and transport model simulations reconstruct concentrations as far back as 1945.

6.1 DON Comment/Statement

For PCE detections, the ATSDR chose the calibration standard to be "±1/2-order of magnitude of the observed valued," such that the higher value in the calibration target range is 10 times greater than the lower value …. In other words, a model-derived PCE concentration can be approximately 3 times higher or 3 times lower than the measured concentration and still fall within the calibration range.

Case 7:23-cv-00897-RJ Document 462-1 Filed 08/24/25 Page 254 of 400

6.2 ATSDR Response

ATSDR generally is in agreement with this statement. For model calibration, ATSDR established, *a priori*, calibration "targets" that were based on the reported accuracy of the available water-level and water-quality measurements. This is in keeping with, and following, the ASTM Standard Guide for Calibrating a Ground-Water Flow Model Application (ASTM 1996). Note, however, that published or accepted groundwater-flow or contaminant fate and transport model calibration standards are currently not established. The lack of model calibration standards is further emphasized by Anderson and Woessner (1992) who state: *"To date, there is no standard protocol for evaluating the calibration process, although the need for a standard methodology is recognized as an important part of the quality assurance in code application (National Research Council 1990)."* In thoroughly reviewing the published literature for contaminant fate and transport model applications, ATSDR did not find any examples wherein calibration targets were established *a priori* and then were followed by a comparison of model simulation results to the calibration targets, as was done in the ATSDR analyses (Maslia et al. 2007b, Faye 2008). For example, at another DON site—the NASJF—contaminant fate and transport simulations of selected chlorinated organic solvents were accepted by the DON, but the simulations did not include any *a priori* contaminant fate and transport calibration targets (Davis 2003, 2007).

7.1 DON Comment/Statement

However, all comparisons did not fall within the calibration range. At the WTP, 12% of the simulated PCE concentrations failed the calibration standard …. at the water supply wells, a majority (53%) of the simulated concentrations fell outside the calibration standard….

7.2 ATSDR Response

ATSDR will address three issues pertinent to the aforementioned DON statement:

(1) ATSDR acknowledges that several simulated head and concentration data fall outside of the range of the ATSDR established calibration targets. As discussed above, ATSDR used available data provided by the U.S. Environmental Protection Agency (USEPA), U.S. Geological Survey (USGS), USMC, and DON, and based on these data, established calibration targets *a priori*, as prescribed in ASTM D5981-96 (1996, Section 6). Furthermore, ATSDR clearly identified and conveyed to the reader (and the public) those data that met and did not meet calibration targets by providing illustrations comparing observed (measured) data, nondetect data, and simulated results with calibration targets for water-supply wells and the Tarawa Terrace WTP. These illustrations are designated as Figures A11 for water-supply wells and A12 for the WTP of the Chapter A report and are located on pages A30 and A31, respectively (Maslia et al. 2007b).

(2) Note, as well, that ATSDR did not discard any nondetect data, as is done in many environmental analyses (Helsel 2005). Rather, ATSDR clearly identified the nondetect data on the aforementioned illustrations so the reader could judge for themselves the usefulness of these data and their relation to the calibration targets. This is very much in keeping with the approach stated by Helsel (2005): "*Deleting nondetects, concentrations*

below a measured threshold, obscures the information in graphs and numerical summaries."

(3) ATSDR maintains that the models (flow, transport, and mixing) are sufficiently calibrated, given the quantity and accuracy of data provided and the intended use of the simulated historically reconstructed concentrations. Although the DON is correct in pointing out that some simulated results did not meet the calibration target, ATSDR believes that the DON should assess these results in terms of: (1) similar peer-reviewed reports, (2) currently established model calibration practices, and (3) the intended use of the modeling results by the epidemiological study. That is, are the ATSDR analyses within the accepted norm of current-day modeling practices, are the ATSDR analyses an exception to this norm, and will there be sufficient reliability for an epidemiological study?

To possibly answer the first two questions, ATSDR looks forward to discussing with the DON the results of other modeling studies of contaminant fate and transport similar to the ATSDR study at Tarawa Terrace and comparing the results of other studies to the calibration targets used by ATSDR at Tarawa Terrace. For example, the results of the ATSDR fate and transport simulations at Tarawa Terrace were compared to results of a similar study of the fate and transport modeling of chlorinated solvents at the NASJF, reported by Davis (2003). The report by Davis (2003) was peer reviewed and published by the USGS, and the published results were subsequently deemed totally acceptable to the DON. No calibration targets for contaminant concentrations were established during the NASJF study. Therefore, to directly compare Tarawa Terrace and NASJF simulation results, the ATSDR calibration targets of ±1/2-order of magnitude were applied to data and simulation results reported in Davis (2003, Figure 34). Attachment 3 shows this comparison along with similar results reported by Maslia et al. (2007b, Tables A9 and A10). The percentage of NASJF simulation results that fell within the calibration target range (passed the calibration target test) is 56% compared with 59% for the ATSDR study (44% of the NASJF results failed the calibration test compared with a failure rate of 41% for ATSDR results). Furthermore, the root-mean-square of concentration difference for the NASJF analysis is 329 μg/L compared with 337 μg/L for the ATSDR analysis. (Data used to conduct these comparisons also are included in Attachment 3.) Thus, one can conclude that the ATSDR analysis is comparable to and of the same order of accuracy and quality as the NASJF analysis that was accepted by the DON.

To address the issue of the intended use of the water-modeling results by the current ATSDR epidemiological study, the DON should be advised that a successful epidemiological study places little emphasis on the actual (absolute) estimate of concentration and, rather, emphasizes the relative level of exposure. That is, exposed individuals are, in effect, ranked by exposure level and maintain their rank order of exposure level regardless of how far off the estimated concentration is to the "true" (measured) PCE concentration. This rank order of exposure level is preserved regardless of whether the mean or the upper or lower 95% of simulated levels are used to estimate the monthly average contaminant levels. It is **not** the goal of the ATSDR health study to infer which health effects occur at specific PCE concentrations—this is a task for

risk assessment utilizing approaches such as meta-analysis to summarize evidence from several epidemiological studies because a single epidemiological study is generally insufficient to make this determination. The goal of the ATSDR epidemiological analysis is to evaluate exposure-response relationships to determine whether the risk for a specific disease increases as the level of the contaminant (either as a categorical variable or continuous variable) increases.

8.1 DON Comment/Statement

It seems reasonable to conclude that the accuracy of the historically reconstructed PCE concentrations would be less than the calibration standard of ±1/2-order of magnitude. Thus, the historical reconstructions may be viewed as rough estimates of actual exposure concentrations, with model-derived PCE concentrations representing a relatively wide range of possible exposures. It is essential that this concept be expressed clearly and consistently to all stakeholders.

8.2 ATSDR Response

ATSDR is in disagreement with DON's assessment and interpretation as expressed in the first two sentences above. As previously discussed, there are no established calibration targets or standards that are universally accepted or used by the contaminant fate and transport modeling community. With respect to the Tarawa Terrace models, the failure of a percentage of data to conform to a designated calibration target is more a commentary on the accuracy and variability of field data used for model calibration than the model's ability to accurately simulate true field conditions. These issues are thoroughly discussed in the "Discussion" sections of the Tarawa Terrace Chapter C and F reports (Faye and Valenzuela 2007, Faye 2008) For example, note on Attachment 3 of this letter the radical changes in PCE concentration at well TT-26 during the approximately 1-month period between January 16 and February 19, 1985. Of the four comparisons of measured PCE concentrations with simulated PCE concentrations, three comparisons failed the calibration target test of ±1/2-order of magnitude while the field data varied by as much as 2.5 orders of magnitude. The two analyses recorded for February 19, 1985, are duplicative but were nonetheless counted as two failures with respect to computing a percentage of comparisons that failed the calibration target test. Furthermore, ATSDR is not aware of any other published report that establishes, *a priori*, contaminant fate and transport calibration targets. ATSDR based its calibration target of ±1/2-order of magnitude on the assumption that very restrictive or "tight" control on model calibration was desired. With 59% of the water-supply well and water treatment plant paired data points meeting these targets, ATSDR believes it met its model calibration goals.

ATSDR is in disagreement with the DON statement that the historical reconstruction results of PCE concentrations are "*rough estimates*" and represent a "*relatively wide range of possible exposures*." Results presented in the Chapter A report (Maslia et al. 2007b) demonstrate just the opposite. ATSDR meticulously followed accepted modeling standards (ASTM 1996, Hill and Tiedeman 2007) for both deterministic (single-valued input and output) and probabilistic (distributed-value input and output) modeling analyses. Results obtained are accurate on a monthly basis within the variability bands indicated, given the quality and quantity of available

data, and the uncertainty and variability of input data, pumping and water treatment plant operations, and quantity of mass released. The monthly resolutions of simulated PCE concentrations are sufficiently refined for the intended use of the epidemiological case-control study. Furthermore, as shown in Figures A25 and A26 (Maslia et al. 2007b), ATSDR clearly described and communicated that reconstructed (simulated) PCE concentrations for a specified month do have a range of values. A tabular listing of these values is provided in the Chapter I report (Maslia et al. 2009) and will be made available to the public on the ATSDR Web site.
These tabular values also are provided herein as Attachment 4. A review of Attachment 4 indicates that during the period of interest to the epidemiological study (1968–1985), when water-supply well TT-26 was pumping, the range of 95% of the Monte Carlo simulated PCE concentration values differ by a factor of about 2 when pumping uncertainty is not considered (e.g., for January 1968, $P_{97.5}$ = 76.43 μg/L and $P_{2.5}$ = 38.91 μg/L). PCE concentration values differ by a factor of about 2.5 when pumping uncertainty is considered (e.g., for January 1968, $P_{97.5}$ = 98.22 μg/L and $P_{2.5}$ = 40.60 μg/L). These ranges are, in fact, very narrow and provide both quantitative and qualitative indications of the precision of the ATSDR historically reconstructed PCE concentrations in drinking water.

ATSDR is in agreement with the DON statement that *"It is essential that this concept be expressed clearly and consistently to all stakeholders."* Upon the release of the Chapter I report (Maslia et al. 2009), ATSDR intends to revise the Camp Lejeune water-modeling Web site to include a listing of ranges of PCE concentrations for a given month and year of interest. When a person queries the ATSDR Web site, they will be provided with a mean exposure concentration and the 95% Monte Carlo simulated range of values.

9.1 DON Comment/Statement

For example, the public needs to understand that the model-derived PCE concentrations represent a range of possible exposures..... The usefulness of the website would be enhanced if it accurately conveyed the degree of uncertainty in the model-derived concentrations.

9.2 ATSDR Response

ATSDR is in agreement with this DON statement. As stated above, ATSDR has revised the Camp Lejeune water-modeling Web site to include a listing of ranges of PCE concentrations for a given month and year of interest. When a person links to the ATSDR Web site, they will be provided with a mean exposure concentration and the 95% Monte Carlo simulated range of values.

Case 7:23-cv-00897-RJ Document 462-1 Filed 08/24/25 Page 258 of 400

10.1 DON Comment/Statement

Other concerns with model calibration include the simulation of contaminant mass loading and groundwater flow. With Dense, Non-Aqueous Phase Liquids (DNAPLs) such as PCE, mass estimation is always quite difficult and subject to very high uncertainty due to irregular movement and distribution of DNAPL in the subsurface.

10.2 ATSDR Response

In principle, ATSDR is in agreement with the DON statement that DNAPL movement and distribution makes it difficult to estimate contaminant mass. However, water-quality data obtained from the USEPA for the unsaturated zone in the vicinity of ABC One-Hour Cleaners and in the Upper Castle Hayne aquifer at Tarawa Terrace (Roy F. Weston, Inc. 1992, 1994; Faye and Green 2007) indicated that measured PCE concentrations in water-quality samples were significantly below the solubility limit of PCE in water. Typical solubility limits for PCE in water reported in the scientific literature range from 150–210 mg/L (Schwille 1988, Pankow and Cherry 1996, ATSDR 1997, Lawrence 2007). Reported concentrations of PCE in all water- quality samples made available to ATSDR were less than 20% of the solubility limit and most concentrations were in the range of less than 1% to 5% of the solubility limit (Faye and Green 2007). Thus, with PCE concentrations well below their solubility limit, the movement of PCE- contaminated groundwater would not be subjected to the complexities and difficulties encountered with estimating mass of density-driven flows. This concept is further borne out by Schwille (1988) who states, in referring to chlorinated hydrocarbons (CHCs): "*In most cases, the concentrations near all CHC spill sites are very low—usually far below the saturation values.*
This indicates that it may be assumed that density-affected flow will be the exception in real- world situations."

In addition, mass computations similar to those described in Pankow and Cherry (1996) were accomplished for the saturated and unsaturated zones in the vicinity of ABC One-Hour Cleaners, using hydrocone and well data made available to ATSDR by USEPA and USMC (Roy F. Weston, Inc. 1992, 1994; Faye and Green 2007). These mass computations provided a lower- limit estimate for dissolved PCE mass in groundwater needed for simulating the contaminant fate and transport of PCE at Tarawa Terrace. Furthermore, the calibration of the Tarawa Terrace fate and transport model is additionally corroborated by comparing the computed mass residing in the saturated zone from December 1991 to April 1992 (1.5×10^6 grams) to the simulated mass residing in the saturated zone during February 1992 (1.0×10^6 grams) (Faye 2008). The mass computation method described in Pankow and Cherry (1996) and similar to that used by Faye and Green (2007) has been further refined. As explained in Ricker (2008): "*this method is applicable to any contaminant dissolved in ground water.*" A copy of the paper by Ricker (2008) is provided as Attachment 5.

11.1 DON Comment/Statement

For Tarawa Terrace groundwater, the difference between observed and simulated elevations is 5 to 10 feet at many times during the 1970's and 1980's. This is a significant disparity because the total change in groundwater elevation from the source area to the receptor wells is approximately 10 to 12 feet.

Case 7:23-cv-00897-RJ Document 462-1 Filed 08/24/25 Page 259 of 400

11.2 ATSDR Response

This DON approach to evaluating model calibration applies a generalized "rule of thumb" to the Tarawa Terrace groundwater-flow models and is possibly based on wording found in ASTM Guide D5981-96, Standard Guide for Calibrating a Ground-Water Flow Model Application, (ASTM 1996, section 6.4.1): *"the acceptable residual should be a small fraction of the difference between the highest and lowest heads across the site."* ATSDR is not in agreement with this approach to evaluate model calibration. A careful review of ASTM D5981-96 in its entirety indicates that the DON's comment, as stated, is totally removed from the context of Section 6 of the ASTM Standard Guide as well as the context of the accuracy of field data used to calibrate the Tarawa Terrace groundwater-flow model, as described in the Chapter C report (Faye and Valenzuela 2007). For example, in Section 6.4, ASTM D5981-96 states: *"the magnitude of the acceptable residual depends partly upon the magnitude of the error of the measurement or the estimate of the calibration target and partly upon the degree of accuracy and precision required of the model's prediction."* Furthermore, Note 2 of ASTM D5981-96 states: *"Acceptable residuals may differ for different hydraulic head calibration targets within a particular model. This may be due to different errors in measurement."* The Tarawa Terrace Chapter C report (Faye and Valenzuela 2007, p. C24) provides a comprehensive discussion of water-level measurement errors arising from the use of airlines and pressure gages to measure water levels. Faye and Valenzuela also point out that this is consistent with the discussions of LeGrand (1959) who described problems associated with the use of airlines to measure water levels at Camp Lejeune as far back as 1959. As pointed out in Faye and Valenzuela (2007, p.
C24): *"Typically, reported water levels* [at supply wells] *vary in excess of 20 ft during the period of measurement, and frequently 10 ft or more from month to month…. Such variability also may indicate leaking or damaged airlines or pressure gages."*

Faye and Valenzuela (2007, p. C24) also provide detailed discussions as to the rationale for selecting two calibration target ranges for the transient groundwater-flow model. At wells where water-level measurements were obtained using airlines and pressure gages, the calibration target was selected as an absolute difference of 12 ft between simulated and measured water levels. This target was based on well-known disadvantages of using pressure gages and airlines to obtain accurate water-level measurements. Where water-level measurements were obtained using the more highly accurate tapes and similar devices at monitor wells, the calibration target was selected as an absolute difference of 3 ft between simulated and measured water levels. This target was based on the least accurate of these water-level measurements where topographic maps were used to estimate the altitude of a measuring point.

Evaluating model calibration using the "rule of thumb," as the DON has suggested, also assumes that no other information is available to determine calibration targets. When information is available, such as direct knowledge of methods of water-level measurements and information characterizing the measurement device(s), the calibration targets should be based on these data, not on a "rule of thumb." Faye and Valenzuela (2007) provide detailed listings of measured water levels in supply and monitor wells throughout Tarawa Terrace (Appendix C5).

The calibration of the Tarawa Terrace groundwater-flow and contaminant fate and transport models and the computation of related calibration metrics are described in great detail in published ATSDR reports (Faye and Valenzuela 2007, Maslia et al. 2007b, Faye 2008). The

calibration approach used by ATSDR closely follows published guidelines for model calibration (National Research Council 1990;Anderson and Woessner 1992; ASTM 2004, 2006, 2008). Nowhere in these publications could we find any reference to the "rule of thumb" for model calibration found in ASTM (1996) and subsequently promoted by the DON. The use of hydraulic head change over a model domain to define an acceptable residual for groundwater model calibration is not found or discussed in any of the aforementioned references. Anderson and Woessner (1992) and ASTM D5940-93 (2008) provide several metrics for evaluating the calibration process and comparing groundwater-flow model simulation to site-specific information. Among these metrics are the use of a scatter diagram and the computation of the mean error, the mean absolute error, the root-mean-square (*RMS*) of error, and standard deviation of error.[1] In conformance with these metrics, the calibration of the ATSDR groundwater-flow models was evaluated using scatter diagrams (Figures C9 and C20 in Faye and Valenzuela [2007] and Figure A10 in Maslia et al. [2007b]) and by computing the mean absolute error of the differences between simulated and observed head at all known observation and water-supply wells within the model domain as well as the *RMS* and standard deviation of these differences (Table C10 in Faye and Valenzuela [2007] and Table A8 in Maslia et al. [2007b]). Attachment 6 to this letter, the scatter diagram from Maslia et al. (2007b), and Attachment 7, Table A8 from Maslia et al. 2007b, describe the computation of the absolute error (head difference) and related *RMS* and standard deviation. The calibration of the ATSDR Tarawa Terrace groundwater-flow and contaminant fate and transport models was based on available water-level and water-quality data to determine calibration targets and closely adheres to accepted model calibration standards and evaluation procedures, such as those described in the aforementioned publications.

12.1 DON Comment/Statement

In addition, model results suggest that the simulated PCE concentrations at the WTP depend significantly on the pumping rates at the various water supply wells. The degree to which simulated well operations match actual operations is a concern. The Navy/Marine Corps would welcome the opportunity for further technical discussion with ATSDR on these issues.

12.2 ATSDR Response

ATSDR is in agreement with the DON that PCE concentrations at the WTP are dependent on the pumping rates assigned to water-supply wells. This dependency is based on the principles of continuity and conservation of mass. The PCE concentration in finished water at the WTP is a function of individual water-supply well pumping rates and their simulated PCE concentrations for a given historical month (stress period)—also referred to as a flow-weighted average PCE concentration (Faye 2008). ATSDR shares the DON's concern that simulated operations may not match historical operations. Thus, when monthly pumpage data were available, ATSDR used these data in the transient groundwater-flow model (for example, Table C8 in Faye and Valenzuela [2007] and Table I16 in Maslia et al. [2009]). To address issues of missing pumping operational data and the effect of uncertain pumping rates on simulated PCE concentrations, ATSDR conducted additional and complex analyses that described in detail: (1) issues of

[1]The term "error" as used in Anderson and Woessner (1992) and some other references is defined in the ATSDR analyses as "head difference" and refers to the difference between measured and simulated potentiometric heads or water levels.

pumping schedule variation on the arrival of PCE at water-supply wells and the WTP (Wang and Aral 2008) and (2) assessment of uncertain pumping rates by conducting a probabilistic analysis wherein pumping rate was defined as an uncertain model parameter (Maslia et al. 2009, Figure I25).

13.1 DON Comment/Statement

. . . certain combinations of input parameters resulted in wells drying out, so only 510 physically viable realizations were produced. Thus, 330 out of 840 realizations were not viable, raising concerns about the representativeness of the input parameter distributions.

13.2 ATSDR Response

The issue that should be addressed is not how many realizations produced physically plausible solutions, but rather, are the 510 realizations that were successfully produced sufficient to represent an infinite number of random solutions? The metric that determines whether or not this question is answered in the affirmative is the relative change in stopping criteria between successive model simulations. If this relative change is small within a predetermined range, then additional simulations are redundant and do not statistically contribute to an improvement of the representativeness of the overall results with respect to the statistical distributions. The Chapter I report (Maslia et al. 2009) describes in detail the criteria used to determine when a sufficient number of realizations have been achieved. Three stopping criteria were used to halt the Monte Carlo simulation: (1) relative change in the arithmetic mean of PCE concentration in finished water at the Tarawa Terrace WTP, ΔC ; (2) relative change in the standard deviation of PCE concentration in finished water at the Tarawa Terrace WTP, $\Delta\sigma_C$; and (3) relative change in the coefficient of variation of PCE concentration in finished water at the Tarawa Terrace WTP, ΔC_v . Mathematical formulae and definitions of the aforementioned stopping criteria metrics are listed in Table I13 of the Chapter I report (Maslia et al. 2009). In applying the stopping criteria to the Monte Carlo simulations, an upper and lower bound of ±0.25% was used for each metric. When the computed relative change (ΔC , $\Delta\sigma_C$, and ΔC_v) was within the aforementioned bounds and the total number of realizations was 500 or more, the Monte Carlo simulation process was halted. Examples of the stopping criteria for each metric are shown graphically in Attachment 8 (Maslia et al. 2009, Figure I26). As can be seen from the stopping criteria, insignificant change (much less than 2.5%) occurs after 300 realizations. Therefore, 510 realizations were more than sufficient to represent an infinite number of random solutions.

14.1 DON Comment/Statement

Although a summary of the probabilistic analysis is presented in Chapter A of the ATSDR modeling report, the details will be in Chapter I, which is not yet available. The Navy/Marine Corps feels that additional information on this matter would likely help our understanding.

14.2 ATSDR Response

An electronic version (508-compliant PDF®) of the Chapter I report (Maslia et al. 2009) was provided to the DON and USMC on February 13, 2009, and is now available on the ATSDR Web site. Printed copies of the report are expected to be available around March 20, 2009. The

Case 7:23-cv-00897-RJ Document 462-1 Filed 08/24/25 Page 262 of 400

Chapter I report describes in detail the Monte Carlo simulation process and how this process was incorporated into Tarawa Terrace groundwater-flow and contaminant fate and transport models. Additionally, details pertaining to generating uncertain parameter distributions using Monte Carlo and sequential Gaussian simulation are discussed. Note, however, results presented in the Chapter I report do not change or alter results and interpretations presented in the Chapter A report.

15.1 DON Comment/Statement

The usefulness and applicability of the model-derived PCE concentrations for Tarawa Terrace are affected by the following ….

15.2 ATSDR Response

ATSDR has responded in detail to the items numbered in the Summary Section of the DON letter of June 19, 2008. To summarize, ATSDR used data and information that were provided by the USEPA and the USMC. In addition, other data sources from the USGS also were used. This formed the basis for the conceptual models of groundwater flow and contaminant fate and transport applied to the Tarawa Terrace area.

Calibration targets were selected based on the quality and availability of water-level and water-quality data provided to ATSDR. Model analyses and calibrations were conducted by following accepted and published standards for groundwater-flow and contaminant fate and transport models (ASTM 1996, 2004, 2006). It must be emphasized, however, that model calibration standards or targets for groundwater-flow and contaminant fate and transport modeling analyses do not exist, as stated in Anderson and Woessner (1992): *"To date, there is no standard protocol for evaluating the calibration process, although the need for a standard methodology is recognized as an important part of the quality assurance in code application (National Research Council 1990)."* Thus, ATSDR maintains that the models (flow, transport, and mixing) are sufficiently calibrated, given the quantity and accuracy of data provided and the intended use of the simulated historically reconstructed concentrations for the epidemiological study, previously discussed above in the last paragraph of section 7.2.

The concept behind the historical reconstruction process is as follows: (1) when data are limited or unavailable for a certain time period, the data that are available are used to calibrate a model (or models), and (2) the missing data are "reconstructed" or "synthesized" using the calibrated model(s).

16.1 DON Comment/Statement

Groundwater modeling studies are always subject to a high degree of uncertainty, and in this sense, the Tarawa Terrace water model is no exception …. Any use of reconstructed concentrations must take into account the inherent uncertainty in the model results.

16.2 ATSDR Response

Case 7:23-cv-00897-RJ Document 462-1 Filed 08/24/25 Page 263 of 400

ATSDR is not in agreement with the DON that there is a *"high degree of uncertainty"* associated with the Tarawa Terrace models. ATSDR acknowledges that uncertainty and variability exist in model input parameter values and in model output (simulated water levels and PCE concentrations). However, ATSDR has quantified the uncertainty and variability through the use of probabilistic analyses that apply Monte Carlo and sequential Gaussian simulation methods to the Tarawa Terrace groundwater-flow and contaminant fate and transport models. The probabilistic analyses, summarized in Chapter A and described in detail in Chapter I, indicate that for 95% of the Monte Carlo simulations, there is a PCE-concentration range of about 2 when pumping is not an uncertain input parameter and a factor of about 2.5 when pumping is an uncertain parameter. This is well within acceptable confidence limits for the intended use of the reconstructed PCE concentrations needed by the epidemiological case-control study. As previously discussed in section 7.2 of ATSDR's response, the ATSDR health study is not trying to infer at what specific PCE concentration effects are seen. Instead, the epidemiological analysis is trying to evaluate an exposure-response relationship in which the exposures are categorized levels, not absolute values.

17.1 DON Comment/Statement

Recommendations
1. Improve communication …, 2. Convene an expert panel …, 3. Finalize remaining sections…, 4. Apply all lessons learned from the Tarawa Terrace modeling efforts to the scoping of the approach for Hadnot Point.

17.2 ATSDR Response

1. ATSDR water-modeling and health study staff will be meeting with the ATSDR Office of Communications to develop effective methods to communicate results of the historical reconstruction analyses and the uncertainty associated with reconstructed concentrations. ATSDR has removed the Web application that provides a "single" value estimate of historical PCE concentration in Tarawa Terrace drinking water. This Web application has been replaced with Figure I29 and Appendix I5 (Maslia et al. 2009).

2. ATSDR is in the process of organizing an Expert Panel for the Hadnot Point and Holcomb Boulevard areas. The panel is scheduled to meet on April 29 and 30 at ATSDR headquarters. Initial information packets have been mailed to the 13 panel members and panel chair, and a courtesy packet has also been provided to USMC headquarters staff.

3. Chapter I is complete and was released to the DON and USMC on February 13, 2009. Printed copies should be available after March 20. Chapters J (water-distribution modeling) and K (Supplemental Information) are anticipated to be final during June 2009.

4. ATSDR agrees and is in the process of applying lessons learned from the Tarawa Terrace analyses as work progresses on the Hadnot Point and Holcomb Boulevard areas.

CONCLUSIONS

ATSDR appreciates the DON's continued support for the agency's current health study and completion of water-modeling activities. The issues of concern and recommendations contained in the DON's assessment of water-modeling analyses at Tarawa Terrace and vicinity have been carefully considered and fully addressed in ATSDR's responses. The online release of Tarawa Terrace Chapter I report (Maslia et al. 2009) on February 13, 2009, provides additional confidence that the historically reconstructed PCE concentrations determined by Faye (2008) are reasonable, conform well to field observations, and are reliable for their intended use in the epidemiological study.

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Response to the Department of the Navy's Letter on Assessment of ATSDR Water Modeling for Tarawa Terrace

Attachment 1: Department of Navy Comments, June 19, 2008

Assessment of
ATSDR Water Modeling for Tarawa Terrace

The purpose of this assessment is (1) to document the Navy/Marine Corps' current understanding of the ATSDR water modeling for Tarawa Terrace and (2) to serve as a basis for additional technical discussions between the Navy/Marine Corps and ATSDR.

Background

1.1 During a Technical Information Meeting with the Marine Corps and Navy on March 26, 2008, the ATSDR presented their water modeling efforts in a summary report entitled "Exposure to Volatile Organic Compounds in Drinking Water and Specific Birth Defects and Childhood Cancer at U.S. Marine Corps Base Camp Lejeune, North Carolina," (March 26, 2008). The report indicates that the following specific information is needed in order to conduct a health study on these birth defects:

1. When did contaminated groundwater reach water supply wells? **month and year**
2. What was the timing, level, and duration of maternal or infant exposure to contaminated drinking water:
    a. In which **months** did exposure occur?
    b. What was the **monthly** average level of contamination?
    c. For how many **months** did exposure occur?

Thus, extensive data are required in order to conduct the proposed health study. Since no measured concentrations of PCE (perchloroethylene) are available prior to 1982, the ATSDR has used modeling to simulate these concentrations at Tarawa Terrace, and proposes a similar modeling approach for Hadnot Point. The results of the Tarawa Terrace modeling are being documented in the ATSDR modeling report entitled "Analysis 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" (ongoing, but initial chapters published in 2007 and 2008).

In general, the usefulness of a groundwater flow and contaminant transport model depends on an accurate estimate of numerous model parameters that describe site geology, groundwater velocity, well pumping rates, and contaminant properties. Many of these parameters are highly variable and difficult to estimate directly. Therefore, model calibration and validation are essential steps in the modeling process. Model calibration involves adjusting the initial parameter values until simulated model concentrations match measured concentrations. In a second step, the calibrated model is validated by comparing simulated concentrations to additional measured concentrations that were not used during calibration. During validation, the model is "put at risk," and it may be judged unsuccessful if the simulated and measured concentrations do not match.

Tarawa Terrace Water Modeling

The Tarawa Terrace housing development at Camp Lejeune was constructed in 1951, and the Tarawa Terrace Water Treatment Plant (WTP) began to distribute drinking water during 1952-1953. The only documented source of contamination at Tarawa Terrace is ABC One-Hour

Cleaners, which began operations during 1953, using the chlorinated solvent PCE in its dry cleaning process. PCE concentrations were measured at the WTP in 1982 and 1985, and no measured concentrations of PCE are available prior to 1982.

2.1 Monthly PCE concentrations are required for the ATSDR health study, which will examine births that occurred from 1968 (when North Carolina computerized its birth certificates) to 1985 (when the contaminated water supply wells were removed from service). Due to lack of measured concentrations, the ATSDR used groundwater flow and contaminant transport modeling in a historical reconstruction process to simulate PCE concentrations in the drinking water on a monthly basis from 1952 to 1987. 3.1

4.1 Figure 1 shows the simulated concentrations of PCE versus measured concentrations in finished water from the WTP. Significantly, measured concentrations of PCE are available only in 1982 and 1985, near the end of the overall time period. Thus, the majority of the simulated concentrations cannot be compared to measured data. Furthermore, all of the measured concentrations were used during model calibration, leaving no data available for model validation. As a result, the Tarawa Terrace model was not validated. 5.1

During calibration, model parameters were adjusted to cause the simulated concentrations at the Water Treatment Plant (WTP) to meet the calibration standard to the degree possible. For PCE detections, the ATSDR chose the calibration standard to be "± 1/2-order of magnitude of the observed valued," such that the higher value in the calibration target range is 10 times greater than the lower value. For example, at the WTP in May 1982, the calibration target range was 25 to 253 ug/L, based on the measured PCE concentration of 80 ug/L. The simulated concentration of 148 ug/L fell within this range. As another example, at supply well TT-26 in January 1985, the calibration target range was 500 to 5,000 ug/L based on the measured PCE concentration of 1,580 ug/L. In this case, the range was quite large because it was calculated from a relatively high measured concentration. The simulated concentration of 804 fell within the range, near the lower end. In summary, based on the chosen calibration standard, the calibration process was viewed as "successful" over a range that spanned a factor of 10. In other words, a model-derived PCE concentration can be approximately 3 times higher or 3 times lower than the measured concentration and still fall within the calibration range. 6.1

Thus, if all comparisons had fallen within the calibration range, the chosen calibration standard would give an idea of the accuracy, or degree of fit, between simulated and measured concentrations. However, all comparisons did not fall within the calibration range. At the WTP, 12% of the simulated PCE concentrations failed the calibration standard (p. F42 in the ATSDR modeling report). It should be noted that these failures involved non-detects or very low concentrations. More significantly, at the water supply wells, a majority (53%) of the simulated concentrations fell outside the calibration standard (p. F33 in the ATSDR modeling report). Graphs of simulated versus observed concentrations of PCE in water supply wells RW2, TT-23, TT-25, TT-26, and TT-54 are shown below in Figures F13 through F17 (p. F34 and F35 of the ATSDR modeling report). The graphs show that only a few observed PCE concentrations are available, and there are substantial differences between observed and simulated concentrations. Model performance at the supply wells raises concerns about the degree to which the model calibration was successful. It seems reasonable to conclude that the accuracy of historically

7.1

8.1

8.1 reconstructed PCE concentrations would be less than the calibration standard of ± 1/2-order of magnitude. Thus, the historical reconstructions may be viewed as rough estimates of actual exposure concentrations, with model-derived PCE concentrations representing a relatively wide range of possible exposures. It is essential that this concept be expressed clearly and consistently to all stakeholders.

9.1 For example, the public needs to understand that the model-derived PCE concentrations represent a range of possible exposures. This concept should be expressed more clearly on the Camp Lejeune website (http://www.atsdr.cdc.gov/sites/lejeune/watermodeling.html). Currently the website has a section that says: "Find Out PCE Levels During Your Tour; Find out the levels of PCE and PCE degradation by-products in the drinking water serving your home in Tarawa Terrace by entering the dates you lived in Tarawa Terrace housing from 1952 to 1987." Following a disclaimer, a search engine produces contaminant concentrations, reported to 4 significant digits, for any or all months between January 1952 and February 1987. With no error bars or ranges included, this webpage conveys a sense of certainty that is not justified. The usefulness of the website would be enhanced if it accurately conveyed the degree of uncertainty in the model-derived concentrations.

10.1 Other concerns with model calibration include the simulation of contaminant mass loading and groundwater flow. With Dense, Non-Aqueous Phase Liquids (DNAPLs) such as PCE, mass estimation is always quite difficult and subject to very high uncertainty due to irregular movement and distribution of DNAPL in the subsurface. For Tarawa Terrace groundwater, the difference between observed and simulated elevations is 5 to 10 feet at many times during the 1970's and 1980's. This is a significant disparity because the total change in groundwater elevation from the source area to the receptor wells is approximately 10 to 12 feet. In addition, 11.1

12.1 model results suggest that the simulated PCE concentrations at the WTP depend significantly on the pumping rates at the various water supply wells. The degree to which simulated well operations match actual operations is a concern. The Navy/Marine Corps would welcome the opportunity for further technical discussion with ATSDR on these issues.

The ATSDR performed a sensitivity analysis to determine the relative importance of individual model parameters. In addition, a probabilistic analysis was performed to assess variability and uncertainty associated with the model results. Both approaches are standard practice. Chapter A of the ATSDR modeling report describes the probabilistic analysis, during which input parameters such as hydraulic conductivity, recharge, and dispersivity were chosen from distributions of possible values. The model was run 840 times to produce "realizations" that form a distribution of simulated PCE concentrations, rather than a single result (pp. A52 – A61 of the ATSDR modeling report). However,

13.1 certain combinations of input parameters resulted in wells drying out, so only 510 physically viable realizations were produced. Thus, 330 out of 840 realizations were not viable, raising concerns about the representativeness of the input parameter distributions. Although a summary of the probabilistic analysis is presented in Chapter A of the ATSDR modeling report, the details will be in Chapter I, which is not yet available. The Navy/Marine Corps feels that additional information on this matter would likely help our understanding. 14.1

Overall, it is important to keep in mind that both the sensitivity analysis and the probabilistic analysis were performed entirely within the "model world," not the "real world." These methods provide valuable insight into the behavior of the model, but they are not a substitute for real, measured PCE concentrations. Again, the Navy/Marine Corps looks forward to additional discussion and clarification of our understanding of these issues.

Summary

The usefulness and applicability of the model-derived PCE concentrations for Tarawa Terrace are affected by the following:

1. Model simulations provide monthly concentrations from 1952 to 1987, but measured concentrations for model calibration are available only in 1982 and 1985. Thus, the majority of the simulated concentrations cannot be compared to measured data.
2. Simulated concentrations did not fall within calibration targets for a majority of the measured PCE concentrations at the water supply wells, suggesting that the "accuracy" of the model is less than the chosen calibration standard of ± 1/2-order of magnitude.
3. Due to lack of measured PCE concentrations, the Tarawa Terrace model was not validated. Therefore, the model was not "put at risk," and it is difficult to judge the accuracy of the simulated PCE concentrations beyond the limited times when calibration data are available.

15.1

Groundwater modeling studies are always subject to a high degree of uncertainty, and in this sense, the Tarawa Terrace water model is no exception. However, the goal of the Tarawa Terrace model is to reconstruct PCE concentrations on a monthly basis over approximately 30 years in order to conduct a health study. This is an extremely difficult goal since measured PCE concentrations are not available prior to 1982, and the historical reconstruction of monthly exposure concentrations must go back to the 1950's. Any use of reconstructed concentrations must take into account the inherent uncertainty in the model results.

16.1

Recommendations

As a starting point for further discussions, the Navy/Marine Corps proposes the following recommendations:

1. Improve communication with the public and other stakeholders by developing a method for presenting the uncertainty in the model-derived PCE concentrations. The method should be clear and readily understood, perhaps using error bars or presenting a concentration range rather than a single number. The method should be applied consistently whenever concentrations are discussed or presented in model reports, websites, public meetings, etc.
2. Convene an expert panel to examine the model results and determine the best use for the data. Overall, the panel should develop a path forward that is scientifically sound and will best meet the critical concerns of the public.
3. Finalize the remaining sections of the Tarawa Terrace water modeling report.
4. Apply all lessons learned from the Tarawa Terrace modeling efforts to the scoping of the approach for Hadnot Point.

17.1

Appendix M — ATSDR Response to National Research Council Report on Contaminated Water-Supplies at Camp Lejeune: Assessing Potential Health Effects (NRC 2009)

Agency for Toxic Substances and Disease Registry (ATSDR)

Response to the National Research Council (NRC) Report
Contaminated Water Supplies at Camp Lejeune—Assessing Potential Health Effects

By: The ATSDR Exposure-Dose Reconstruction Program Staff

July 1, 2009

INTRODUCTION

The Agency for Toxic Substances and Disease Registry's (ATSDR) Exposure-Dose Reconstruction Program staff has reviewed the National Research Council (NRC) report titled, "*Contaminated Water Supplies at Camp Lejeune—Assessing Potential Health Effects*." Specifically, our review focused on Section 2 of the report (p. 28–66), "Exposure to Contaminants in Water Supplies at Camp Lejeune." Based on our review of Section 2, we conclude the following:

> The National Research Committee report (NRC 2009) contains numerous misrepresentations and distortions of ATSDR water-modeling analyses, field data and related interpretations and conclusions that are clearly contradicted by findings in ATSDR technical reports. Those ATSDR reports that describe groundwater contamination and the results of model studies related to contamination of drinking water at the Tarawa Terrace base housing area, Camp Lejeune, North Carolina, along with additional supporting information from the Department of Navy, the U.S. Marine Corps, and other sources were provided to the NRC committee during the course of their deliberations. Because the NRC report contains many errors and misrepresentations with respect to the findings of the ATSDR water-modeling analyses and because conclusions and recommendations contained in the NRC report are at such odds with recommendations rendered by several review panels consisting of national and international experts in water modeling and epidemiology, the NRC report cannot be considered an authoritative interpretation or guidance document related to the historical exposure assessment of contaminated drinking water at Camp Lejeune.

We base the aforementioned statements on four overarching issues discussed below. In addition, we present specific examples wherein the NRC committee arrived at erroneous conclusions by using incorrect data and otherwise misrepresenting data and information contained in reports that summarize ATSDR investigations at Tarawa Terrace and vicinity. Additional supporting documentation and in-depth technical reviews related to specific NRC report comments are provided in Appendix I and II of this document.

ISSUE 1: USE OF HISTORICAL RECONSTRUCTION FOR EXPOSURE ASSESSMENT

Models must be used and have been successfully used to reconstruct historical contaminant concentrations when pertinent data are limited or unavailable (Rodenbeck and Maslia 1998, McLaren/Hart-ChemRisk 2000, Maslia et al. 2001, Reif et al. 2003, Kopecky et al 2004). If models cannot be used to reconstruct historical exposure to contaminants, then models also should not be used for predictive analyses such as planning for remediation strategies or the management of future water supplies. Furthermore, the NRC report (2009) erroneously states

that "cutting-edge" models used by ATSDR were not in the public domain and were not documented, and, as such, falsely claims that ATSDR simulation results are invalid and unacceptable.

ISSUE 2: CHARACTERIZATION OF PCE AS A DENSE NON-AQUEOUS PHASE LIQUID (DNAPL)

Characterizing 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" DNAPL (NRC 2009, p. 38) contradicts and misrepresents concentration data presented in ATSDR and in other reports and documents. Those reports and documents unequivocally describe the PCE in groundwater in the vicinity of ABC One-Hour Cleaners as "dissolved-phase" PCE (Shiver 1985, Roy F. Weston, Inc. 1992, 1994, Faye and Green 2007). The solubility limit of PCE in water occurs at a concentration of at least 210,000 micrograms per liter (µg/L) (Pankow and Cherry 1996, Lawrence 2007). PCE in groundwater that occurs at concentrations much less than the solubility limit is, by definition, dissolved-phase PCE. The ATSDR conceptualization of groundwater flow and of dissolved-phase PCE conditions at ABC One-Hour Cleaners and the Tarawa Terrace base housing area is shown below in Figure 1. PCE-concentration data presented in ATSDR reports (Faye and Green 2007, Tables E5 and E7) indicate that concentrations of PCE in groundwater at Tarawa Terrace and vicinity occur at much less than 10% of the solubility limit. The NRC characterization of PCE in the vicinity of ABC One-Hour Cleaners as DNAPL PCE is further discredited by the process selected to remediate the PCE contamination in groundwater at Tarawa Terrace and vicinity, as described below.

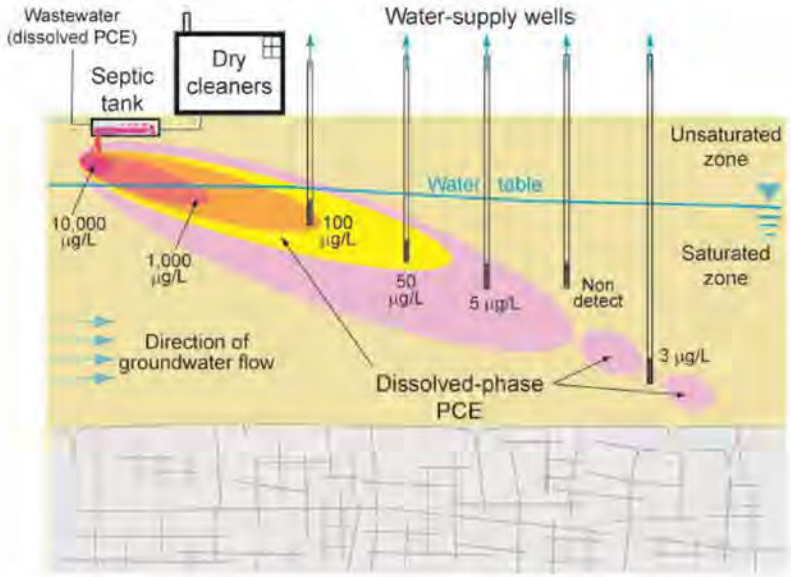


Figure 1. Conceptual model of groundwater flow and dissolved-phase PCE transport at, and in the vicinity of, ABC One-Hour Cleaners (solubility of PCE is at least 210,000 µg/L [Pankow and Cherry 1996, Lawrence 2007])

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). This remediation process was approved by the North Carolina Department of Environment and Natural Resources (NCDENR) and is correctly described as "groundwater extraction by wells and treatment by air stripping" (i.e., pump-and-treat). This remediation process is appropriate only for dissolved-phase PCE—not DNAPL PCE (NCDENR 2003, Weston Solutions Inc. 2005, 2007).

ISSUE 3: EVALUATION OF UNCERTAINTY

Uncertainties with respect to model input parameters and field data accuracy are common to all model investigations and are particularly evident when models are used to reconstruct historical groundwater conditions and contaminant concentrations. Uncertainties related to model studies at Tarawa Terrace and vicinity were largely the result of imperfect knowledge regarding the parameters input to equations solved as part of the historical reconstruction process. To quantify uncertainty, ATSDR systematically applied well-established, scientifically accepted techniques to analyze field data and simulation results (McLaren/Hart-ChemRisk 2000, Wang and Aral 2008, Maslia et al. 2009). For example, model parameters based on field data were characterized by a range of values that described what was known about each parameter's uncertainty and variability. The uncertainty and variability were then described using statistical determinations of probability and confidence limits. The uncertainty techniques developed and applied by ATSDR were never intended to provide "accurate" answers, as implied in the NRC report (NRC 2009, p. 16). Rather, ATSDR's uncertainty analyses outcome indicate the possible range of concentrations at a given historical time, which is the intended purpose of an uncertainty analysis.

ISSUE 4: RELIABILITY OF RECONSTRUCTED HISTORICAL CONCENTRATIONS

ATSDR's analyses presented in the water-modeling reports indicate that reconstructed historical contaminant concentrations in drinking water (finished water delivered from the Tarawa Terrace water treatment plant) provide reliable and acceptable comparisons with measured PCE-concentrations in drinking water samples collected at the water treatment plant. Twenty-five water-quality samples obtained from the Tarawa Terrace water treatment plant during May 1982–October 1985 contained PCE concentrations ranging form 215 µg/L to non-detect (detection limits of 2–10 µg/L). For the same period, model predictions of PCE concentrations at the water treatment plant ranged from 176 µg/L to 3.6 µg/L (Maslia et al. 2007, Table A10). Reconstructed PCE concentrations in drinking water vary by a factor of 2-3 from measured concentrations at specific times, which is within acceptable limits for model studies and also within limits required by the epidemiological study. These data and findings are never presented or discussed in the NRC report (NRC 2009).

EXAMPLES OF MISREPRESENTATION OF DATA AND INCORRECT INFORMATION IN THE NRC REPORT

Listed below are specific examples wherein the NRC committee scientists used incorrect data and misrepresented data and information contained in ATSDR Tarawa Terrace reports to come to erroneous conclusions. All report statements and page numbers refer to the referenced NRC report (NRC 2009).

- NRC Report, p. 33: "*Figure 2-3 illustrates various possible pathways for groundwater contamination from a DNAPL source*"

  Figure 2-3 in the NRC report grossly misrepresents the migration and transport of PCE-contaminated groundwater away from the source area at ABC One-Hour Cleaners toward the Tarawa Terrace base housing area. All relevant field data indicate that dissolved-phase PCE—not DNAPL PCE—was transported along groundwater pathways, probably within one or several contaminant plumes, as illustrated in the conceptual drawing shown in Figure 1 above.

- NRC Report, p. 38: *"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 PCE in water is about 110,000 µg/L)"*

  These statements from the NRC report not only incorrectly define the solubility limit of PCE in water but conclude incorrectly that a single PCE concentration in groundwater is indicative of a "pure-phase" PCE source at ABC One-Hour Cleaners. Pankow and Cherry (1996) and Lawrence (2007) report the highest possible concentration of PCE in water (also known as the solubility limit of PCE) is 237,000 µg/L and 210,000 µg/L at 25° C, respectively. The NRC report does not provide a reference for the solubility limit of 110,000 µg/L noted above. The "extremely high concentration of 12,000 µg/L" is less than 6% of the PCE solubility in water (12,000/210,000 = 5.7%). Thus, the location of this high PCE concentration sample can only be used to identify the source location, but is not a guarantee or confirmation that "free-phase" or "pure-phase" PCE exists at this sample location, at the ABC One-Hour Cleaners site, or within the Tarawa Terrace base housing area.

- NRC Report, pgs. 38-39: *"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."*

  The contamination referred to above is a "gasoline-type odor" noted at supply well TT-53 and described in Chapter E of the Tarawa Terrace series of reports (Faye and Green, p. 14). No effort is made in Chapter E or any other report of the Tarawa Terrace series to link the gasoline odor at well TT-53 to any source. The statement to the contrary quoted above from the NRC report is totally false.

- NRC Report, p. 43: ". . . *and the U.S. Environmental Protection Agency (EPA) model MT3DMS to simulate PCE transport . . .*"

The model MT3DMS is the second generation of the modular three-dimensional transport model MT3D. The model MT3D was developed by Zheng (1990) and released as a public domain code by EPA during 1990. MT3DMS was developed by Zheng and Wang (1999) on behalf of the U.S. Army Engineer Research and Development Center.

- NRC Report, p. 43: *"For example, MT3DMS can predict 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)."*

  The NRC report misrepresents the characterization of PCE contamination as a DNAPL or pure-phase source. The fact is that ATSDR and other reports and documents unequivocally describe the PCE in groundwater in the vicinity of ABC One-Hour Cleaners as dissolved-phase PCE (see Figure 1, above). Therefore, MT3DMS or any other model capable of simulating dissolved-phase contaminants in groundwater is an appropriate model choice and no approximation is needed (with respect to dissolved-phase PCE) to correctly characterize the occurrence of PCE in the source area at ABC One-Hour Cleaners.

- NRC Report, p. 43: *"Unlike the MODFLOW and MT3DMS codes, the PSOpS and TechFlowMP codes lack validation by a broad spectrum of practicing geoscientist in an open-source environment."*

  The NRC report misrepresents the PSOpS and TechFlowMP codes as not validated and not in the public domain. Model validation is not determined by the number of "practicing geoscientists" that use and apply a particular model; rather, numerical models are validated by comparing model predictions to known mathematical (analytical) solutions and site-specific field data when available—this was done with TechFlowMP. Both PSOpS and TechFlowMP are open source and the source codes are available by contacting the principal investigator of the ATSDR-Georgia Tech Research Program on Exposure-Dose Reconstruction Program, Dr. M.M. Aral (email: maral@ce.gatech.edu). These codes can also be accessed through the website of the Multimedia Environmental Simulations Laboratory at Georgia Tech (http://mesl.ce.gatech.edu/).

  It is equally important to note, however, that the use and application of specialized codes to address specific problems that routinely used codes, such as MODFLOW and MT3DMS, cannot address, is not shunned by government-based scientific organizations, but rather, it is recognized and encouraged. As stated in the U.S. Environmental Protection Agency report, "Guidance on the Development, Evaluation, and Application of Environmental Models" (USEPA 2009, p. 31):

  > "However, the Agency acknowledges there will be times when the use of proprietary models provide the most reliable and best-accepted characterization of a system."

  The point being made in this statement is that the most appropriate model should be applied to characterize a system, not necessarily, the most popular or often-used model; and this is the exact modeling philosophy and approach that ATSDR took when applying the TechFlowMP and PSOpS models at ABC One-Hour Cleaners and Tarawa Terrace and vicinity.

- NRC Report, p. 48: "*. . ., 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 (which we estimate at about 10-100 ft^3).*"

  This statement from the NRC report completely and falsely misrepresents the application of field water-quality data applied to the calibration of the Tarawa Terrace fate and transport model. Chapter F of the Tarawa Terrace series of reports states clearly and unambiguously that scale effects were taken into account when selecting field water-quality data for model calibration and, as such, only data collected at supply wells were used (Faye 2008, p. 31). Control volumes related to operating water-supply wells at Tarawa Terrace are of the same order of magnitude represented by grid cells in model layer 1.

- NRC Report p. 48: "*Because insufficient historical pumping data were available to constrain the model predictions form 1953 to 1980, the ability of the advanced optimization models to estimate the dates accurately is questionable*."

  In this statement, the NRC report misrepresents the rationale behind the development, use, and application of the PSOpS optimization model. The PSOpS model was not developed and applied to "estimate dates accurately"—scientifically, this is not possible. Rather, ATSDR's optimization model was developed and applied to Tarawa Terrace calibrated groundwater flow and contaminant fate and transport models to derive alternate pumping scenarios by systematically and objectively varying the on-off cycling of water-supply wells. In doing so, the 5 µg/L PCE concentration front arrived at water-supply wells at times that differed from the calibrated arrival date. This approach provided an "envelope" or range of arrival times. Uncertainty and variability issues related to modeling can never be answered with exactitude as use of the term "accuracy" implies.

- NRC Report p. 49: "*Constant values of dispersivity (longitudinal dispersivity of 25 ft and transverse of 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."*

  Constant values of dispersivity were used in the calibrated, deterministic fate and transport model (Faye 2008). However, for the uncertainty analyses using Monte Carlo simulation, dispersivity values were assigned on a cell-by-cell basis, as discussed in Chapter I of the Tarawa Terrace report series (Maslia et al. 2008, Table I15, and p. I42) Furthermore, the NRC report fails to discuss that although assigned dispersivity values were constant for the deterministic modeling approach, the resulting dispersion matrix values (in the fate and transport equation) were not constant because specific discharge (Darcy velocities) and groundwater velocities vary cell-by-cell. Assigning constant dispersivity values to model arrays is a commonly used approach, especially when pertinent site-specific field data, such as the results of tracer tests, are unavailable. Furthermore, in the absence of site-specific field data the longitudinal dispersivity of 25 ft was chosen based on: (1) literature values for similar aquifer materials, and (2) numerical requirements for Peclet and Courant numbers that minimize numerical dispersion and oscillation.

- NRC Report p. 49: "*Review of water-quality monitoring data indicates substantial temporal variability even at a single well. For example, seven measurements taken on well TT-26 from January to September 1985 indicates that the concentration at this well varied from 3.8 to 1,580 µg/L (see Table 2-3). The model predictions for the same timeframe ranged from 804 to 788 µg/L.*"

  The NRC report fails to mention that the "monitoring data" are from a single water-supply well (TT-26) and not a properly constructed monitor well. Thus, the temporal variation of PCE concentration could equally be caused by errors in, and different methods of, water-sample collection and analysis. These issues are thoroughly discussed in Chapter F of the Tarawa Terrace series of reports (Fay 2008, p. 45) and largely rebut the NRC example of "substantial temporal variability" of contaminant concentrations at wells. Additionally, the NRC report does not list or discuss the 25 water-quality samples obtained from the Tarawa Terrace water treatment plant from May 1982–October 1985 that range in value from 215 µg/L to non-detect (detection limits of 2–10 µg/L) nor does it compare these data with model predictions of 176 to 3.6 µg/L at the water treatment plant for the same timeframe (Maslia et al. 2007, Table A10).

- NRC Report p. 49: "*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 1,418 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.*"

  The NRC report grossly misrepresents the aforementioned model predicted values. The fact is, as specifically discussed in Chapter A of the Tarawa Terrace report series, the value "1,418 µg/L" refers to the maximum simulated PCE concentration in groundwater (model layer 1) at the Tarawa Terrace elementary school during December 1984. The maximum simulated vapor-phase PCE concentration in the top 10 ft of soil was 137 µg/L during December 1984 (Maslia et al. 2007, p. A44). The aforementioned measured PCE-vapor concentration referred to in the NRC report (55 µg/L) was obtained from buildings that house or are near a residential dry cleaning facility in New York City during 2001–2003 (McDermott et al. 2005). There is absolutely no basis, rationale, or scientific justification for comparing ATSDR model simulations of vapor concentration in the pore space of soils beneath the Tarawa Terrace elementary school area for December 1984 with dry-cleaner PCE-vapor measurements made in a building in New York City during 2001–2003.

- NRC Report p. 49: "*The biodegradation model used within the TechFlowMP code is based on an untested preliminary research model. . . The simple first-order modeling framework that also used a single decay coefficient for the entire modeling domain may not capture those biologic complexities . . .* "

  The TechFlowMP code represents a series of processes such as vapor migration, unsaturated flow, saturated groundwater flow, multiphase fate and transport of a contaminant, decay, and biodegradation. Thus, biodegradation is just one of a number of hydrologic and geochemical

processes that are contained within the TechFlowMP modeling framework. The NRC report is incorrect in implying that the TechFlowMP code and the aforementioned process are an "untested preliminary research model." To the contrary, processes within the TechFlowMP model were tested against known analytical solutions and available field data provided to ATSDR by the Department of the Navy and the U.S. Marine Corps. The TechFlowMP code is a public domain code, so anyone who wants to further test the code, can do so by contacting the principal investigator of the ATSDR-Georgia Tech Research Program on Exposure-Dose Reconstruction Program, Dr. M.M. Aral (email: maral@ce.gatech.edu) or they can access the code through the website of the Multimedia Environmental Simulations Laboratory at Georgia Tech (http://mesl.ce.gatech.edu/).

Manipulating the constant decay coefficient value during the model calibration process to arrive at non-constant decay coefficient values (i.e., spatial variation) in the absence of site-specific field data, is not a defensible technical or scientific approach to model simulation and calibration. The decay coefficient assigned to ATSDR fate and transport models was derived from limited field data and literature reported values. For example, ATSDR used a mean value for decay coefficient (reaction rate) of 5.0×10^{-4} day^{-1} with a range of 2.3×10^{-4} to 7.7×10^{-4} d^{-1} (Maslia et al. 2007, 2009).

- NRC Report p. 50: "*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* "

  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 reaction of TCE is highly site-specific. For example, Christiansen et al. (1997) and Miller et al. (2005) reported 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.

  In the modeling of contaminant transport at a contaminated site, the field measurement data at the site are very important in validating the numerical models and in obtaining more accurate simulation results. For the numerical study at the Tarawa Terrace area, we had limited field data regarding the concentrations of PCE, TCE, and *trans*-1,2-DCE. Review of degradation byproduct data analyses, provided to ATSDR by the Department of the Navy, U.S. Marine Crops, the North Carolina Department of Environment and Natural Resources, 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). As mentioned above, since the primary byproduct of the biological degradation of TCE depends on site-specific conditions, it is more reasonable to select *trans*-1,2-DCE instead of *cis*-1,2-DCE as a primary TCE-bioreaction-byproduct in the study on the groundwater contamination at the Tarawa Terrace area. This NRC critique, therefore, ignores site-specific TCE degradation

byproduct data pertinent to Tarawa Terrace and vicinity, listed in Chapter E of the Tarawa Terrace report series.

- NRC Report p. 50: "*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 prediction.*"

  All modeling analyses have "inherent" uncertainties. ATSDR openly acknowledges that concept. Uncertainty is not limited solely to historical reconstruction modeling as represented by this NRC report statement but is an inherent feature of all models when useful data are absent or sparse. The "profound limitation" that seems to so concern the NRC committee 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).

  ATSDR agrees with the last part of the aforementioned NRC report statement that uncertainties should be communicated along with model predictions. ATSDR has done exactly that as explained in detail in Chapters A and I of the Tarawa Terrace report series (Maslia et al. 2007, p. A47-A61, Maslia et al. 2009) as well as on ATSDR's website, which can be found at the following internet addresses:

  http://www.atsdr.cdc.gov/sites/lejeune/cljweb/disclaimer_ChapterIgraph.html and
  http://www.atsdr.cdc.gov/sites/lejeune/cljweb/disclaimer_ChapterItable.html.

CONCLUSIONS AND RECOMMENDATIONS IN THE NRC REPORT (P. 65–66)

As articulated in the paragraphs above and in detail in Appendices I and II, Section 2 of the NRC report "Contaminated Water Supplies at Camp Lejeune-Assessing Potential Health Effects" (NRC 2009) substantially lacks the scientific credibility and attention to technical details one has come to expect from and indeed appreciates in other scientific reports published by the NRC. Section 2 of the NRC report contains technical errors, misrepresentations of data, and erroneous interpretations of published information. Because of these deficiencies, ATSDR believes conclusions contained in Section 2 of the NRC report must be discredited. In addition, most of the conclusions and recommendations in Section 2 of the NRC report are substantially at odds with recommendations rendered by several review panels consisting of national and international experts in water modeling and epidemiology. For these reasons, ATSDR concludes that Section 2 of the NRC report cannot be considered an authoritative, scientifically valid interpretation or guidance document related to the historical exposure assessment of contaminated drinking water at Camp Lejeune.

The NRC committee "concluded that ATSDR applied scientifically rigorous approaches to address the complex groundwater-contamination scenario at Tarawa Terrace." ATSDR does agree with the NRC report that simpler methods to model Hadnot Point should be considered, recognizing, though, that simpler models will be characterized by greater uncertainty because of simplifying and limiting assumptions. ATSDR strongly disagrees, however, with the NRC report's recommendation that monthly estimates of contaminants levels not be used on the

epidemiological studies. Therefore, to complete historical reconstruction of contaminant levels for the Hadnot Point area of Camp Lejeune, ATSDR recommends the following approach:

- Application of simpler modeling approaches,
- Application of "locally-refined-grid" numerical models for selected sites,
- Development of algorithms to reconstruct water-supply well on-off cycling patterns,
- Application of sensitivity and uncertainty analyses to further refine estimates of model parameters based on data for Hadnot Point and vicinity, and
- Address and pursue recommendations made by water-modeling expert panels.

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APPENDIX I: RESPONSE TO SPECIFIC NRC REPORT COMMENTS BY R.E. FAYE, CONSULTANT TO EASTERN RSEARCH GROUP, INC.

1. DNAPL (PCE) SOURCE

The National Research Council (NRC) report implicitly characterizes the source area for PCE contamination at Tarawa Terrace as containing a free-phase DNAPL mass (NRC 2009, p. 33, 38, 43, and 49). Extensive field data collection and analyses of soil and groundwater samples in the immediate vicinity of ABC One-Hour Cleaners, the source of PCE to the subsurface and to groundwater, and subsequently within the center of mass of the PCE plume as it migrated downgradient from ABC One-Hour Cleaners substantially contradict the NRC's characterization of the PCE source as a free-phase DNAPL mass. These data indicate conclusively that the source area was characterized solely by PCE dissolved in groundwater at concentrations ranging from about 15 percent to less than 1 percent of PCE solubility in water (210,000 µg/L) (Roy F. Weston, Inc. 1992, 1994, Weston Solutions, Inc. 2005). The earliest of these data are published and described in detail in Chapter E of the Tarawa Terrace series of reports (Faye and Green 2007). The maximum simulated PCE concentration in the source area was about 88,000 µg/L, which is less than 42 percent of water solubility. Multi-phase flow as described in the NRC report (NRC 2009) was never observed during the collection and analyses of numerous soil and groundwater samples and most probably never occurred within the domain of the Tarawa Terrace models.

A floor drain at ABC One-Hour Cleaners transferred waste from the dry cleaning processes, including PCE waste or spillage, to a septic tank which in turn transferred liquid wastes to a drain field where PCE was introduced into the subsurface. This septic tank was the major source of PCE to groundwater at ABC None-Hour Cleaners and also received waste water from several bathrooms and washing machines at the dry cleaners (Shiver 1985; Meltz 2001). Use of the floor drain and septic system was terminated in 1985 or early in 1986. Concentrations of PCE in the liquid phase of the septic tank used by ABC One-Hour Cleaners were determined in 1991 and equaled 6,800 µg/L. Samples of the liquid phase collected in 1986 contained PCE concentrations of 1,040 µg/L (Roy F. Weston, Inc. 1992, 1994). Substantial dilution of free phase PCE undoubtedly occurred continuously within the septic tank at ABC One-Hour Cleaners prior to the introduction of the septic waste to the drain field and subsequently to groundwater where additional dilution occurred. A similar characterization of the PCE source at ABC One-Hour Cleaners is described in Chapter F of the Tarawa Terrace series of reports (Faye 2008).

With the exception of a passing reference to a PCE concentration of 12,000 µg/L determined in groundwater in the vicinity of ABC One-Hour Cleaners, no basis is provided in the NRC report (NRC 2009) for a free-phase characterization of DNAPLs in the PCE source area and no technical or scientific rationale for such a characterization is otherwise provided. Such omissions are professionally and scientifically irresponsible and seriously diminish the credibility of NRC's findings and conclusions with respect to the PCE source characterization.

2. CALIBRATION TARGETS

Assigning calibration targets prior to the beginning of model simulations is an accepted and well-recognized adjunct to trial-and-error model calibration (Anderson and Woessner 1992; van der Heijde and Elnawawy 1993, ASTM 2002). The determination of calibration targets is, by definition, somewhat to highly subjective and is dependent on the desired degree of fidelity or

APPENDIX I: RESPONSE TO SPECIFIC NRC REPORT COMMENTS BY R.E. FAYE, CONSULTANT TO EASTERN RSEARCH GROUP, INC.—continued

correspondence to the hydrogeologic environment accorded to the model simulations. For the Tarawa Terrace models, a high degree of fidelity was anticipated and calibration targets were assigned accordingly in conjunction with the estimated accuracies of field data. For example, the calibration target for field potentionmetric levels determined by a tape down method was ± 3.0 ft.This target was derived from the least accurate water-level measurements at locations where land-surface altitude was determined using topographic maps. Similarly, the calibration target for water-level measurements determined by airline measurements was ± 12 ft and was based on the presumed resolution of airline pressure gages. These approaches are described in detail in Chapter C of the Tarawa Terrace series of reports (Faye and Valenzuela 2007, p. 24) and, as such, partly contradict the finding of the NRC report that "the basis used for setting the values of the 'calibration target range' was unclear" (Faye and Valenzuela 2007, p. 49). Assignment of a calibration target to contaminant concentration data was more subjective than the methods used for water-level measurements. Expected guidance from literature sources was not forthcoming as, apparently, calibration targets are not widely used as adjuncts to fate and transport model calibration. Nevertheless, simulation results and related residuals were examined in the few reports that summarized results of investigations similar to those undertaken at Tarawa Terrace and a half-order of magnitude range was decided upon as a reasonable and rigorous calibration target for the fate and transport simulations.

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APPENDIX I: RESPONSE TO SPECIFIC NRC REPORT COMMENTS BY R.E. FAYE, CONSULTANT TO EASTERN RSEARCH GROUP, INC.—continued

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APPENDIX II: RESPONSE TO SPECIFIC NRC REPORT COMMENTS BY M.M. ARAL, PRINCIPAL INVESTIGATOR, ATSDR-GEORGIA TECH RESEARCH PROGRAM ON EXPOSURE-DOSE RECONSTRUCTION

MEMORANDUM

To: Morris Maslia, PE
Project Manager
Exposure-Dose Reconstruction Program
ATSDR, CDC

From: Prof. Mustafa M. Aral
Director, Multimedia Environmental Simulations Laboratory
School of Civil and Environmental Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0355
Phone: 404 · 894 · 2243
Fax: 404 · 894 · 5111
E-mail: maral@ce.gatech.edu
WWW: http://mesl.ce.gatech.edu/

Date: June 27, 2009

Subject: **Response to Comments of the NRC Report on ATSDR Water Modeling Study.**

The National Research Council (NRC) was requested to conduct a review by the Department of Navy (DON), under a mandate by the U.S. Congress (Public Law 109-364, Section 318). The U.S. Navy requested the NRC review to address whether adverse health outcomes are associated with past drinking-water contamination at U.S. Marine Corps (USMC) Base Camp Lejeune, North Carolina. The NRC review included an assessment of the Agency for Toxic Substances and Disease Registry's (ATSDR) current health study on birth defects and specific childhood cancers at Camp Lejeune and in particular, water-modeling analyses and findings to date. The NRC report released on Saturday July 13, 2009 (NRC 2009) covers a wide range of topics that include: (i) conceptual topics of exposure analysis and source characterization that are based on expert opinions of NRC committee members; (ii) water modeling based on observations of the NRC committee and the critique of the science-based tools and analyses that are described in ATSDR technical reports on Tarawa Terrace and vicinity (Maslia et al. 2007); and, (iii) the critique of findings and interpretation of water-modeling study results that were completed by ATSDR at Tarawa Terrace and vicinity at Camp Lejeune.

To accurately respond to the comments made under each category that I have identified above, the review comments I am providing below are grouped under two specific headings. This is in an effort so as not to confuse the reader and mix-and-match the review comments reported by the NRC committee which range from "conceptual topics" to the "actual data reported" in the ATSDR water-modeling study. I hope this approach will provide ATSDR with a clear picture of a range of erroneous statements and mischaracterizations made in the NRC report which are very puzzling. Accordingly, the discussion included in my review comments will cover the range

APPENDIX II: RESPONSE TO SPECIFIC NRC REPORT COMMENTS BY M.M. ARAL, PRINCIPAL INVESTIGATOR, ATSDR-GEORGIA TECH RESEARCH PROGRAM ON EXPOSURE-DOSE RECONSTRUCTION—continued

from "conceptual" perspectives on exposure analysis to "water-modeling analysis" and "application specific" topics that are addressed in the NRC report.

It is important to note that the review comments I am providing below are only associated with the water-modeling aspects of the current ATSDR health study and the NRC report and do not cover any epidemiological aspects. All references to the "NRC report" refer to the recently released NRC report titled, "*Contaminated Water Supplies at Camp Lejeune—Assessing Potential Health Effects*" and cited as NRC (2009) in the Reference section of this memorandum. Furthermore, the reader should recognize that sentences in *italic font* are extracted verbatim from the NRC report and statements in "regular" font are my responses to those specific NRC report statements.

A. REVIEW COMMENTS ASSOCIATED WITH CONCEPTUAL TOPICS OF EXPOSURE ANALYSIS AND SITE CHARACTERIZATION:

1. **Comment on p. 29:** *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.*

   Response: In this comment, which also includes a reference to the work of one of the committee members (Nuckols et al. 2004), the NRC committee is providing the reader with their understanding of the components of an exposure study that is associated with pollutants that may exist in an aquatic pathway at a contaminated site. The aquatic exposure analysis framework described in this statement is a conceptual statement and represents a very restrictive view of the exposure pathway analysis that needs to be considered at contaminated sites given the current understanding of the interaction between environmental pathways and the behavior of chemicals along those pathways.

   Current knowledge in this scientific field recognizes that in an aquatic exposure study the environment must be considered as a whole and scientific and regulatory approaches alike must take into account complex interactions between multimedia and intermedia interactions that exist in a multitude of potential environmental pathways at a site. In my opinion one should not emphasize only the concept of a "**hydrogeologic** connection" between the contaminant source and the exposure point as put forth by the NRC

APPENDIX II: RESPONSE TO SPECIFIC NRC REPORT COMMENTS BY M.M. ARAL, PRINCIPAL INVESTIGATOR, ATSDR-GEORGIA TECH RESEARCH PROGRAM ON EXPOSURE-DOSE RECONSTRUCTION—continued

committee. This conceptual suggestion made by the NRC committee would be a very elementary and a restrictive exposure analysis framework.

As specialists in this field, we are well aware of the fact that pollutants released to an aquatic environment are distributed among environmental media such as air, water, soil, vegetation etc., as a result of complex physical, chemical and biological processes. Thus, environmental pollution is a **multi-pathway problem** and environmental exposure assessment methods require that we carefully consider the transport, fate and accumulation of pollutants in the environment as a whole, (Cohen 1986). Methods that are proposed to evaluate environmental migration or exposure characterization in this envirosphere must consider all potential pathways and also the interactions between these pathways. In the scientific literature, the multi-pathway approach to environmental exposure analysis is identified as Total Exposure Characterization (TEC).

Elements of this multi-pathway analysis for an aquatic contamination source are imbedded in the ATSDR water-modeling study that is being conducted for the Tarawa Terrace area of the Camp Lejeune site as much as possible given the data restrictions. The specific pathways and processes considered in the ATSDR water-modeling study are: (i) saturated groundwater; (ii) unsaturated groundwater; (iii) vapor emissions; (iv) multispecies analysis of contaminants in these three pathways; (v) mixing in the water treatment system; and, (vi) water-distribution system estimates.

In this analysis framework it is also important to recognize that one should not try to fit a physical problem to a model that may be readily available for use. Instead, appropriate models should be selected or developed that would fit the characterization of the physical problem at hand. Thus, selection of appropriate modeling tools to complete such an analysis is very important and is considered in sufficient detail in the ATSDR study. This is a very important point, which was either completely ignored in the NRC report or, steps taken by the ATSDR water-modeling team to address these issues in a sound scientific manner were considered scientifically not credible without the NRC committee providing any supporting evidence. I will revisit this issue in more detail in my comments below while providing case-specific public domain data and public domain information.

2. **Comment on p. 33:** *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).....* (after a lengthy discussion of what DNAPL is and how DNAPL-based contaminants behave in the subsurface and what the consequences of such a source are, the NRC report continues in this section with the following remarks linking DNAPL presence to the aquifers at Camp Lejeune.) ..... *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.....*

Response: The NRC report does not provide any information for the **justification** of this conceptualization of the contamination source at the ABC One-Hour Cleaners site and

APPENDIX II: RESPONSE TO SPECIFIC NRC REPORT COMMENTS BY M.M. ARAL, PRINCIPAL INVESTIGATOR, ATSDR-GEORGIA TECH RESEARCH PROGRAM ON EXPOSURE-DOSE RECONSTRUCTION—continued

Tarawa Terrace and vicinity other than providing a reference to a source concentration of 12,000 µg/L, reported in Chapter E of the ATSDR Tarawa Terrace report series (Faye and Green 2007, p. 38). This is followed by a reference to a number of 110,000 µg/L (p. 38 of the NRC report, second paragraph from bottom of page). As indicated in the NRC report, this is the highest possible concentration of tetrachloroethylene (PCE) in water. Because this reference number is given in the NRC report **without a reference citation, I question the credibility of this reference number. The NRC report also does not discuss the importance of this number in their conceptualization of the contaminant source as a DNAPL**. Furthermore, the NRC report does not refer to a data source on the solubility levels of PCE in water like those data sources reported in Chapter D of the ATSDR Tarawa Terrace report series (Lawrence 2007). The NRC report does not refer to or cite a database that may exist in USMC files at Camp Lejeune, unknown to the ATSDR water-modeling team, that NRC committee members may have had access to that would indicate the presence of DNAPL-phase PCE at the site. The NRC report also does not refer to a systematic dry-cleaner disposal procedure that is reported in the documents they have reviewed for handling the disposal of the chemical PCE as a pure-phase PCE at the ABC One-Hour Cleaners site.

In the NRC report, the highest concentration of dissolved PCE, 110,000 µg/L, must imply the NRC committee understanding of the solubility level of PCE in water. Because a reference is not provided, I could not confirm this number. However, our references indicate that the solubility of PCE in water is around 200,000 µg/L (= 200 mg/L) at 15°C or higher. In Chapter D of the ATSDR Tarawa Terrace report series (Lawrence 2007, p. D12, Table D9), solubility of PCE is reported to be 210, 000 µg/L (=210 mg/L) at 25°C, which is the solubility number I would like to work with for my analysis below. There are other references in the literature that report the solubility of PCE at much higher concentrations as well, which are not referenced here. This is because I would like to focus on what is reported in the ATSDR Tarawa Terrace series of reports.

The 12,000 µg/L concentration reported in NRC report (and also in Chapter E of the ATSDR Tarawa Terrace report series [Faye and Green 2007]) as a justification for the presence of a DNAPL phase is about 5.7% to 6% of the solubility level of PCE (12,000/200,000 = 6% or 12,000/210,000 = 5.7%). The 12,000 µg/L concentration is the dissolved-phase PCE concentration in the groundwater at ABC One-Hour Cleaners as reported by ATSDR (Faye and Green 2007). Although this is a high concentration, this value is much less than PCE's solubility limit in water (200,000 µg/L at 15°C or 210,000 µg/L at 25°C). The location of the highest concentration sample within Tarawa Terrace and vicinity can be used to identify the source location at the site. High concentrations at a site may suggest the possibility of non-aqueous phase (NAPL) PCE (PCE in form of NAPL) presence but this does not guarantee a NAPL presence at the site, because in this case, 12,000 µg/L is 6% or less of the solubility limit of PCE.

Thus, the conceptual DNAPL contaminant source characterization that is provided in the NRC report without any justification and without any field data support is both extremely bothersome and irresponsible. This reference to the presence of a DNAPL-phase

APPENDIX II: RESPONSE TO SPECIFIC NRC REPORT COMMENTS BY M.M. ARAL, PRINCIPAL INVESTIGATOR, ATSDR-GEORGIA TECH RESEARCH PROGRAM ON EXPOSURE-DOSE RECONSTRUCTION—continued

contaminant source at the site not only appears in the aforementioned comment on NRC report page 33, but it is repeatedly referred to in other pages of the NRC report which is an attempt to discredit the ATSDR analysis and its findings from its source conceptualization origins. As a member of the ATSDR water-modeling team, I respectfully request that, through ATSDR, I should be provided with the recorded field data evidence that the NRC committee was privy to that would support the DNAPL conceptualization. Also reporting the solubility of PCE in water at about **half the value of the data reported in the ATSDR Chapter D report** (Lawrence 2007) **without providing a reference** (page 38 of the NRC report) is a scientifically unacceptable practice. Short of citing field data evidence and an appropriate reference for the solubility level of PCE as reported in the NRC report, I would question the scientific basis of the complete NRC report that relies on the accuracy of this erroneous conceptualization. Without field data evidence, the NRC review is based on hypothetical conditions and assumptions that are extracted from the scientific work of others (Figure 2-3 of the NRC report) which is based on studies that are conducted at other sites—and these sites have no relevance to the ABC One-Hour Cleaners site or Tarawa Terrace and vicinity. The purpose of this assertion (PCE DNAPL source conceptualization) and misrepresentation of data and site-specific conditions by the NRC committee is not clear to me.

During the NRC committee review process, the question of the characterization of the source was brought to the attention of ATSDR water-modeling team members in a request for information by an NRC committee member (Email communication from P. Clement to M.L. Maslia, ATSDR, May 5-11, 2008). During that time, ATSDR water-modeling team members provided the NRC with data ATSDR had on the subject matter clearly showing why we selected to simulate the PCE source as a dissolved-phase source. Furthermore, we clearly identified why the dissolved-phase injection procedure applied in the models used for the ATSDR water-modeling analyses. The information that was provided to the NRC was based on data from several remedial investigation reports, site reports, and other DON and USMC files (Shiver 1985, Roy F. Weston 1992, 1994). In these field study reports, there is no recorded data reported by DON and USMC consultants that would provide evidence of, or substantiate the existence of, the presence of a DNAPL source at ABC One-Hour Cleaners or Tarawa Terrace. If the DNAPL source conceptualization that appears in the NRC report is based solely on the data source and information we provided to the NRC committee, then I do not agree with the NRC's source characterization. I, therefore, consider this to be a misrepresentation of the conditions at the site. If this conceptualization is based on any other information or data that we are not aware of, and if this information was provided to NRC by DON, the USMC, or their consultants, we need to be provided with that information and data. Because the reference to a DNAPL-phase in the aquifers underlying ABC One-Hour Cleansers and Tarawa Terrace and vicinity appears in several places within the NRC report, I will revisit this topic again in my discussion below.

In the aforementioned statement on page 33 of the NRC report, I also noticed that the NRC committee acknowledged that the PCE source was discharged to the unsaturated zone of the aquifer underlying ABC One-Hour Cleaners and Tarawa Terrace and vicinity.

APPENDIX II: RESPONSE TO SPECIFIC NRC REPORT COMMENTS BY M.M. ARAL, PRINCIPAL INVESTIGATOR, ATSDR-GEORGIA TECH RESEARCH PROGRAM ON EXPOSURE-DOSE RECONSTRUCTION—continued

However, given that observation, the NRC committee fails to provide a justifiable critique of the use of the MODFLOW family of codes that only considers a saturated groundwater zone by which analyze the physical problem at the site. On the contrary, the NRC committee considers the MODFLOW family of codes to be an acceptable modeling choice. This is probably because the NRC committee considers these MODFLOW codes as accepted state-of-the-art tools for typical groundwater pathway modeling. This is an example of a typical case of fitting a physical problem to a code "concept" I referenced in my response statement "A-1" above, which the ATSDR water-modeling team tried to avoid as much as possible.

In recognition of this problem and also in recognition of the general perception that prevails in the scientific community that the MODFLOW family of codes is an accepted procedure, the ATSDR water-modeling team first utilized the MODFLOW and MT3DMS codes in their simulations. In addition, to enhance our understanding of conditions at the site, ATSDR has and extended their analyses. The ATSDR water-modeling team applied the TechFLOW^{MP} software to understand and evaluate the unsaturated zone injection conditions that are implemented at the site. TechFLOW^{MP} is a public domain code that can be accessed from the Georgia Tech website for individual use without a fee (http://mesl.ce.gatech.edu/). The NRC report attempts to discredit this extra effort and the steps taken by the ATSDR water-modeling team to simulate the proper source disposal conditions at the ABC One-Hour Cleaners site by classifying: (i) the TechFLOW^{MP} code as a research tool; and, (ii) a proprietary code that is not verified. Again, this is very puzzling and a misrepresentation of the scientific and public domain facts of this case by the NRC committee. These NRC statements that appear in several places in the NRC report ignore a scientifically sound attempt by the ATSDR water-modeling team to properly solve a physical problem, above and beyond a traditional MODFLOW and MT3DMS application which the NRC review committee accepts (NRC 2009, p. 43). Additionally, these NRC statements misrepresent the public domain information of the status of a model used in the analysis. NRC committee remarks in this regard misrepresent a public domain code as a proprietary code without checking with the authors of the code or the web site where this code can be accessed freely by anybody without a fee. Further, the NRC committee failed to check current technical literature and scientific publications containing substantial evidence of publications involving the TechFLOW^{MP}. Contained in this technical literature and scientific publications is evidence where the TechFLOW^{MP} code has been tested and verified against other applications. (see web site : http://mesl.ce.gatech.edu/PUBLICATIONS/Publications.html) This lack of due diligence by the NRC committee is also very puzzling.

I am very familiar with the expertise of the scientists who prepared the NRC report, many of whom I know personally and respect. What I do not understand is how they reached these puzzling and in some cases erroneous conclusions, which are not justified in the NRC report they prepared. Misrepresentation of these scientific and public domain facts is extremely bothersome and, in my opinion, sheds a dark cloud over the scientific credibility and integrity of the overall NRC report.

APPENDIX II: RESPONSE TO SPECIFIC NRC REPORT COMMENTS BY M.M. ARAL, PRINCIPAL INVESTIGATOR, ATSDR-GEORGIA TECH RESEARCH PROGRAM ON EXPOSURE-DOSE RECONSTRUCTION—continued

B. REVIEW COMMENTS ASSOCIATED WITH SCIENCE-BASED TOOLS, ANALYSES, AND INTERPRETATION OF STUDY RESULTS:

1. **Comment on p. 43:** *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).*

   Response: This NRC report statement relies on their unsubstantiated and undocumented source characterization concept (see my review comment "A-2"). Using this conceptualization as an undisputable fact, the NRC committee then attempts to discredit the groundwater-modeling study conducted by ATSDR at the ABC One-Hour Dry Cleansers site and Tarawa Terrace and vicinity. This statement is a hyperbole, wherein first an "assumption" is made and then that "assumption" is considered to be a "fact" to critique the findings of a study. This approach in a critique does not even deserve a scientific response; and again, brings about more questions as to the scientific credibility and integrity of the NRC report.

2. **Comment on p. 43:** *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.*

   Response: I have addressed the path the NRC committee chose in reference to the misrepresentation of TechFLOW^{MP} as a proprietary code in my aforementioned response A-2. I will not repeat that here again. In reference to the PSOpS model developed by the Georgia Tech group, I would like to enquire of the NRC committee the following: Can a reference to a public domain code be provided by the NRC that is available through the published literature? Has such a public domain code been developed for, and applied to, any study that they are aware of to manage pumping-schedule operations in an optimal manner for a complex system such as the one at Tarawa Terrace? The answer to these questions is obvious and the answer is: "This type of public domain model does not exist."

   PSOpS is an optimization application that was developed by the Georgia Tech group participating in the ATSDR water-modeling analysis to yield answers to specialized uncertainty-related questions pertinent to the current health study at Camp Lejeune. The analysis is based on the MODFLOW family of codes in the generation of the database used to solve an optimization problem. The development of this optimization model was necessary to respond to scientific questions raised by the ATSDR Expert Panel (March 2005) whose members guided our study and contributed significantly to its quality. The members of this ATSDR Expert Panel are well known and respected scientists in the field and their names are listed in the Expert Panel report (Maslia 2005) that also is available on the ATSDR website. The question ATSDR Expert Panel members raised in this case

was related to the uncertainty of a pumping-schedule operation that may be implemented at the site and the characterization of its effects on the study outcome. The PSOpS model that was developed for the purposes of this analysis and used in the ATSDR water-modeling analyses to address this question became part of the PhD thesis of a graduate student at Georgia Tech. In that sense, the theoretical background of the model is reviewed and accepted by an independent PhD thesis committee at Georgia Tech and the detailed documentation of this model can be found in the PhD thesis of Dr. J. Wang, which is public domain information (Wang 2008)

In conclusion, the NRC committee is most likely aware of the following: (1) specialized models such as PSOpS are not available in the technical public-domain literature; and, (2) codes such as PSOps only are developed for the specialized purposes of the current study to find answers to specialized questions that are raised by the current water-modeling analysis. The concept of using an optimization algorithm that is fed by a database through the MODFLOW family of models, which is a common and routine procedure, is both scientifically sound and scientifically necessary in a study such as the one ATSDR is conducting at Camp Lejeune. If the NRC committee can provide us with a reference to another public domain model that can be used for our study and that would serve the same purpose, instead of the PSOpS model, we would be glad to use that model instead of the PSOpS model. To my knowledge, such a model is not available. In my opinion, the NRC committee also should recognize that the ATSDR water-modeling effort is not a run-of-the-mill work product and the problem at hand is not a routine problem that can be or should be analyzed using routine models. In such cases it is expected that specialized methods can be developed and implemented—this should not be shunned by the NRC, but instead, it should be applauded. It is most puzzling to see, that under the name "NRC," this approach is not encouraged, but instead, it is criticized.

3. **Comment on p. 44:** *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).*

Response: Again, in this statement, the NRC committee is asserting that the DNAPL source zone was misrepresented in the current study. I refer the reader to my previous comments in my response A-2 in reference to the DNAPL source mischaracterization by the NRC committee.

To reiterate, we have not represented a DNAPL source zone as an injection point in our models because there is no DNAPL source zone in the aquifer underlying the ABC One-Hour Dry Cleaners site and Tarawa Terrace and vicinity. If the claim of the NRC committee can be substantiated by any field data, not only we will modify our modeling study efforts, **but also we would strongly recommend that the U.S. Environmental Protection Agency (USEPA), their consultants, and the North Carolina Department of Environment and Natural Resources (NCDENR) should immediately abandon their current remediation efforts at the ABC One-Hour Dry Cleaners site and Tarawa Terrace and vicinity and adopt remediation strategies that would yield**

APPENDIX II: RESPONSE TO SPECIFIC NRC REPORT COMMENTS BY M.M. ARAL, PRINCIPAL INVESTIGATOR, ATSDR-GEORGIA TECH RESEARCH PROGRAM ON EXPOSURE-DOSE RECONSTRUCTION—continued

more effective results for a DNAPL source contaminant. USEPA and NCDENR field consultants who are currently not implementing DNAPL remediation technologies at the site is additional evidence that these agencies and their consultants also does not agree with the NRC committee as to the characterization of the contamination source as DNPL-phase PCE.

4. **Comment on p. 48:** *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.*

Response: There are obvious uncertainties in the physical problem being studied at ABC One-Hour Dry Cleaners and Tarawa Terrace and vicinity. The NRC committee would most likely agree with this statement. If we accept this statement, then the question becomes, should one completely ignore uncertainty in the analysis or, should one try to develop techniques that would provide an estimate of the effects of the uncertainty on the solution in a systematic way? We have chosen the second route.

The NRC committee should accept the fact that answers to uncertainty questions cannot be answered "**accurately**" as the report states in the above statement. Expecting that from an uncertainty analysis outcome would be scientifically irresponsible. Our uncertainty analyses are not provided to give "**accurate**" answers to the problem studied. Instead, our uncertainty analyses are used as estimates that would indicate the variability range of deterministic results provided earlier. The domain of uncertainty analysis is a scientific field which is not in the realm of the traditional groundwater fate and transport analysis expertise and should be viewed using a different microscope and expertise.

5. **Comment on p. 48:** *(5) there is no spatial variation in the microbiologic or geochemical characteristics.*

Response: The NRC committee correctly identified that in the application of the TechFLOW^{MP} model to the aquifers underlying the ABC One-Hour Dry Cleaners site and Tarawa Terrace and vicinity, we assumed no spatial variation of microbiologic characteristics. If the NRC committee is familiar with the finite element procedures used in the TechFLOW^{MP} model, they would acknowledge that this is not a restriction of the model but a restriction of the available field data for the site. If the microbial distribution in an aquifer can be accurately characterized, which we doubt can be accomplished in this case or any case, we can certainly include that heterogeneity in our modeling effort.

Having pointed out this fact, I would also like to question issues pertaining to levels of acceptable homogeneity considered in our modeling effort and compare it with levels of unacceptable homogeneity that are shunned in our modeling analysis based on the critique presented in the NRC report. For example the assumption of uniform infiltration across the model domain when the MODFLOW family of model codes is utilized was not critiqued in the NRC report, but the assumption of uniform microbial distribution in the multilayer aquifer domain is critiqued. Between these two processes, which would be the

APPENDIX II: RESPONSE TO SPECIFIC NRC REPORT COMMENTS BY M.M. ARAL, PRINCIPAL INVESTIGATOR, ATSDR-GEORGIA TECH RESEARCH PROGRAM ON EXPOSURE-DOSE RECONSTRUCTION—continued

easier process to characterize? I think the answer to this question is obvious—the infiltration process. Thus, although both processes are characterized by heterogeneity in the aquifer, accepting the homogeneity assumption for the infiltration case but not accepting homogeneity assumption for the microbial distribution case would be setting the bar too high and would be scientifically irresponsible considering the levels of data that may be available to characterize either process. A scientific review committee should be able to make these distinctions easily and come up with appropriate conclusions in their prepared review comments.

6. **Comment on p. 49:** *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.*

   Response: There are limitations of the modeling analyses conducted by ATSDR water-modeling team. We would be the first to acknowledge these limitations. This is evident by the level of detail of the uncertainty analysis conducted as part of the water-modeling analysis to envelope the effect of those uncertainties on the outcome presented. However, in my opinion, characterizing the uncertainty analysis outcome as not "**accurate**" as previously stated (see response B-4) or, that uncertainty analysis only should be conducted in "**verifiable**" cases as stated above is not a scientifically sound assessment or procedure. An uncertainty that can be verified is no longer uncertain.

7. **Comment on p. 49 first bullet:** *The effects of the DNAPL in both unsaturated and saturated zones have not been included in the studies.*

   Response: The NRC report brings back the DNAPL issue here again. Please see my response in A-2 and other comments above.

8. **Comment on p. 49 second bullet:** *Constant values of dispersivity (longitudinal dispersivity of 25 ft and transverse 2.5 ft) were used in the transport model.*

   Response: Although dispersivity is considered to be constant, based on the definition of the hydrodynamic diffusion coefficient, the hydrodynamic diffusion coefficients are variable because they depend on the velocity field at the site. This is a common assumption in most studies where field data are not available to support spatially variable dispersion coefficients. This comment again is related to my discussion of acceptable homogeneity and unacceptable homogeneity conditions at a site study (see my response B-5).

9. **Comment on p. 49 bullet four:** *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.*

APPENDIX II: RESPONSE TO SPECIFIC NRC REPORT COMMENTS BY M.M. ARAL, PRINCIPAL INVESTIGATOR, ATSDR-GEORGIA TECH RESEARCH PROGRAM ON EXPOSURE-DOSE RECONSTRUCTION—continued

Response: This characterization is a misrepresentation of the aforementioned models, clearly identified in my response A-2. As the NRC committee may acknowledge, the availability of codes with the capabilities of these models are very limited (see my response A-2 and B-2). In my opinion the use of these models in complex analysis should not be shunned by NRC, but instead, it should be encouraged since they are providing supplemental information beyond MODFLOW family of code applications (see my response in B-2).

10. **Comment on p. 49 bullet five:** *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 nonunique and uncertain.*

Response: PSOpS modeling concept is based on the effort of estimating the effects of uncertainty on the modeling outcome. This analysis is approached in a systematic manner following a well accepted process such as an optimization analysis based on some constraints to satisfy the demands. The PSOpS model uses the MODFLOW family of codes as its database engine. We are not claiming that the outcome provides the exact conditions representing the problem at the site. But the outcome of the analysis provides us with an envelope which bounds our deterministic analysis. This is a standard uncertainty analysis procedure similar to, for example, Monte Carlo analysis that is routinely used in uncertainty analysis. Monte Carlo analysis, according to a well established procedure, systematically evaluates the effects of uncertainty on the problem solution. In such an application, it is not **certain** that the random numbers generated would **exactly** represent the actual conditions for the problem at the site. However, the bounding limits of the analysis are the ultimate goal. The application of PSOpS, in essence, is very similar to that analogy.

As I have stated earlier, this goes back to the NRC report statement about the "**accuracy**" of the uncertainty analysis results that cannot be justified scientifically. Please see my response in B-4. Also, I have to emphasize again what I stated earlier: The domain of uncertainty analysis is a scientific field which is not in the realm of the traditional groundwater fate and transport analysis expertise and should be viewed using a different microscope and expertise.

11. **Comment on p. 49 bullet seven:** *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 1,418 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.*

Response: This reference to a vapor concentration at 1,418 µg/L is another example of misrepresentation of the results of the modeling analyses by the ATSDR water-modeling team. This aforementioned information was taken from Chapter A of the ATSDR Tarawa Terrace report series (Maslia et al. 2007, p. A44). The statement provided in the ATSDR report reads as follows:

APPENDIX II: RESPONSE TO SPECIFIC NRC REPORT COMMENTS BY M.M. ARAL, PRINCIPAL INVESTIGATOR, ATSDR-GEORGIA TECH RESEARCH PROGRAM ON EXPOSURE-DOSE RECONSTRUCTION—continued

"b. the maximum simulated PCE concentration in groundwater (model layer 1) at the Tarawa Terrace elementary school was 1,418 µg/L (Figure A15b), whereas the maximum simulated vapor-phase PCE (in the top 10 ft of soil) was 137 µg/L (Figure A20a)"

The above sentence, taken directly from the ATSDR report submitted to NRC, clearly states that the groundwater (not vapor) concentration of PCE in layer "1" is 1,418 µg/L concentration. Vapor concentration is given separately in the paragraph towards the end of that sentence. For the NRC report to represent this number (1,418 µg/L) as the vapor concentration that is simulated at the site in order to discredit a study does not fit into any norm of a scientific review. I will provide a more detailed analysis of this case using simulation results to bring clarity to the concern raised in the NRC report.

In this case, the work product referred to are the TechFLOW^{MP} modeling results and the particular analysis mentioned was conducted by the Georgia Tech group participating in the ATSDR water-modeling analysis of the ABC One-Hour Cleaners site and Tarawa Terrace and vicinity (Jang and Aral 2007). In order to provide the reader with clear evidence of scientific misrepresentation of the facts which seem to appear too frequently in the NRC report, the actual data reported in our report is presented below in sufficient detail—unlike the other responses I have provided to other comments in this document.

In the numerical study of the multispecies, multiphase groundwater contamination at ABC One-Hour Dry Cleaners and Tarawa Terrace and vicinity, TechFLOW^{MP} simulations used two boundary-conditions to characterize the ground surface under the original pumping schedule: (1) GSBC = 0.01 and (2) GSBC = 1.0 (Jang and Aral 2007, p. G15). Here the acronym "GSBC" stands for the Ground Surface Boundary Condition. For the in-/out-flux of gas between the atmosphere and the unsaturated zone, if the ground surface does not have low-permeable zones or hindrances due to pavement, lakes, or buildings, the GSBC value is set to be 1.0. This implies that the soil gas can be freely released into the atmosphere from the unsaturated zone. However, when some objects, including roads, buildings, ponds, or highly water-saturated areas, are present at the ground surface, the soil gas can not be released into the atmosphere freely. Under such a condition, GSBC is set to be 0.01 in the current study. Actually any number between these two extremes can be considered in the analysis. However, just to show the bounds of the results, the discussion here will be confined to these two extreme cases.

In order to analyze the concentration distribution around the school area as it is referred to in the aforementioned NRC report comment, the location of the school at Tarawa Terrace has to be identified, and it shown in Figure 1.

APPENDIX II: RESPONSE TO SPECIFIC NRC REPORT COMMENTS BY M.M. ARAL, PRINCIPAL INVESTIGATOR, ATSDR-GEORGIA TECH RESEARCH PROGRAM ON EXPOSURE-DOSE RECONSTRUCTION—continued



Figure 1. Location of the Tarawa Terrace Elementary School

In the school area, the groundwater table is near the ground surface (CH2MHILL 2007). In this study, the ground surface is at z = 7.6 meters (m, z = 25 ft), and the groundwater table is around z = 2.4 – 4 m (z = 8 – 13 ft) (Jang and Aral 2007, Figure G3, p. G10). Thus, the concentration distributions of the vaporized PCE at z = 6 m are presented below, where the unsaturated zone is at this location.

As shown in Figure 2, under GSBC = 0.01, which is more representative of an area where there are buildings and pavements, the predicted vaporized PCE concentrations in the pore space of the soil at the center of the school area (x = 2,580 m, y = 1,975 m) are about 15.5 µg/L during December 1984 (Figure 2a) and 3.7 µg/L during December 1994 (Figure 2b). Within the school area (marked with the circle in this figure), the PCE concentration ranges 0.1-100 µg/L during December 1984 (Figure 2a) and 0.1-50 µg/L during December 1994 (Figure 2b).

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APPENDIX II: RESPONSE TO SPECIFIC NRC REPORT COMMENTS BY M.M. ARAL, PRINCIPAL INVESTIGATOR, ATSDR-GEORGIA TECH RESEARCH PROGRAM ON EXPOSURE-DOSE RECONSTRUCTION—continued

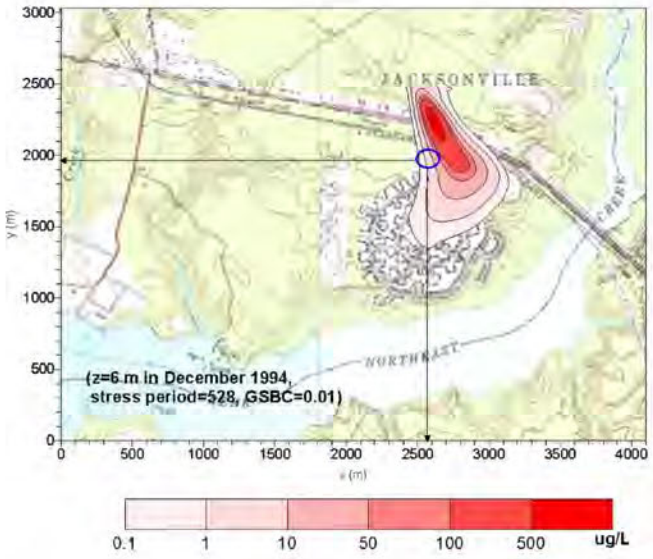


Figure 2b. Vaporized PCE concentrations in the gas phase under the original pumping schedule (PS-O) with GSBC=0.01, at z=6, December 1994.

Having provided this comparison, I also question the source of the reference number, 55 µg/L, that is used in the NRC report. The NRC report provides a reference in this case and this reference is McDermott et al. (2005). I was curious about this reference; therefore, I located and obtained a copy of the referenced paper. In the McDermott et al. (2005) study, the authors are analyzing and reporting data on the PCE vapor concentrations in a building where dry-cleaner operations are housed in New York City. Does the NRC committee expect us to accept the concept that what is observed (measured) as vapor concentration in a building that houses a dry-cleaner facility in New York City should also apply to the pore space of the soils at the site of an elementary school area in Camp Lejeune, North Carolina? Or do they expect that what we have simulated in the pore space of the soils at a site in North Carolina should also confirm the observations made in New York City, 17–20 years beyond our final simulation date (2001–2003), in some dry-cleaner facility building? In my opinion, these types of comparisons, expectations, and assertions are scientifically not acceptable and credible; they discredit the NRC report in its entirety.

In the groundwater contamination study that utilized TechFlow^{MP} (Jang and Aral 2007), the local equilibrium of contaminant partitioning between the water and gas phases is

APPENDIX II: RESPONSE TO SPECIFIC NRC REPORT COMMENTS BY M.M. ARAL, PRINCIPAL INVESTIGATOR, ATSDR-GEORGIA TECH RESEARCH PROGRAM ON EXPOSURE-DOSE RECONSTRUCTION—continued

implemented while calculating the contaminant distribution between the two phases (gas and liquid). Thus, we can use the Henry coefficient, H, in estimating PCE concentration in the gas phase from the concentration in the groundwater phase as follows:

$$C_{Vapor,PCE} = HC_{GroundWate,PCE}$$

For PCE, H is 0.35 (Jang and Aral 2007, Table G2). Using the dissolved PCE concentration in the groundwater shown in Figure G5 of Jang and Aral (2007) (in the unsaturated and saturated zones), the overall concentration distribution of the vaporized PCE within the gas phase in the unsaturated zone can also be estimated. This simple calculation could have been done by the NRC committee to confirm the vapor concentration numbers they are reporting in their statement. In Figure G5 of Jang and Aral (2007), the dissolved PCE concentration in the groundwater is 100-500 µg/L near the ground surface at the location of the elementary school (x = *2,580* m, y = *1,975* m). Therefore, the vaporized PCE concentration will be approximately 35-175 µg/L in the unsaturated zone near the school area. The cross section line A-A' in Figure G5 is located at x = 2,606 m.

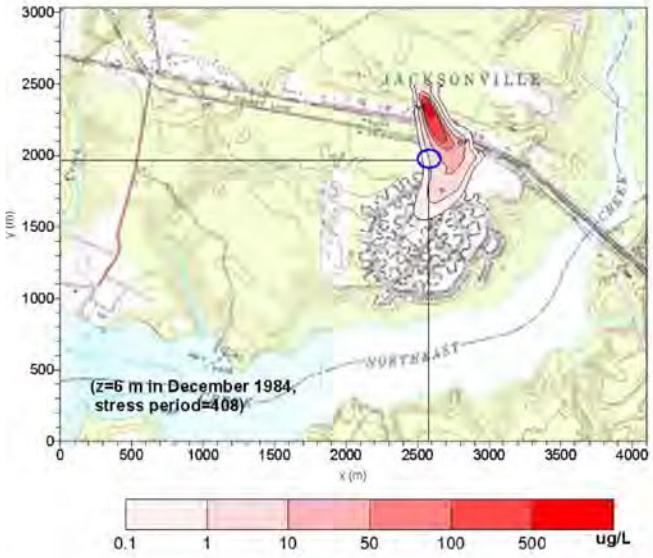


Figure 3a. Vaporized PCE concentrations in the gas phase under the original pumping schedule (PS-O) with GSBC=0.01, z=6, December 1984.

APPENDIX II: RESPONSE TO SPECIFIC NRC REPORT COMMENTS BY M.M. ARAL, PRINCIPAL INVESTIGATOR, ATSDR-GEORGIA TECH RESEARCH PROGRAM ON EXPOSURE-DOSE RECONSTRUCTION—continued

Let us also analyze the results of the other boundary condition that is used in the TechFLOW^{MP} model out of curiosity and see if the vapor concentration value of 1,418 µg/L reported in the NRC report was referring to that case. The results reported in (Jang and Aral 2007) under the condition GSBC = 1 are shown in Figure 3. The predicted vaporized PCE concentrations at the center of the school area ($x = 2580$ m, $y = 1975$m) are about 0.99 during December 1984 (Figure 3a) and 0.1 µg/L during December 1994 (Figure 3b) (i.e. more PCE vapor is released to the atmosphere and less is remaining in the pore space when compared to the previous results). Within the school area (marked with the circle in the figure), the concentration ranges 0.1-10 µg/L in December 1984 (Figure 3a) and less than 5 µg/L in December 1994 (Figure 3b).

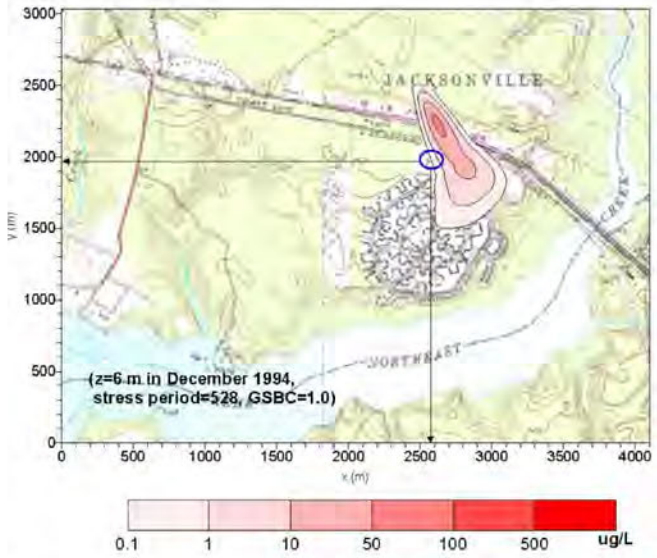


Figure 3b. Vaporized PCE concentrations in the gas phase under the original pumping schedule (PS-O) with GSBC=0.01, z=6, December 1994.

As can be seen from these results the number reported in the NRC report does not exist in the ATSDR water-modeling analysis as vapor concentration. This is a clear misrepresentation of the ATSDR water-modeling results. The purpose of this misrepresentation is not clear to us.

The field investigation during 2007 (CH2MHILL 2007) it was reported that the vaporized concentrations of PCE near the ground surface were below detection limits or very low,

APPENDIX II: RESPONSE TO SPECIFIC NRC REPORT COMMENTS BY M.M. ARAL, PRINCIPAL INVESTIGATOR, ATSDR-GEORGIA TECH RESEARCH PROGRAM ON EXPOSURE-DOSE RECONSTRUCTION—continued

3.9 ppbv (parts per billion volume), which is equivalent to 0.028 µg/L. Considering the time gap between the end of the historical simulation time (December 1994) and the field investigation time (July 2007), the simulation results that are provided in the Chapter G report of the ATSDR Tarawa Terrace report series (Jang and Aral 2007) provide reasonable modeling results and represent acceptable levels of expected vapor concentration near the Tarawa Terrace elementary school. Are we asserting that this is absolutely the case? The answer to that question is absolutely "No." This outcome is only an estimate based on the assumptions and limitations of the models considered in the ATSDR water-modeling analyses and the assumptions and limitations are based on our best judgment of the conditions that may exist at the ABC One-Hour Dry Cleaners site and Tarawa Terrace and vicinity.

The ATSDR water-modeling reports do not report such high concentration of vaporized PCE concentration in the gas phase. The vaporized PCE concentration of 1,418 µg/L is equivalent to a dissolved PCE concentration of 4,051 µg/L, in the groundwater:

$$C_{Vapor,PCE} = HC_{GroundWate,PCE}$$
$$C_{GroundWate,PCE} = 1418/0.35 = 4051.4$$

I also note that the unsaturated zone is located at a very thin layer near the ground surface (z = 7.6 m (25 ft)) in Jang and Aral (2007, Figure G5) which is characterized in terms of several layers in water-modeling analysis. The maximum thickness of the unsaturated zone is about 7.6 m.

In conclusion the data, the associated discussion of the vapor levels near the Tarawa Terrace elementary school area, and also the reference provided in the NRC report (McDermott et al. 2005) are far from the facts of the case and the results that are presented by the ATSDR water-modeling team. Again I see here a misrepresentation of the data reported in a study to discredit a study. The purpose of that approach is not clear to me. However, I can declare without hesitation that this approach does not have any scientific credibility and place in any scientific document.

12. **Comment on p. 49 bullet eight:** *The biodegradation model used within the TechFlowMP code is based on an untested preliminary research model.*

and also,

Comment on p. 50: *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.*

Response: The detailed description of "why *trans*-1,2-dichloroethylene is chosen as the representative byproduct of TCE bioreaction at the Tarawa Terrace area instead of *cis*-

APPENDIX II: RESPONSE TO SPECIFIC NRC REPORT COMMENTS BY M.M. ARAL, PRINCIPAL INVESTIGATOR, ATSDR-GEORGIA TECH RESEARCH PROGRAM ON EXPOSURE-DOSE RECONSTRUCTION—continued

1,2-DCE" is given in page G4 of the report, Chapter G (Jang and Aral 2007). Additional explanation regarding this issue is given below.

As shown in Figure G2 of the report (Jang and Aral 2007), the anaerobic biological degradation of trichloroethylene (TCE) generates three isomers, *cis*-1,2-dichloroethylene (*cis*-1,2-DCE), *trans*-1,2-dichloroethylene (*trans*-1,2-DCE), and 1,1-dichloroethylene (1,1-DCE). As discussed in the report (Jang and Aral 2007), *cis*-1,2-DCE (1,2-cDCE) is the most common byproduct among the three DCE isomers produced theoretically (Wiedemeier 1998). Even though *cis*-1,2-DCE has been often used as a primary byproduct of TCE-biodegradation under the anaerobic conditions in contaminant-transport modeling of chlorinated ethenes (Clement et al. 2000; Jang and Aral 2008), but the primary byproduct of the TCE bioreaction highly depends on the chemical-biological conditions (especially, microorganisms and nutrients) at the contaminated sites (Bradley 2003), implying that the biological reaction of TCE is highly site-specific. For example, Christiansen et al. (1997) and Miller et al. (2005) reported 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.

In the modeling of contaminant transport at a contaminated site, the field measurement data at the site are very important in validating the numerical models and in obtaining more accurate simulation results. For the numerical study at the Tarawa Terrace area, we had limited field data regarding the concentrations of PCE, TCE, and *trans*-1,2-DCE. This is indicated in the following statement of the ATSDR report: Review of degradation byproduct data analyses, provided to ATSDR by the Department of the Navy, U.S. Marine Crops, the North Carolina Department of Environment and Natural Resources, 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).

As mentioned above, since the primary byproduct of the biological degradation of TCE depends on site-specific conditions, it is more reasonable to select *trans*-1,2-DCE instead of *cis*-1,2-DCE as a primary TCE-bioreaction-byproduct in the study on the groundwater contamination at the Tarawa Terrace area.

The NRC critique, therefore, ignores site-specific TCE degradation byproduct data pertinent to Tarawa Terrace and vicinity, listed in Chapter E of the Tarawa Terrace report series. This statement again clearly demonstrates the lack of due diligence by the NRC review committee in their review of the data that exists at the Tarawa Terrace, Camp Lejeune site and their lack of understanding of the facts of the site specific case based on this data. This is very bothersome.

APPENDIX II: RESPONSE TO SPECIFIC NRC REPORT COMMENTS BY M.M. ARAL, PRINCIPAL INVESTIGATOR, ATSDR-GEORGIA TECH RESEARCH PROGRAM ON EXPOSURE-DOSE RECONSTRUCTION—continued

13. **Comment on p. 50 next to last bullet:** *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.*

    Response: Historical reconstruction is a procedure that is accepted in the literature. It uses models to predict the past in a conceptually similar manner the models are routinely used to predict the future in engineering studies. The ATSDR response document provides references to such historical reconstruction applications.

14. **Comment on p. 65:** *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.*

    Response: Use of simpler models may be easier to implement. We are already proceeding in that direction for the Hadnot point study. However, how the detailed questions that are raised in the NRC report could be answered using simpler models is not clear to me.

CONCLUSIONS:

Examples of the scientific evidence presented in this response statement and the discussion of this evidence herein clearly indicate that the data and the analysis presented in the NRC report (NRC 2009) are misrepresentations and mischaracterizations of the findings of the ATSDR water-modeling analyses conducted at the ABC One-Hour Cleaners site and Tarawa Terrace and vicinity. The conceptual characterizations made by the NRC committee also do not fit available field data or reported field conditions by the USEPA, their consultants, or the NCDENR which are guiding current remediation efforts at ABC One-Hour Cleaners and Tarawa Terrace and vicinity. Thus, what is in question here is the credibility of the complete contents of the NRC report as a scientific document of any value.

As I have said earlier, I know and respect many of the NRC committee members. What I do not understand is, how they reached these puzzling and in some cases erroneous conclusions in their review.

Thus, I believe, due to the presence of numerous errors, misrepresentations and mischaracterization of the scientific facts of the ATSDR water-modeling analyses, the NRC report cannot be used as a guidance document in its entirety. In light of the concerns that I have raised in this response statement, I recommend that the NRC should be asked to: (i) prepare a supplemental document in which detailed correction of all the facts of the case would be

included without misrepresentation or mischaracterization; (ii) based on these facts a reanalysis and reinterpretation of the ATSDR water-modeling analysis should be conducted and documented; and, (iii) the outcome be reissued in a report immediately to serve the public health concern of the former Marines at Camp Lejeune, North Carolina. Otherwise, in the opinion of many scientists who will review the contents of the NRC report and the responses to the report such as this one, what is in question is the credibility of the NRC as an institution.

This response statement is respectfully submitted to ATSDR to document my scientific evaluation of the findings of the NCR report.

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APPENDIX II: RESPONSE TO SPECIFIC NRC REPORT COMMENTS BY M.M. ARAL, PRINCIPAL INVESTIGATOR, ATSDR-GEORGIA TECH RESEARCH PROGRAM ON EXPOSURE-DOSE RECONSTRUCTION—continued

Maslia ML. 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: Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2005.

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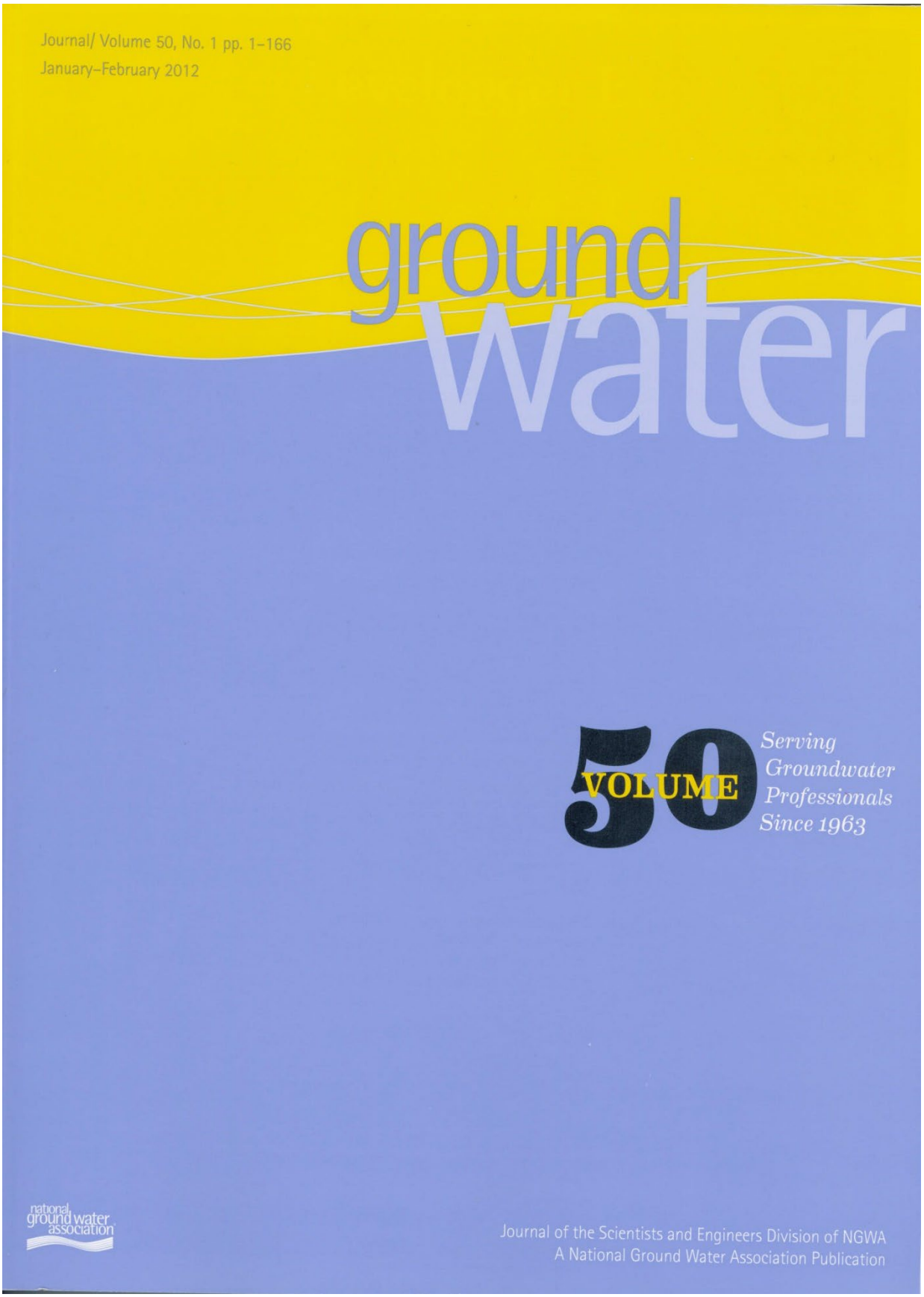
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Appendix N — ATSDR Editorial Response in Ground Water Journal (Maslia et al. 2012) to the Article, "*Complexities in Hindcasting Models—When Should We Say Enough Is Enough*?" by T. P. Clement (2010)


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B. Sautner[7], Barbara A. Anderson[8], Frank J. Bove[9], Perri Z. Ruckart[10], and Susan M. Moore[11]
[1]Corresponding author: Agency for Toxic Substances and Disease Registry, Division of Health Assessment and Consultation (ATSDR/DHAC), 4770 Buford Highway, N.E., Mail Stop F-59, Atlanta, GA; (770) 488-3842; mmaslia@cdc.gov
[2]Multimedia Environmental Simulations Laboratory, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA; (404) 894-2243; maral@ce.gatech.edu
[3]R.E. Faye and Associates, Inc., Blairsville, GA; (706) 745-4048; refaye@windstream.net
[4]Eastern Research Group, Inc., Lexington, MA.
[5]W.M. Grayman Consulting Engineer, Cincinnati, OH; (513) 761-1722; grayman@fuse.net
[6]Agency for Toxic Substances and Disease Registry, Division of Health Assessment and Consultation, Atlanta, GA; rsuarezsoto@cdc.gov
[7]Agency for Toxic Substances and Disease Registry, Division of Health Assessment and Consultation, Atlanta, GA; (770) 488-0667; jsautner@cdc.gov
[8]Agency for Toxic Substances and Disease Registry, Division of Health Assessment and Consultation, Atlanta, GA; (770) 488-0710; baanderson@cdc.gov
[9]Agency for Toxic Substances and Disease Registry, Division of Health Studies (DHS), Atlanta, GA; (770) 488-3809; fbove@cdc.gov
[10]Agency for Toxic Substances and Disease Registry, Division of Health Assessment and Consultation, Atlanta, GA; (770) 488-3808; pruckart@cdc.gov
[11]Agency for Toxic Substances and Disease Registry, Division of Health Assessment and Consultation, Atlanta, GA; (770) 488-3667; smoore1@cdc.gov

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

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.

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

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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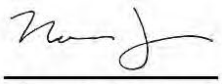
Note: Comment received May 3, 2011, accepted May 18, 2011.

Appendix O — Post-Audit of the Tarawa Terrace Flow and Transport Model, N. L. Jones and R. Jeffrey Davis, Integral Consulting, Inc., October 25, 2024

Tarawa Terrace Flow and Transport Model
Post-Audit

Prepared for
Bell Legal Group
219 Ridge Street
Georgetown, SC 29440

Prepared by



Norman L. Jones
Norm Jones Consulting LLC
4174 N 430 E
Provo, UT 84604



R. Jeffrey Davis
integral
Integral Consulting Inc.
2231 E Murray Holladay Road
Suite 201
Salt Lake City, UT 84117

October 25, 2024

CONTENTS

LIST OF FIGURES iii
LIST OF TABLES iv
ACRONYMS AND ABBREVIATIONS v
Executive Summary vi
1 Introduction 1-1
2 Importing and Running the Original Model 2-1
3 Extending the Flow Model 3-1
3.1 SIMULATION PERIOD 3-1
3.2 RAINFALL-RECHARGE 3-1
3.3 PUMPING AT WELLS 3-2
4 Extending the Transport Model 4-1
4.1 OBSERVED CONCENTRATIONS 4-1
4.2 TEMPORTAL AND SPATIAL ANOMALIES 4-1
5 Results 5-1
5.1 MONITORING WELLS 5-2
5.2 MIGRATION OF PCE PLUME 5-3
6 Conclusions 6-1
7 References 7-1
8 Qualifications 8-1
9 Compensation 9-1
10 Previous Testimony 10-1
Exhibit 1. Resume for R. Jeffrey Davis
Exhibit 2. Resume for Norman L. Jones

LIST OF FIGURES

Figure 1. Comparison of Original Model-Simulated Head Contours to Updated Model-Simulated Head Contours

Figure 2. Comparison of Original Model-Simulated PCE Concentrations to Updated Model-Simulated PCE Concentrations

Figure 3. National Weather Service Rain Gauge Locations Selected for Extended Simulation

Figure 4. Location of Remediation Wells Active During the 1995 to 2008 Period

Figure 5. Location of Monitoring Wells Active During the 1995 to 2008 Period

Figure 6. Simulated vs. Observed PCE Concentrations from (a) Original Model and (b) Extended Model

Figure 7. Simulated vs. Observed PCE Concentrations for Monitoring Well Locations

Figure 8a-b. Time Series Plots of Simulated and Observed PCE Concentrations at Monitoring Well Locations

Figure 9. Simulated PCE Concentration for Three Model Layers Compared to Measured Values, June 1997

Figure 10. Simulated PCE Concentration for Three Model Layers Compared to Measured Values, February 2000

Figure 11. Simulated PCE Concentration for Three Model Layers Compared to Measured Values, March 2003

Figure 12. Simulated PCE Concentration for Three Model Layers Compared to Measured Values, March 2006

Figure 13. Simulated PCE Concentration for Three Model Layers Compared to Measured Values, March 2008

Figure 14. Simulated PCE Plume for December 2008 for Model Layer 1

Figure 15. Simulated PCE Plume for December 2008 for Model Layer 3

Figure 16. Simulated PCE Plume for December 2008 for Model Layer 5

LIST OF TABLES

Table 1. Annual Rainfall and Effective Recharge Rates
Table 2. Pumping Rates for Remediation Wells Operating 1995 to 2008
Table 3. Monitoring Wells Included in Extended Simulation
Table 4. Observed PCE Concentrations at Monitoring Wells, 1995 to 2008
Table 5. Observed and Simulated PCE Concentrations at Monitoring Well Locations
Table 6. Mean Error and Mean Absolute Error for Monitoring Wells

ACRONYMS AND ABBREVIATIONS

ATSDR	Agency for Toxic Substances and Disease Registry
PCE	tetrachloroethylene
GMS	Groundwater Modeling System
MAE	mean absolute error
ME	mean error
NGWA	National Groundwater Association

EXECUTIVE SUMMARY

This post-audit report evaluates the performance of groundwater flow and transport models developed for the Tarawa Terrace region of Camp Lejeune by the Agency for Toxic Substances and Disease Registry (ATSDR). The models were originally designed to simulate the migration of tetrachloroethylene (PCE) contamination from the ABC Cleaners site, located adjacent to the northern boundary of Tarawa Terrace. The audit extends the original model's simulation period from 1995 to 2008 and assesses the accuracy of its predictions by comparing simulated PCE concentrations to actual concentrations measured at monitoring wells during this extended period.

The first step of the audit involved updating the original models, which were created using MODFLOW 96 and MT3DMS software. Both models covered a period between 1951 and 1994. These were successfully updated to MODFLOW 2000 and MT3DMS v5.3, ensuring compatibility with current software versions. Importantly, no significant discrepancies were detected between the original and updated models, confirming that the update process did not alter the results.

The simulation period was then extended to cover the years from 1995 through 2008. During this update, new rainfall and recharge data were incorporated in the MODFLOW model based on nearby weather stations, as the original station's data was incomplete. Additionally, the pumping rates for a set of remediation wells were included, as these wells played a role in altering groundwater flow during this period. The PCE source, which originated from ABC Cleaners and was terminated in the original model at the end of 1984, was left unchanged.

The extended MT3DMS model was found to perform well in simulating PCE concentrations at monitoring wells across the study area. The errors are remarkably well balanced, indicating a good overall fit between simulated and observed concentrations. There were localized discrepancies in error magnitude, particularly in areas where monitoring wells showed significant temporal and spatial variability. Some wells exhibited large fluctuations in measured concentrations over time, which likely resulted from natural subsurface variability, sampling errors, or differences in analytical methods. In other cases, wells showed significant differences in the magnitude of measured concentrations despite being adjacent to one another.

Despite these localized anomalies, the extended MT3DMS model captured the broader patterns of PCE plume migration with reasonable accuracy, particularly during the later years of the simulation. The largest errors were concentrated in a few monitoring wells that were already noted for irregularities in the observed data, but the model's predictions were generally consistent with observed concentrations at most well locations.

In summary, this post-audit found that the original Tarawa Terrace groundwater flow and transport models were developed using sound methodology and continue to provide reliable

insights into the migration of PCE contamination. Despite the inherent challenges in simulating complex subsurface conditions and dealing with incomplete data, the model effectively simulates long-term trends in contaminant migration. Based on this post-audit, we can find no significant evidence that would invalidate the analyses performed by ATSDR with the original model.

1 INTRODUCTION

Our names are Norman L. Jones and R. Jeffrey Davis, and we have been asked to provide a post-audit of groundwater flow and transport models originally developed by the Agency for Toxic Substances and Disease Registry (ATSDR). This post-audit included extending both models from 1995 through 2008. Based on this review, effort, and analysis, as more fully described herein, we have reached the conclusions and opinions set forth below. A complete list of all materials relied upon to form the opinions in the report will be produced within seven days of the report's submittal. Our conclusions are subject to any new materials, data, or other information provided to us prior to depositions or trial at which time our opinions and conclusions may be updated.

In July 2007, the ATSDR, U.S. Department of Health and Human Services, published a report on a groundwater flow and transport model of the Tarawa Terrace region of the Camp Lejeune military base (Maslia et al. 2007; Faye and Valenzuela 2008; Faye 2008). The model was developed to simulate groundwater flow in the aquifers beneath Tarawa Terrace and to simulate the migration of tetrachloroethylene (PCE)[1] in the aquifers resulting from the release of PCE by ABC Cleaners, which is directly adjacent to the northern boundary of the Tarawa Terrace property. The original model was developed using the MODFLOW 96 software (USGS 1996) to simulate groundwater flow and the MT3DMS software (Zheng and Wang 1999) to simulate contaminant transport. MODFLOW and MT3DMS are companion programs where the groundwater flow field computed by MODFLOW is used by MT3DMS to simulate the fate and transport of PCE.

The original Tarawa Terrace flow model was designed to simulate flow conditions over a period from 1951 to 1994. The computation grid used by the model consisted of 270 rows and 200 columns, resulting in a uniform grid cell size of 50 ft x 50 ft. In the vertical direction, the model contained seven layers corresponding to a series of hydrogeologic units, including the Tarawa Terrace aquifer and the underlying Castle Hayne aquifer system. Model features include recharge resulting from vertical percolation of water from rainfall, general head boundary conditions on the north simulating exchange (primarily inflow) of water with the aquifer north of Tarawa Terrace, no-flow boundary conditions on the west representing a no-flow boundary along a topographic divide, and specified head boundary conditions on the south and east representing Northeast Creek. The model also included the withdrawal of groundwater via pumping wells and a drain representing potential discharge of groundwater to the channel of Frenchmans Creek on the west side of the model.

For the transport model, PCE was introduced through a single cell corresponding to the ABC Cleaners spill location at a mass loading rate of 1,200 g/day for a period from January 1953 to December 1984, and the resulting plume migration was simulated through the end of the flow

[1] PCE is also known by other names, including tetrachloroethene. In this report we refer to it as tetrachloroethylene.

and transport simulation period in December of 1994. Transport processes simulated include advection, dispersion, sorption, and biodegradation.

The original flow and transport models were calibrated using a multi-stage process. In the first stage, the flow model was calibrated to steady state flow conditions representing a pre-development state prior to the introduction of groundwater extraction wells. It was then converted to a transient model with pumping wells and time-varying recharge over the period of 1951 to 1994. The transient model was calibrated to transient water levels measured at monitoring wells in the region. In the final stage, the MT3DMS transport model was included, and the parameters of both the flow and transport model were adjusted until both the heads simulated by MODFLOW and the concentrations simulated by MT3DMS matched the field-observed heads, flows, and PCE concentrations within a reasonable range.

The objective of the post-audit is to extend the range of the groundwater flow and transport models from 1995 to 2008 and compare the output of the transport model with concentrations sampled at monitoring wells in Tarawa Terrace during the 1995–2008 period to assess the performance of the model as an interpretive and predictive tool. This comparison involved both a quantitative analysis of simulated versus observed concentrations and a qualitative analysis of the shape and migration of the simulated PCE plume over that period.

In the following sections, we described the steps we took to a) import the original model and update it to work with recent versions of MODLOW and MT3DMS, b) extend the flow model to 1995–2008 conditions, c) extend the transport model to 1995–2008 conditions, and d) compare the simulated PCE concentrations to field-observed PCE concentrations over the extended simulation period.

2 IMPORTING AND RUNNING THE ORIGINAL MODEL

To begin the post-audit, we were provided with a copy of the MODFLOW96 and MT3DMS input files used in the original model. We elected to use the Groundwater Modeling System (GMS) software, version 10.8 (Aquaveo LLC 2024) to perform the model updates. The GMS software is developed and distributed by Aquaveo LLC in Provo, Utah. GMS is a graphical user interface for the MODFLOW and MT3DMS codes and works as a pre- and post-processor (Owens et al. 1996). GMS can be used to build new models from scratch, or to import and modify existing models. The model data are then saved by GMS to input files that can be read by MODFLOW/MT3DMS. The model results output by MODFLOW/MT3DMS are then read by GMS where they can be displayed graphically and analyzed numerically.

We began by attempting to import the MODFLOW 96 files. MODFLOW has been continuously updated and improved since it was initially launched in 1984 (McDonald and Harbaugh 1984), resulting in numerous versions. MODFLOW 96 was released in 1996 and was widely used but was updated to MODFLOW 2000 (Harbaugh et al. 2000) and MODFLOW 2005 (Harbaugh 2005) in 2000 and 2005, respectively. More recent versions include MODFLOW-USG (Panday et al. 2013) and MODFLOW 6 (Langevin et al. 2017). While newer versions provide some new capabilities, both MODFLOW 2000 and MODFLOW 2005 are widely used and provide access to all of the model features used in the original Tarawa Terrace model. However, MODFLOW 96 has been mostly discontinued and is not supported by the GMS software. GMS does provide the capability to import MODFLOW 96 files and convert them to newer versions. When we attempted to import the original MODFLOW 96 files to GMS, we discovered that the files would not import properly, and GMS displayed an error message. After some exploration, we determined that we had to make a minor edit to the original WEL (wel.dat). Lines 4 through 13 were changed from a "-1" value to a value of "0." Once the model was imported, we saved a copy of the model in MODFLOW 2000 format. To import the MT3DMS files, we had to manually update the mass loading of 1,200 g/day in GMS from January 1953 through December 1984. This was due to an outdated version of the Source Sink Mixing (SSM) package used in the original simulation. The MT3DMS files were saved in an updated format compatible with the current version of MT3DMS (v5.3) used by GMS.

After importing and converting the MODFLOW and MT3DMS files and saving them to the newer formats, we re-ran the flow and transport simulations and imported the solutions to GMS. At this point, we performed a qualitative analysis to ensure that the process of converting the files and updating to the newer versions did not change the model outputs. First, the simulated head contours from the updated flow model were compared to the head contours described in the ATSDR modeling report (Faye and Valenzuela 2008) as shown in Figure 1. The results of the updated model seem to match the results of the original model. Next, we compared PCE concentrations simulated by the updated MT3DMS model and to the concentrations simulated by the original MT3DMS model (Figure 2). Once again, the results seem to match well, indicating that no errors were introduced to the model in the conversion process.

3 EXTENDING THE FLOW MODEL

After confirming that the flow and transport simulations were properly imported and updated, we proceeded to modify both the flow and transport simulations for the post-audit. The changes made to the MODFLOW model are described in this section. The only changes made to the MODFLOW model were to extend the simulation period, update recharge values over the new period, and modify the pumping rates at remediation wells. No other changes were made to simulation settings or boundary conditions and sources/sinks.

3.1 SIMULATION PERIOD

The original simulation was from January 1951 through December 1994. We extended the simulation period through December 2008 so that the simulation included the period from 1995 to 2008. For the new simulation, no changes were made to the inputs for the original 1951–1994 period and thus the model solution for that period remained unchanged in the new model. For 1995–2008, we used the same stress period interval used in the original model, with monthly stress periods and one time step per stress period.

3.2 RAINFALL-RECHARGE

For the original flow model, the primary source of water to the aquifer was input from precipitation that infiltrated to the water table, which is simulated in MODFLOW as recharge where the units are length/time (feet/day). In the original model, a single annual recharge rate was used for each year of the simulation as illustrated in Table C7 of Faye and Valenzuela (2008). The recharge rate was found by applying a recharge coefficient of 0.235 to the annual precipitation to find an effective recharge rate representing the fraction of rainfall that percolates to the water table. This recharge rate is then entered into the Recharge Package in MODFLOW, and the package applies water to the top active cell during each stress period.

The precipitation values used in the original simulation were obtained from the Maysville-Hofman Forest station, which is north of Tarawa Terrace. For the post-audit, we attempted to obtain precipitation data from the same station. We found three different precipitation data sets that were purported to be from the Hofman Forest station, but each of these data sets was determined to be unusable. None of the data sets had a complete set of precipitation data for the 1995 to 2008 period. Furthermore, for the partial data during the period of interest, one of the data sets contained some extreme anomalies in monthly precipitation that did not appear in neighboring rain gauge stations. As a result, we elected to use rain gauge data from other stations in the vicinity of Tarawa Terrace. Using the National Oceanic and Atmospheric Administration National Weather Service website (National Weather Service 2024), we located three rain gauges near Tarawa Terrace that had a complete set of rainfall measurements during the period 1995 to 2008. The locations of these gauges relative to Tarawa Terrace are shown in

Figure 3. The mean rainfall for each of these gauges over the 1951 to 1994 period is similar to the mean rainfall for the Hofman Forest station over the same period, and the annual variations were in a consistent range. Thus, we took a simple average of each of the three stations over the 1995 to 2008 period to estimate the average annual rainfall at Tarawa Terrace and multiplied these averages by 0.235 to get the effective recharge rate and converted it to units of feet/day for use in the extended MODFLOW simulation. The rainfall values, averages, and effective recharge rates are summarized in Table 1.

3.3 PUMPING AT WELLS

Another change to the MODFLOW model over the extended simulation period was related to pumping associated with a set of remediation wells. These wells withdraw water from the aquifer, thus impacting both the flow field and the subsequent movement of contaminants simulated by the MT3DMS simulation. We were provided with a list of remediation wells and their pumping history for a period beginning in 1999 and continuing through the end of 2008. The well names, coordinates, model layers, and pumping histories over the period of interest are shown in Table 2. In each case, the pumping rates were turned on for each well at the rates shown on the corresponding dates and held constant at that rate until the next rate change or until the wells were turned off. All the other pumping wells in the model had zero pumping rates during the extended simulation period. The locations of the remediation wells are shown in Figure 4.

4 EXTENDING THE TRANSPORT MODEL

For the transport model, no changes were required to the MT3DMS inputs for the extended simulation period, except for enabling the Transport Observation package. The same dynamic transport step options used in the original model were applied to the new stress periods from 1995 to 2008. The PCE source at the location of the ABC Cleaners facility was turned off at the end of 1983, matching the original model.

4.1 OBSERVED CONCENTRATIONS

The main objective of extending the flow and transport simulation was to assess the performance of the model in simulating the migration of the PCE plume over the extended period and to compare the simulated PCE concentrations to PCE concentrations observed at monitoring wells during the 1995–2008 period. A list of the monitoring wells is shown in Table 3, the PCE concentrations observed at the wells in Table 4, and the locations of the wells in Figure 5. As presented in Table 4, the samples were all taken at 12 distinct dates beginning in 1997 and ending in 2008. The model layers associated with each well were determined by comparing the well screen depths with the grid cell top and bottom elevations for the grid cells containing the monitoring well locations and confirmed by documents provided by counsel (Weston ABC One-Hour Cleaners Dataset).

The monitoring well locations and the observed concentrations were imported as observation points in an "observation" coverage (spatial features layer) in the Map Module of the GMS software. This information was then linked by GMS to the MT3DMS Transport Observation package, which was turned on and used in the simulation. This allows MT3DMS to calculate the simulated PCE concentrations at the cells containing the observation wells and output the results in a format that we could easily access and use in our analysis.

4.2 TEMPORTAL AND SPATIAL ANOMALIES

While the observed concentrations at each monitoring well listed in Table 4 are generally consistent over time, there are some exceptions that should be noted. For Well C13 in Model Layer 3, the observed concentration of 5,400 µg/L in 2002 is an order of magnitude higher than any subsequent concentrations observed at the same well and is substantially higher than all other concentrations but one. The highest concentration of 6,900 µg/L was measured at Well RWS-4A in Layer 1. The observed concentrations at this well showed extreme fluctuations over time. The observed concentration of 280 µg/L in January 2002 was followed only 3 months later by an observed concentration of 6,900 µg/L—the highest value measured. Then for the sequence of observations from 2003 to 2007, the concentrations oscillated from 1,100 → 0 → 1,000 → 92 → 1,600. This high degree of fluctuation could be due to sampling errors,

differences in analytical techniques, and/or extreme heterogeneity in aquifer properties near the well.

In addition to variations over time, there are spatial variations in the observed concentrations. Well FWS-13 has zero or low (<5 µg/L) observed concentrations over the entire range of sampling dates. However, as shown in Figure 5, it is immediately adjacent to FWS-12, RWS-3A, and RWS-4A, all of which show high concentrations over the entire range of sampling dates. Likewise, in Model Layer 3, monitoring well C12 has low observed concentrations despite being adjacent to RWC-2, which has high concentrations. Furthermore, Wells FWC-11 and C5 have zero or low (<5 µg/L) observed concentrations over all sampling dates and are relatively close to C3, which has high concentrations over most dates. C14 has high concentrations over the four dates sampled despite being directly adjacent to C13, C15-S, C15-D, and C16, all of which have low concentrations on those dates.

This temporal and spatial variability in concentrations at selected wells illustrates the extreme variability often seen when dealing with concentration data from monitoring wells. It highlights why focusing on absolute concentrations at specific dates and locations when analyzing the performance of a flow and transport model is less important than assessing the overall distribution of simulated concentrations and comparing the shape of the simulated plume with the general spatial distribution of observed concentrations. Each of these sites with high variability is generally correlated with higher model error, as shown below in the Results section.

5 RESULTS

The main objective of this post-audit is to assess the performance of the flow and transport model over the extended period of 1995 to 2008 using PCE concentrations observed in monitoring wells over that period. Before presenting the results, it is helpful to remember that when simulating the migration of a PCE contaminant plume using MODFLOW and MT3DMS, achieving a close match between simulated and observed concentrations can be challenging for several reasons:

1. **Complex Subsurface Conditions**: The subsurface environment is inherently complex, with variations in soil heterogeneity, permeability, porosity, and hydraulic conductivity. These properties vary spatially in ways that are not fully captured in the model, affecting how the contaminant plume moves through the groundwater system.
2. **Temporal Variability**: The concentration of contaminants can change over time due to factors like seasonal variations in groundwater flow, biodegradation, and chemical reactions. Simulating these dynamic processes accurately over the entire simulation period is challenging.
3. **Limitations in Model Resolution**: MODFLOW and MT3DMS rely on discretizing the subsurface into numerical grids consisting of cells that represent a subset of the aquifer. The resolution of these grids can limit the model's ability to capture fine-scale variations in plume behavior, particularly in areas with sharp concentration gradients, small-scale heterogeneities, or preferential pathways.
4. **Measurement Variability**: The observed concentrations at observation wells may contain some degree of measurement error or uncertainty. Field data collection is subject to variability, which adds another layer of complexity when trying to match it closely with model outputs. As outlined above in Section 4.2, extreme variations were observed in some of the measured concentrations used in this post-audit.

Each of these challenges was highlighted in the Faye (2008) report on pp. F44–45. It was reported that at several sites, measured concentrations varied by several orders of magnitude over a few feet of depth.

Given these challenges, it is important to qualitatively assess the overall behavior of the simulated plume in addition to quantitatively analyzing the differences in simulated and observed concentrations at specific times and locations. A qualitative evaluation helps ensure that the model captures the key processes governing plume migration, such as its general direction, spread, and interaction with sources, sinks, and aquifer boundaries. This broader perspective can offer valuable insights into the overall value of the model as an interpretive or predictive tool.

After running both the extended MODFLOW and MT3DMS simulations, we analyzed the resulting PCE concentrations at a set of monitoring well locations and compared them to the

observed concentrations. In the MT3DMS simulation, the spill at ABC Cleaners was simulated using a mass loading rate of 1,200 g/day at a single cell from January 1953 to December 1983 as described in Faye (2008). We did not alter this mass loading rate for the extended simulation. The resulting concentrations computed by the MT3DMS model are in units of grams/cubic foot. We converted these concentrations to units of micrograms/liter by multiplying the MT3DMS concentrations by a conversion factor of 35,314.7. We chose to present the simulated concentrations in micrograms/liter to match the units used in the original Faye (2008) report. This was applied to both the simulated concentrations at monitoring well locations and to the gridded data used to display the migration of the PCE plume.

5.1 MONITORING WELLS

A complete list of the observed and simulated concentrations at the monitoring well locations is shown in Table 5. The "Error" column represents the difference between the simulated and observed concentrations, and the "Abs(Error)" column is the absolute value of the error. These observations were sampled at a unique set of time periods as shown in Table 4. Taking all values into consideration, the mean error (ME) = 21 µg/L, indicating that the positive and negative errors are well balanced. The mean absolute error (MAE) = 334 µg/L.

These concentration values are displayed on a scatter plot of simulated concentrations versus observed concentrations in Figure 6. Because this is a log-log plot, it does not show values where either the simulated or observed concentrations are zero. The results are similar to the results for the original model shown in Figure F12 on p. F33 of the Faye (2008) report; although in this case, there are far more samples to compare. The dashed line in Figure 6 indicates a perfect match between the simulated and observed values. The points on the plot are mostly centered on the line, but as was the case with the original model, the simulated values appear to be biased on the high side, with the simulated values greater than the observed values. However, when the sites with zero observed or simulated concentrations (not shown on Figure 6) are factored in, the errors are balanced, as indicated by the low ME (21 µg/L) reported above.

We calculated a scatter plot of simulated versus observed concentrations for each monitoring well location where both the simulated and observed concentrations are non-zero, and the plots are shown in Figure 7. While there is high variability at some sites, most of the sites show good agreement.

Next, we generated time series plots of simulated versus observed concentrations at monitoring well locations. The results are shown in Figure 8. For Sites C1, S8, and S11, both simulated and observed concentrations were zero for all measurement dates. In general, the simulated and observed curves become closer as the simulation progresses. It should be noted that the vertical scale on each plot is variable, and the magnitude of the differences between simulated and observed concentrations can vary greatly from one plot to the next.

5.2 MIGRATION OF PCE PLUME

To get a qualitative understanding of the of the spatial distribution of the simulated PCE plume versus time and how it correlates with the temporal and spatial distribution of the observed PCE concentrations, we next generated a series of maps showing the simulated PCE plume in Model Layers 1, 3, and 5 at selected sampling dates (Figures 9–13). For each date, we overlaid the monitoring wells that were sampled on that date in each layer. The intervals and colors for the simulated PCE plume contours were selected to match those used in Figures F18–F25 in the Faye (2008) report. The monitoring well symbols are colored based on the relative magnitude of the absolute error at that date.

The results for each of the sampling dates are generally consistent. The spatial distribution of green and yellow symbols at monitoring well locations shows good overall fit of the simulated plume relative to observed concentrations, especially at the later sampling dates. The larger errors tend to be concentrated in the center of the plume where the simulated concentrations are greater. This is somewhat expected because comparing larger numbers will organically result in larger differences. Furthermore, the high errors generally coincide with the monitoring wells exhibiting high temporal and spatial variation, as described in Section 4.2. The wells identified in that section with extreme variability include FWS-13, RWS-4A, RWC-2, FWC-11, C5, and C14, all of which exhibit high errors. Other wells, such as S3 and S5, have high errors in the earlier dates but are in better agreement at later dates when the high simulated concentrations in the center of the plume dissipate over time.

To further compare the spatial distribution of the PCE plume with the PCE concentrations observed at monitoring wells, we took the errors and absolute errors from Table 5 and calculated the ME and MAE at each monitoring well location. The results are tabulated in Table 6. These MAE values were then used to create the maps shown in Figures 14–16. There is a separate map for each of the Model Layers 1, 3, and 5. In each figure, the MAE magnitudes for each monitoring well are displayed at the monitoring well locations and are superimposed on contour plots of the simulated PCE plume. The MAE error norm represents errors from multiple sampling dates, and the footprint of the plume migrated over time as illustrated previously in Figures 9–13. However, the intent here is to illustrate the spatial distribution of the error relative to the overall plume footprint, and the plume footprint is at the largest state at this point in the simulation, so it represents a useful basis of comparison.

The PCE plume for December 2008 for Model Layer 1 and the MAE at monitoring wells located in Layer 1 are shown in Figure 14. The errors at the wells are color-coded for three ranges, as shown in the figure legend. The spatial distribution of the errors indicates that there is a good overall agreement between the shape of the plume and the observed PCE concentrations at the monitoring wells. The wells with the highest errors are Wells FWS-13 and RWS-4A, which were noted in Section 4.2 as having high temporal and spatial anomalies. The simulated PCE plume for Layer 3 for the same date and the errors for monitoring wells in Layer 3 are shown in Figure 15. Once again, most of the wells on the fringes of the plume are in good agreement.

The highest errors are at Wells FWC-11, C5, C13, C14, and RWC-2, which were identified in Section 4.2 as having high anomalies. The simulated PCE plume and errors for Layer 5 are shown in Figure 16. This layer contained only two monitoring wells, and the errors are low.

In summary, the 7 wells identified as having anomalies in the observed data have high errors while the remaining 30 wells exhibit low or moderate errors, indicating good overall agreement between the simulated PCE plume and the observed concentrations over the range of the extended simulation.

6 CONCLUSIONS

Our conclusions from the post-audit analysis are as follows:

1. **Model Import and Update**: The original MODFLOW and MT3DMS models were successfully imported and updated to modern versions (MODFLOW 2000 and MT3DMS v5.3), ensuring compatibility with current software. The updated models matched the original model outputs, validating the update process.

2. **Extended Simulation Period**: The flow and transport models were extended from the original period (1951–1994) to cover the period from 1995 to 2008. Modifications included updating the recharge data based on new precipitation data and incorporating pumping rates for the remediation wells. The PCE source at ABC Cleaners was left unchanged, consistent with the original simulation ending in 1984.

3. **Observed vs. Simulated Concentrations**: The post-audit revealed that the updated MT3DMS model adequately simulated PCE concentrations at monitoring wells over the extended period. While there was a high variability at some monitoring well locations, the errors are remarkably well balanced, indicating a good overall fit between simulated and observed concentrations.

4. **PCE Plume Migration**: The extended model captured the overall migration of the PCE plume between 1995 and 2008. Simulated plumes were consistent with observed concentrations at most monitoring wells, especially during the latter stages of the simulation. The largest discrepancies occurred at a relatively small subset of wells that exhibited high temporal and spatial variability in observed concentrations. This variability may be due to sampling errors, aquifer heterogeneity, or variations in analytical methods.

5. **Model Performance**: The model performance was evaluated using both qualitative and quantitative methods. Despite challenges inherent in simulating subsurface flow and transport, such as soil heterogeneity, data uncertainty, and model resolution limits, the model reasonably captured the key behaviors of the PCE plume. The high variability in certain well measurements introduced some error but did not significantly undermine the model's overall accuracy.

In summary, the extended model demonstrates that the original model was developed using sound methods, and the model remains a reliable tool for understanding the general trends of contaminant migration in the Tarawa Terrace region. Based on this post-audit, we can find no significant evidence that would invalidate the analyses performed by ATSDR with the original model.

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[2] Reference will be updated.

8 QUALIFICATIONS

I, **R. Jeffrey Davis**, P.E., CGWP, have almost 30 years of experience with civil and environmental engineering, hydrogeology, groundwater fate and transport modeling, and software and model development. I have both undergraduate and graduate degrees from Brigham Young University in civil engineering. I currently serve on the board of directors for the National Ground Water Association (NGWA), as well as on NGWA's per- and polyfluoroalkyl substances and Managed Aquifer Recharge advisory groups. I was one of the leads for NGWA's Groundwater Modeling Advisory Panel. I have developed and used numerous groundwater models for the agricultural industry and the mining industry, including projects involving environmental impact statements, environmental assessments, water management, groundwater–surface water interaction and contamination, dewatering, and water treatment. I also have extensive experience with the oil and gas industry, including water supply, hydraulic fracturing, and groundwater protection for the upstream market, and worked on a variety of oil release projects. I have extensive knowledge of groundwater flow-and-transport principles and have led numerous workshops and classes in the United States and around the world. I have taught several classes and workshops in association with NGWA and other professional organizations and universities for the past 3 decades. I also share my research and project work regularly with the professional societies with which I am affiliated. I frequently use groundwater models to explain fate and transport of contaminants or groundwater supplies and availability. Recent such examples include groundwater impacts from agricultural activities in Minnesota; aqueous film-forming foam contamination impacts to groundwater in Martin County, Florida; a pipeline of produced water spill in North Dakota; and groundwater availability and surface water impacts in Ventura County, California. I am regularly asked to provide opinions or participate on panels to discuss groundwater, water supply, or contaminated groundwater issues.

I, **Norman L. Jones**, Ph.D., have 33 years of experience in civil and environmental engineering. I graduated with a B.S. degree in civil engineering from Brigham Young University and with M.S. and Ph.D. degrees in civil engineering from the University of Texas at Austin. I have been a faculty member in the Civil and Construction Engineering Department at Brigham Young University since January 1991 where I currently hold the rank of Professor. I have taught university courses in a variety of subjects, including computer programming, soil mechanics, seepage and slope stability analysis, and groundwater modeling. The primary focus of my research has been groundwater flow and transport modeling, software development, remote sensing, groundwater sustainability analysis, and hydroinformatics. I was the original developer of the GMS software, which is a graphical user interface for MODFLOW and MT3DMS and is used by thousands of organizations all over the world. GMS is now developed and maintained by Aquaveo, LLC in Provo, Utah, a company that I helped found in 2007. I have taught numerous short courses on groundwater flow and transport modeling over my career. I am a member of the Hydroinformatics Research Laboratory at Brigham Young University. I have been the principal or co-investigator on more than $20M of externally funded research. I

have authored 179 technical publications, including 88 peer-reviewed journal articles, and 1 book. I am a recipient of the Walter L. Huber Civil Engineering Research Prize from the American Society of Civil Engineers and the John Hem Award for Science and Engineering from NGWA. I have been involved in a number of consulting projects, including work as a technical expert in litigation cases. I am an active member of the American Water Resources Association, the NGWA, the American Geophysical Union, and the American Society of Civil Engineers.

9 COMPENSATION

My, **R. Jeffrey Davis**, experience is summarized in my resume, which is included as Exhibit 1. I am being compensated at a rate of $498 an hour for my time in preparation of this report and $498 an hour for my deposition and trial testimony, if necessary. My compensation is not contingent upon the opinions I developed or the outcome of this litigation case.

My, **Norman L. Jones**, experience is summarized in my resume, which is included as Exhibit 2. I am being compensated at a rate of $500 an hour for my time in preparation of this report and $1,000 an hour for my deposition and trial testimony, if necessary. My compensation is not contingent upon the opinions I developed or the outcome of this litigation case.

10 PREVIOUS TESTIMONY

I, **R. Jeffrey Davis**, have not given any deposition or trial testimony in the last 4 years.

I, **Norman L. Jones**, gave deposition testimony on October 20, 2021, in MICHAEL YATES and NORMAN L. JONES vs TRAEGER PELLET GRILLS LLC, in the United States District Court for the District of Utah Central Division, Case No. 2:19-cv-00723-BSJ. With the exception of this case, I have not given any deposition or trial testimony in the last 4 years.

Figures

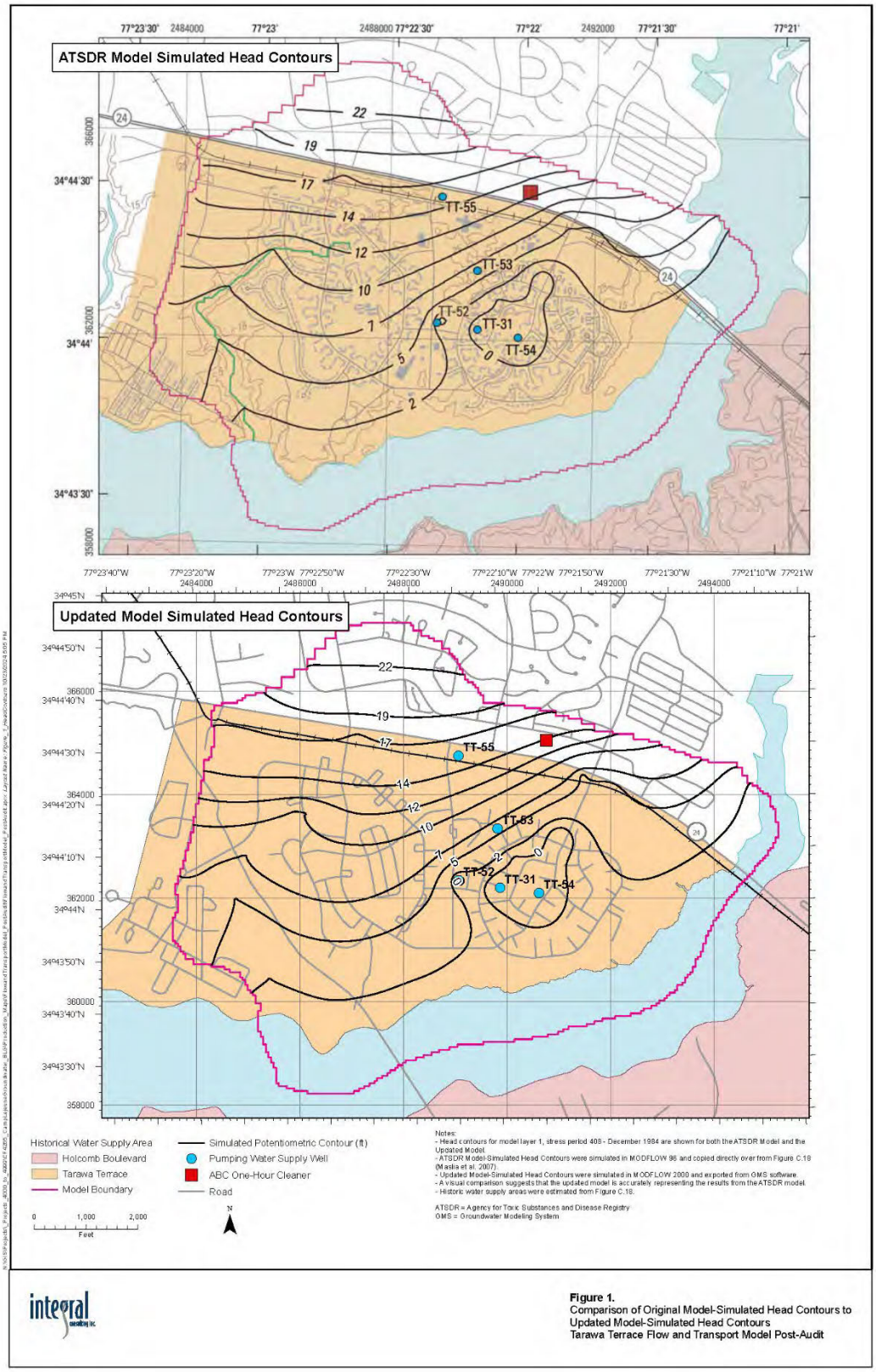
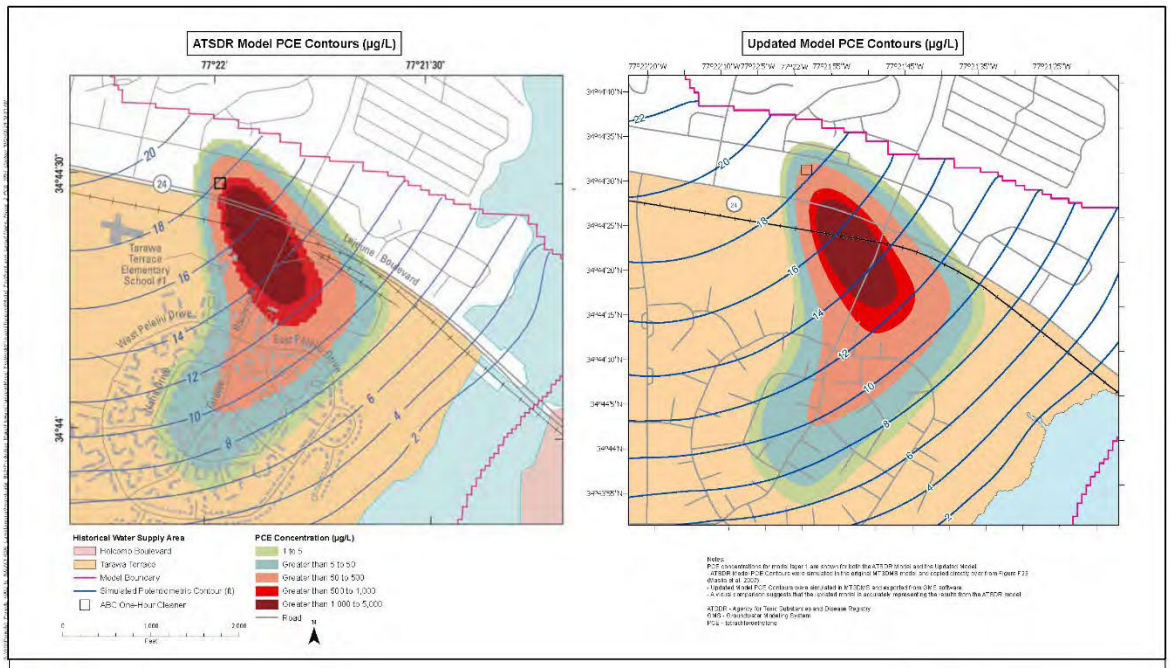


Figure 1.
Comparison of Original Model-Simulated Head Contours to Updated Model-Simulated Head Contours
Tarawa Terrace Flow and Transport Model Post-Audit



integral

Figure 2.
Comparison of Original Model-Simulated PCE Concentrations to Updated Model-Simulated PCE Concentrations
Tarawa Terrace Flow and Transport Model Post-Audit



Figure 3.
National Weather Service Rain Gauge Locations Selected for Extended Simulation
Tarawa Terrace Flow and Transport Model Post-Audit

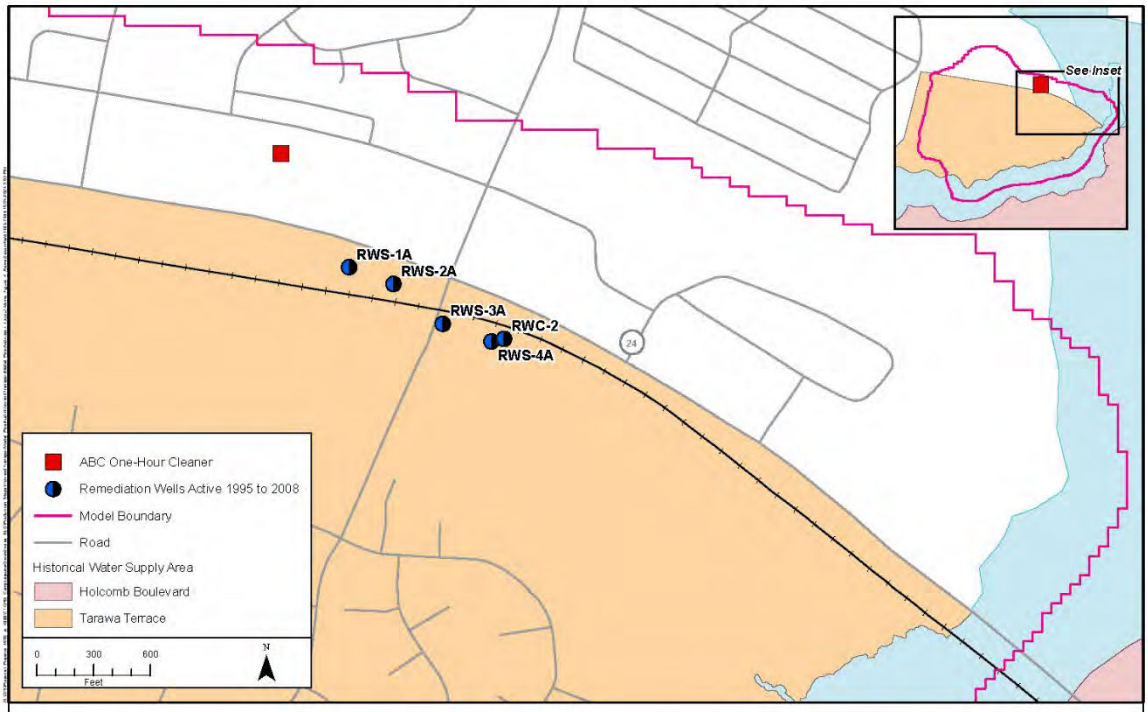


Figure 4.
Location of Remediation Wells Active During the 1995 to 2008 Period
Tarawa Terrace Flow and Transport Model Post-Audit

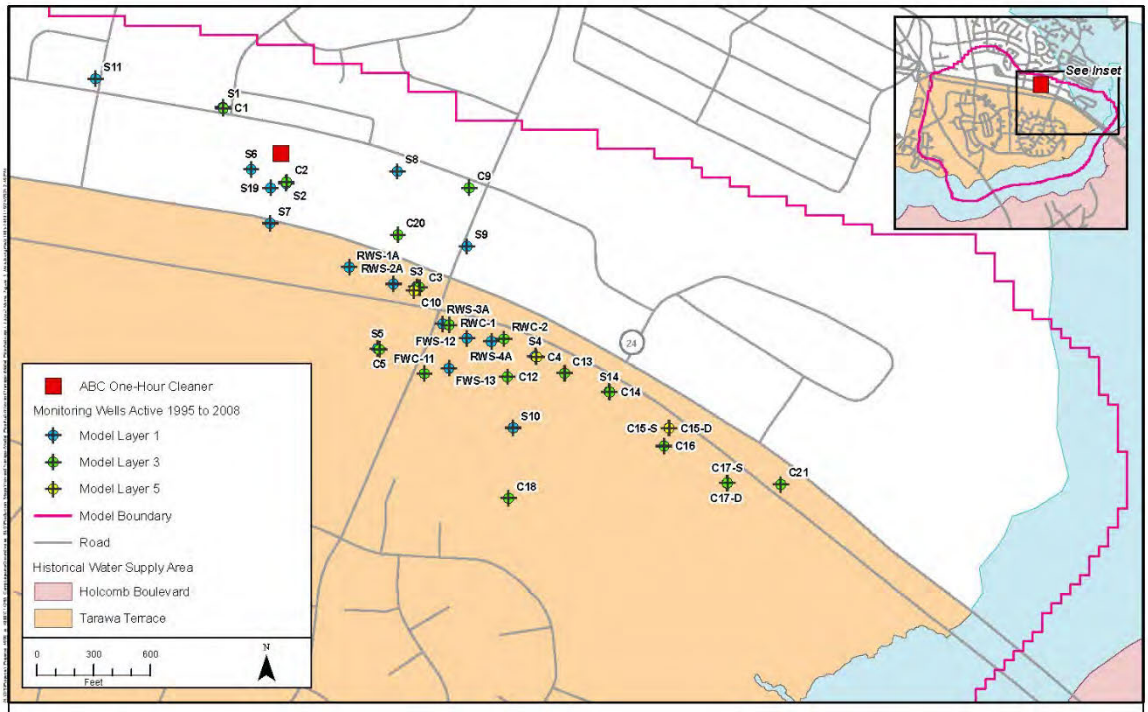
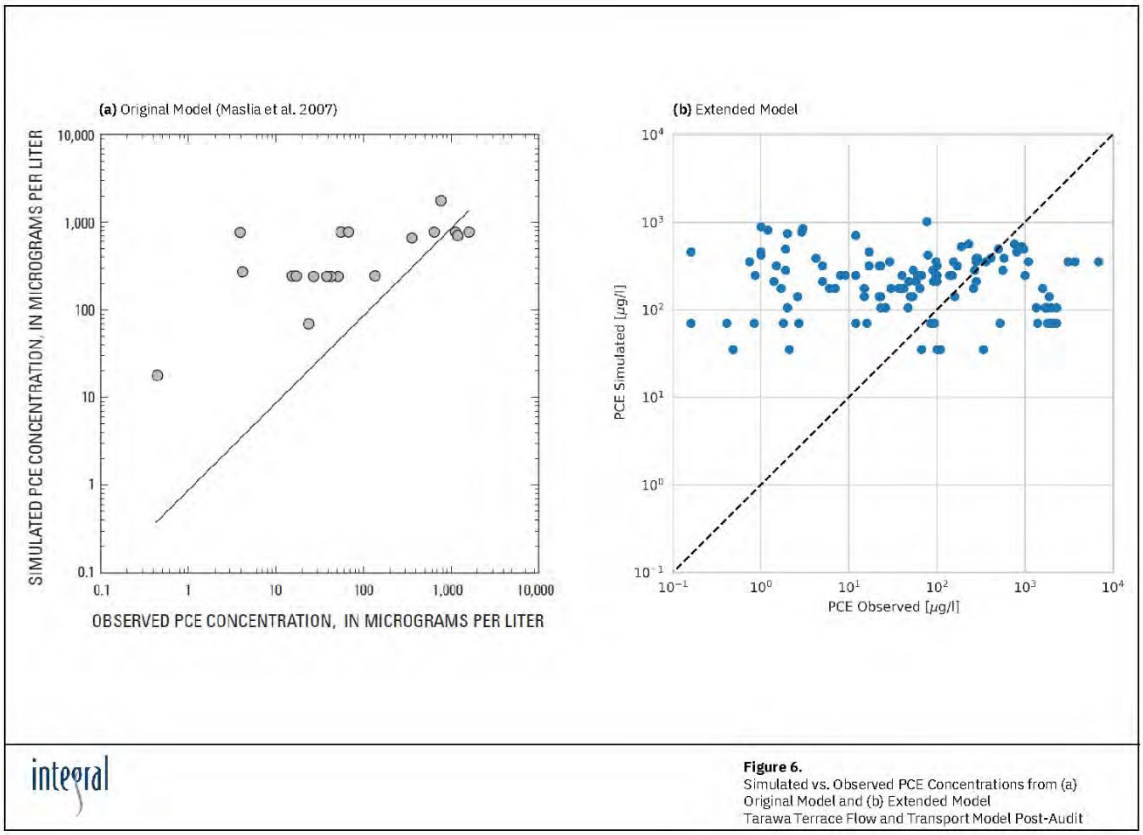
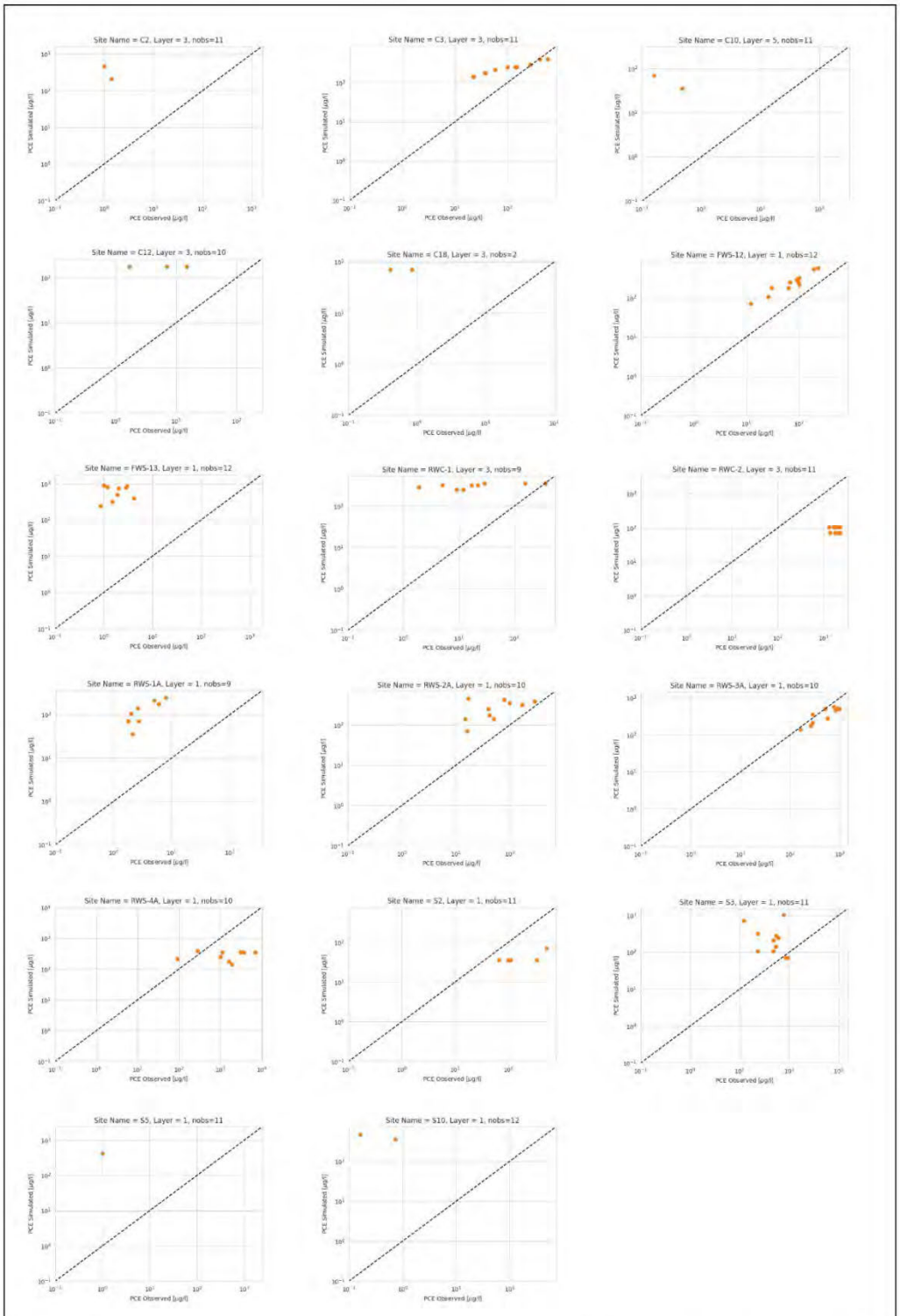


Figure 5.
Location of Monitoring Wells Active During the 1995 to 2008 Period
Tarawa Terrace Flow and Transport Model Post-Audit



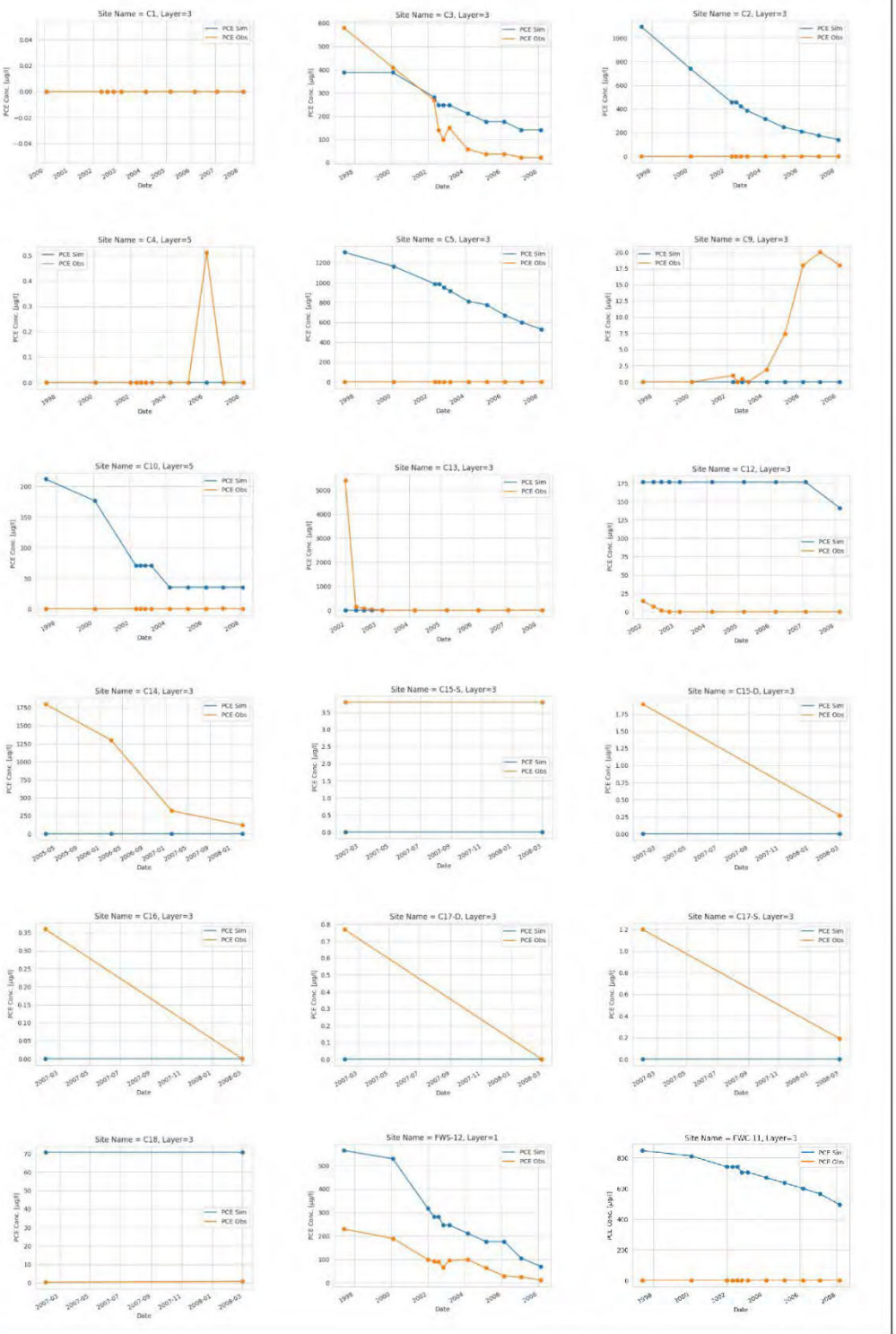
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Figure 6.
Simulated vs. Observed PCE Concentrations from (a) Original Model and (b) Extended Model
Tarawa Terrace Flow and Transport Model Post-Audit



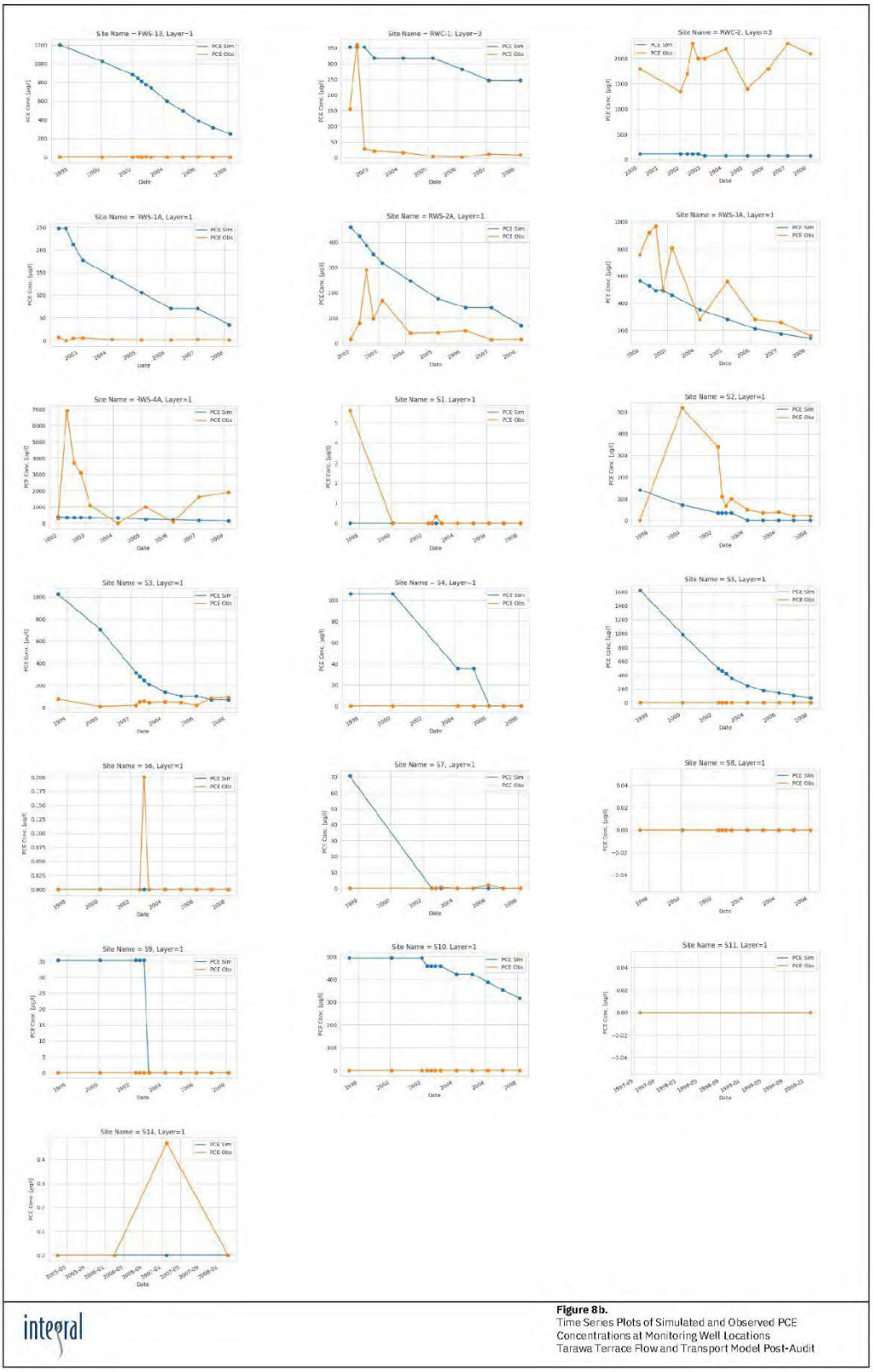
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Figure 7.
Simulated vs. Observed PCE Concentrations for Monitoring Well Locations
Tarawa Terrace Flow and Transport Model Post-Audit



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Figure 8a.
Time Series Plots of Simulated and Observed PCE Concentrations at Monitoring Well Locations
Tarawa Terrace Flow and Transport Model Post-Audit



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Figure 8b.
Time Series Plots of Simulated and Observed PCE Concentrations at Monitoring Well Locations
Tarawa Terrace Flow and Transport Model Post-Audit

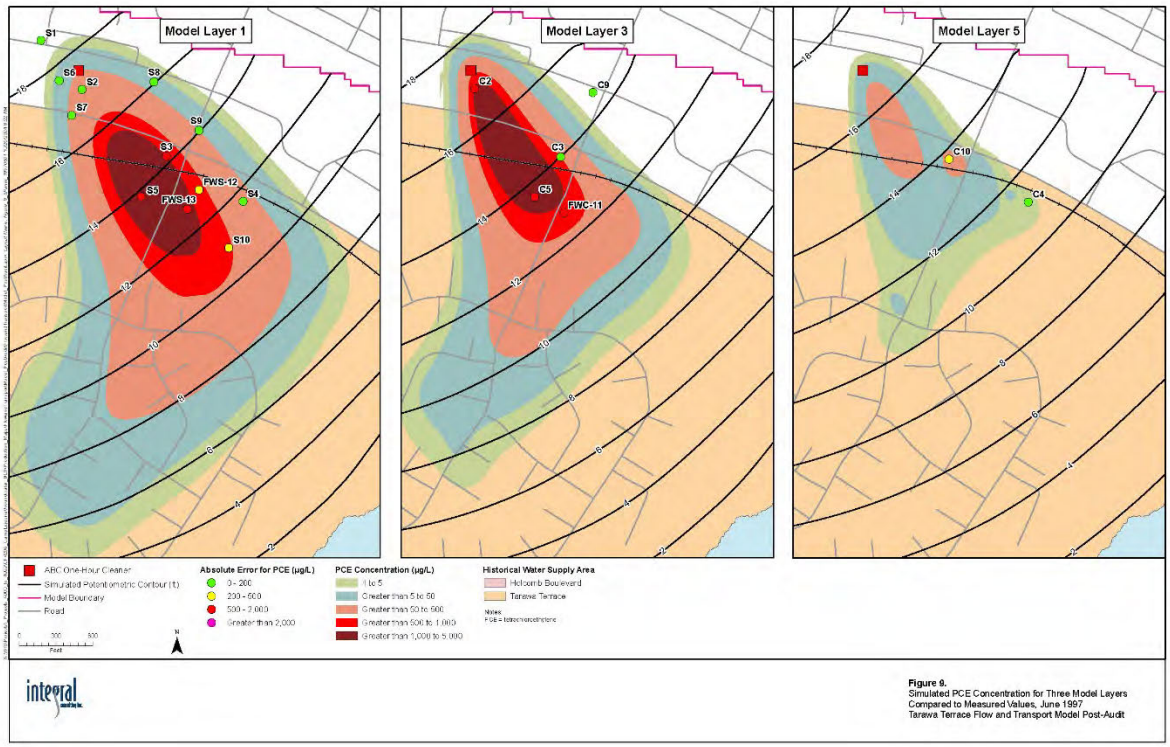


Figure 9.
Simulated PCE Concentration for Three Model Layers
Compared to Measured Values, June 1997
Tarawa Terrace Flow and Transport Model Post-Audit

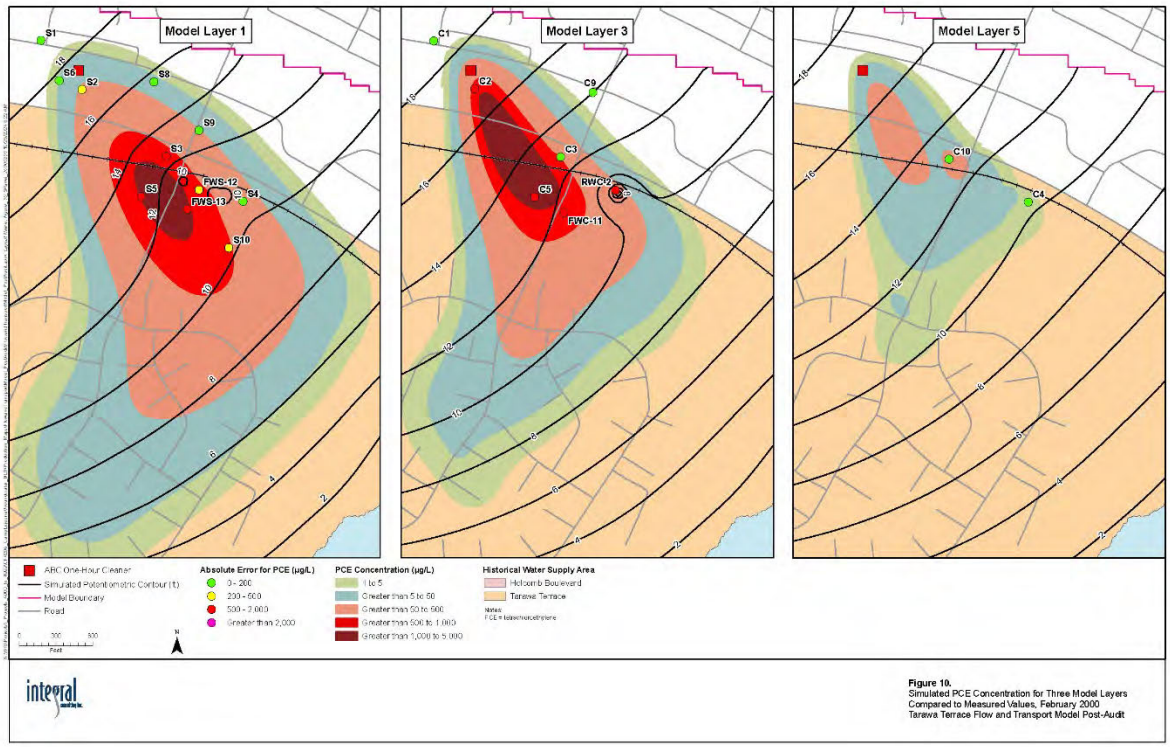


Figure 10.
Simulated PCE Concentration for Three Model Layers
Compared to Measured Values, February 2000
Tarawa Terrace Flow and Transport Model Post-Audit

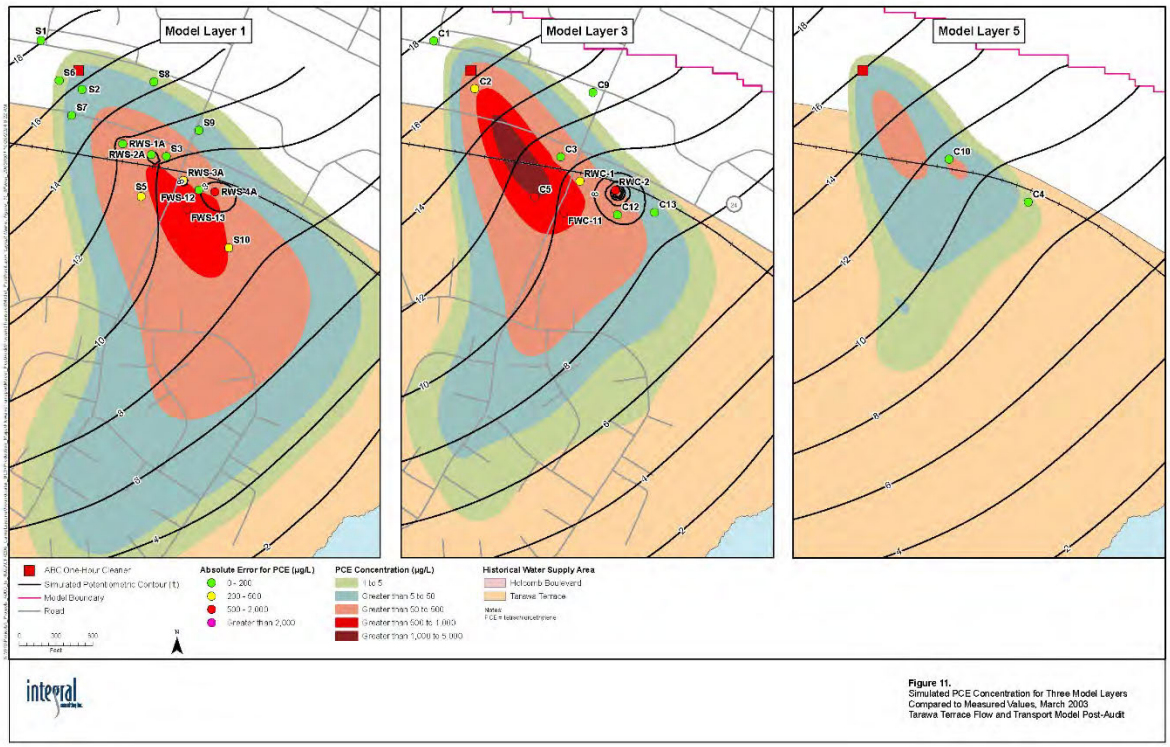


Figure 11.
Simulated PCE Concentration for Three Model Layers Compared to Measured Values, March 2003
Tarawa Terrace Flow and Transport Model Post-Audit

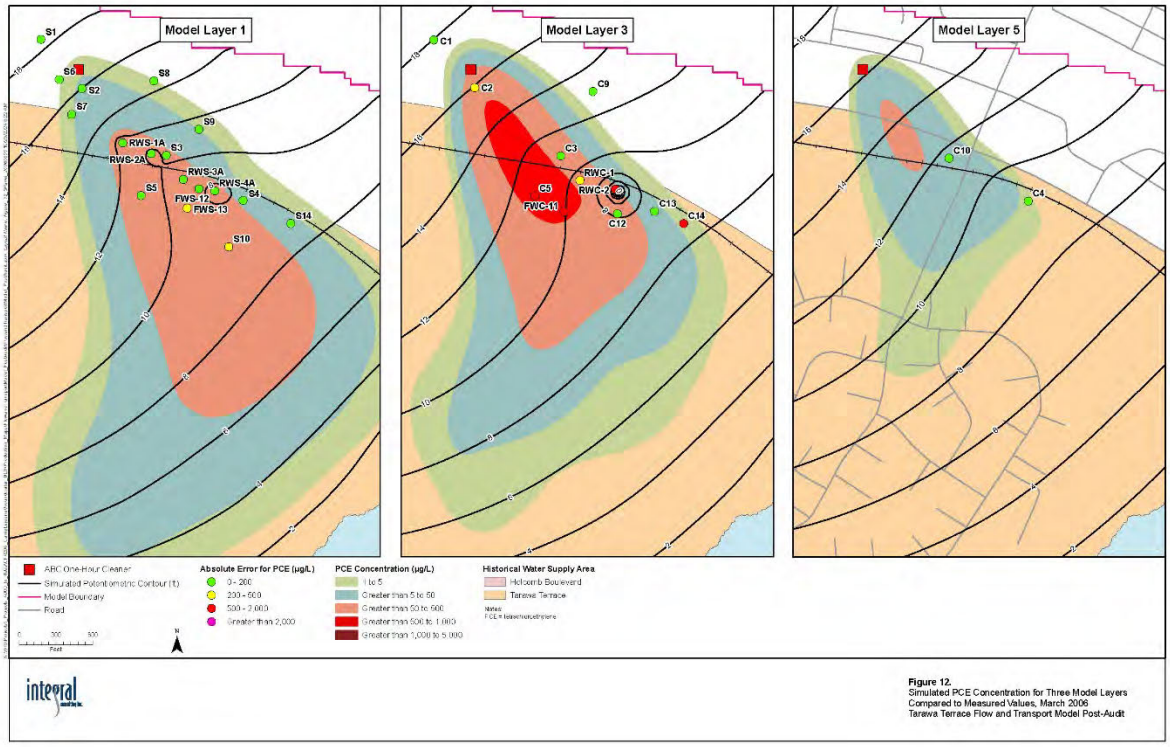


Figure 12.
Simulated PCE Concentration for Three Model Layers Compared to Measured Values, March 2006
Tarawa Terrace Flow and Transport Model Post-Audit

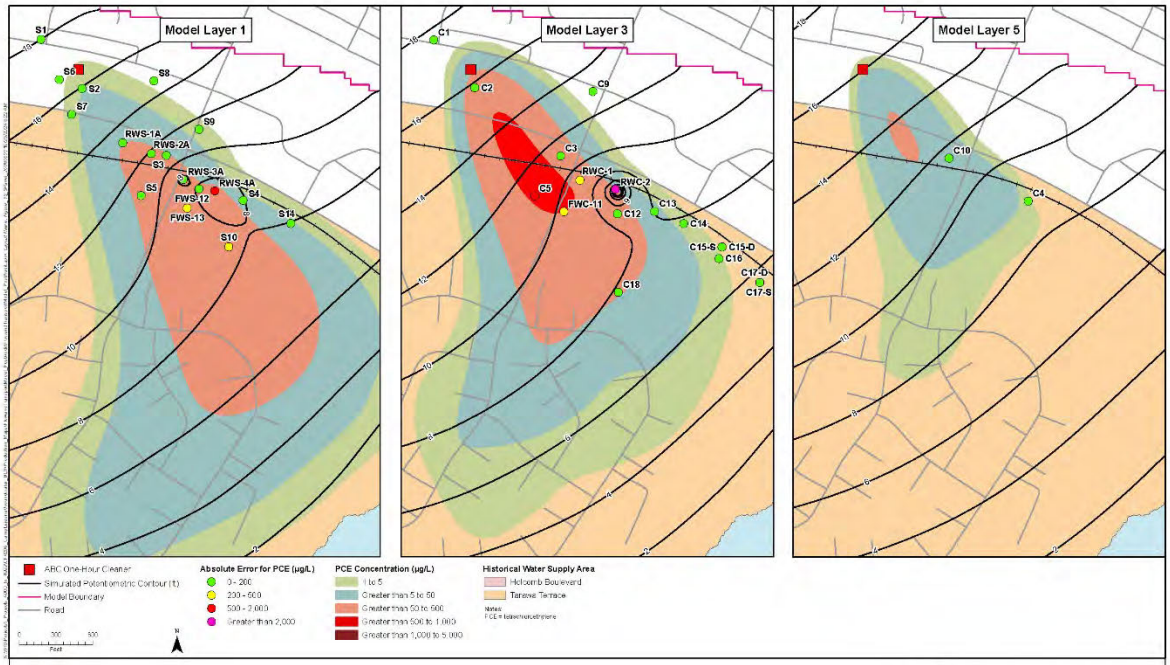


Figure 13.
Simulated PCE Concentration for Three Model Layers
Compared to Measured Values, March 2008
Tarawa Terrace Flow and Transport Model Post-Audit

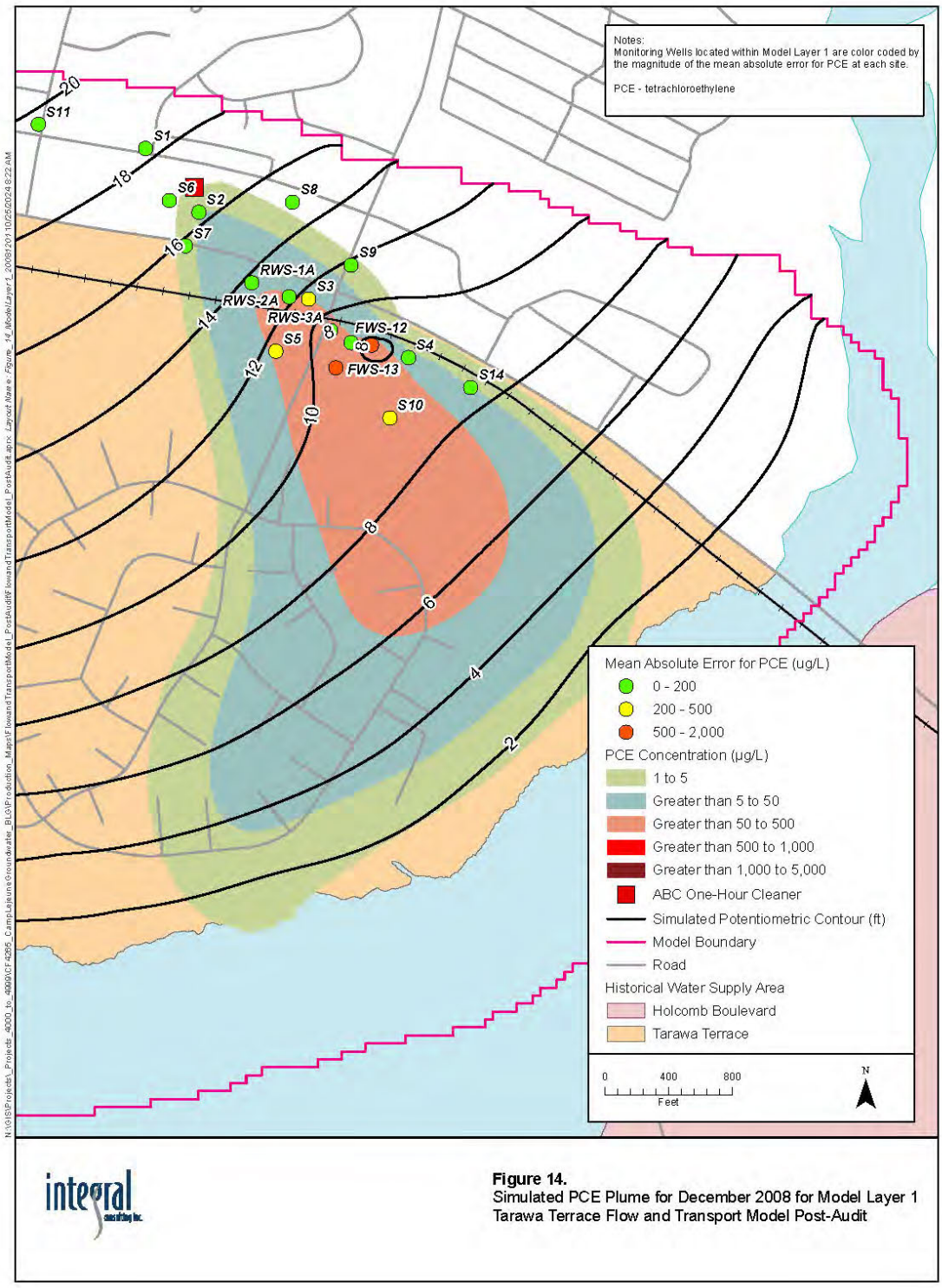


Figure 14.
Simulated PCE Plume for December 2008 for Model Layer 1
Tarawa Terrace Flow and Transport Model Post-Audit

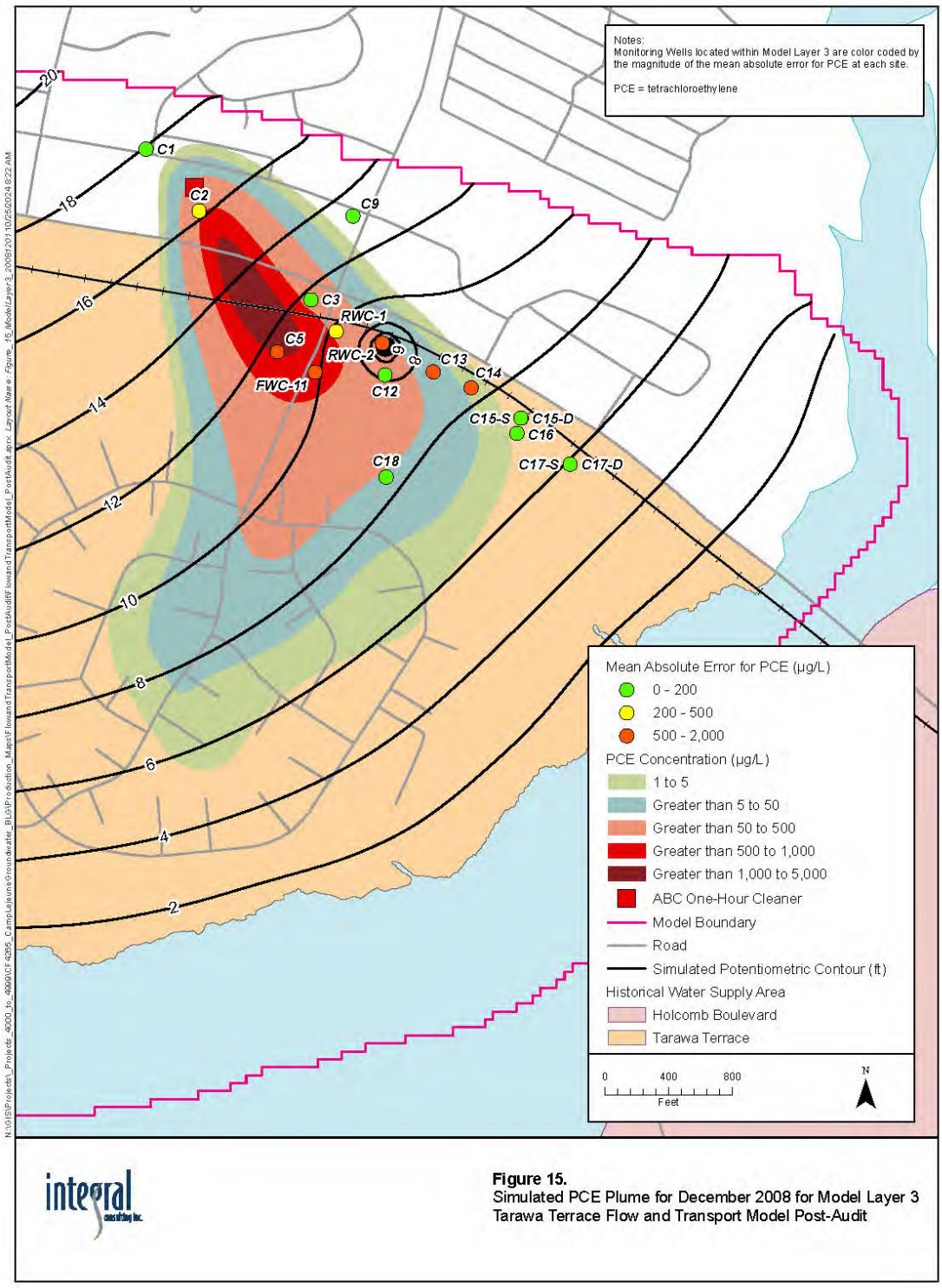


Figure 15.
Simulated PCE Plume for December 2008 for Model Layer 3
Tarawa Terrace Flow and Transport Model Post-Audit

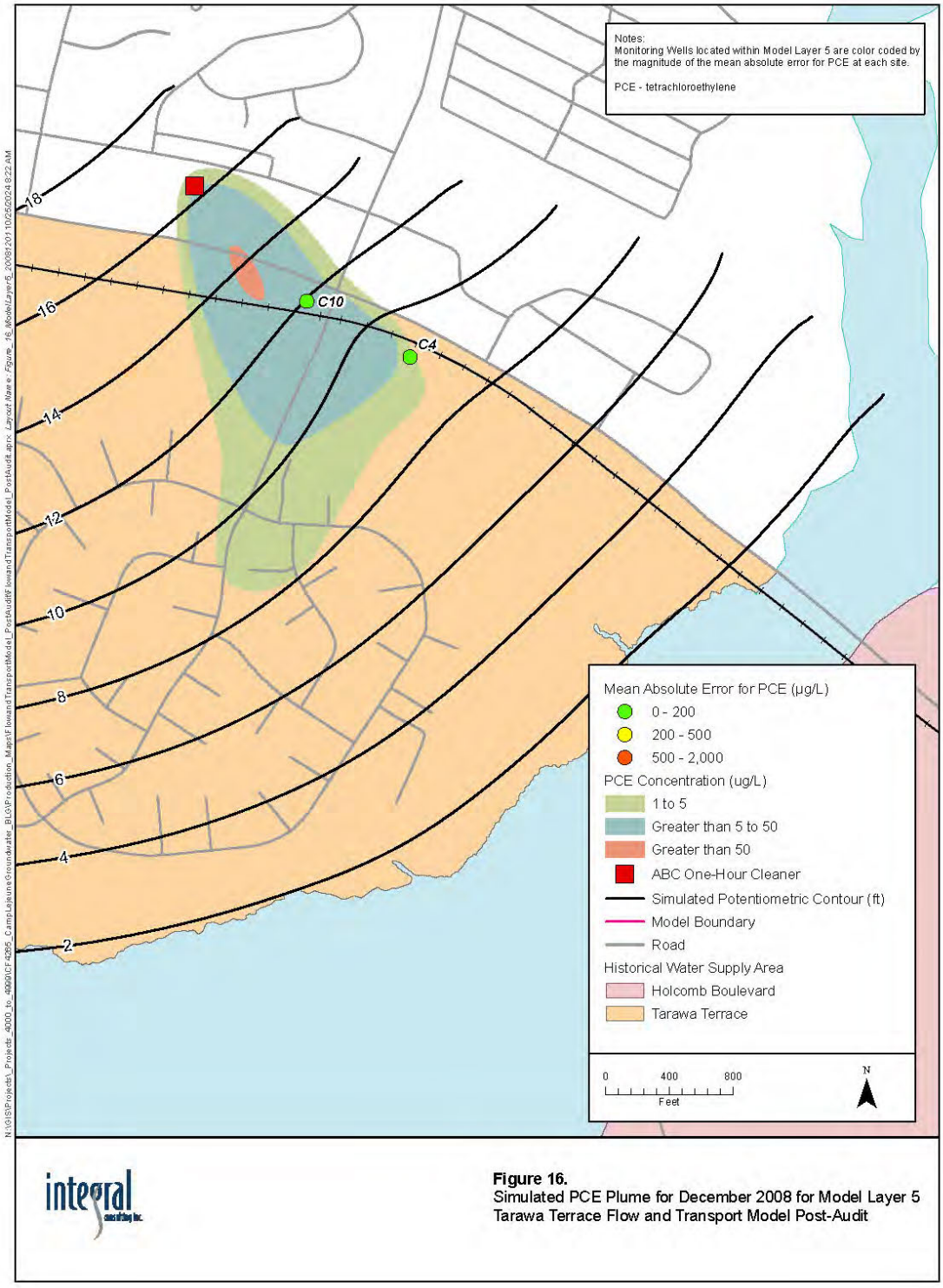


Figure 16.
Simulated PCE Plume for December 2008 for Model Layer 5
Tarawa Terrace Flow and Transport Model Post-Audit

Tables

Table 1. Annual Rainfall and Effective Recharge Rates

	Rainfall (in./yr)				Effective Recharge	
Year	Wilmington Airport	Wilmington 7N	New River MCAF	Average Rainfall	(in./yr)	(ft/day)
1995	65.1	64.4	48.6	59.3	13.94	0.00318
1996	64.4	52.7	75	64	15.04	0.00343
1997	49.6	51	53.6	51.4	12.07	0.00276
1998	64.2	77.2	70.1	70.5	16.55	0.00378
1999	72.1	82.1	63.2	72.5	17.02	0.00389
2000	53.8	59.2	50.4	54.5	12.79	0.00292
2001	38	57.4	43.5	46.3	10.87	0.00248
2002	49.3	56.9	49.4	51.9	12.18	0.00278
2003	63.6	72.8	50.5	62.3	14.64	0.00334
2004	50.7	71.7	51.7	58.1	13.63	0.00311
2005	69.3	68.4	59.2	65.6	15.41	0.00352
2006	63.8	62.7	62.5	63	14.8	0.00338
2007	33.4	37.3	60.4	43.7	10.26	0.00234
2008	60.8	48.4	56.4	55.2	12.96	0.00296
2009	59.7	59.4	53.6	57.6	13.53	0.00309

Notes:

Data publicly available at: https://www.weather.gov/wrh/Climate?wfo=ilm

Annual rainfall data were available for three locations proximal to the Tarawa Terrace: Wilmington Airport, Wilmington 7N, and New River MCAF.

Table 2. Pumping Rates for Remediation Wells Operating 1995 to 2008

Well	Northing	Easting	Model Layer	Pumping Rate (gpm)							
				11/1/1999	11/6/2001	3/7/2004	12/16/2004	3/31/2005	3/6/2006	2/20/2007	3/11/2008
RWS-1A	364445.7	2491125	1	5.5	18	20.8	12.1	20	20	0	0
RWS-2A	364351.5	2491359	1	3.8	18	3.5	2.34	28	24	0	0
RWS-3A	364146.8	2491620	1	29.2	24	18	1.07	15	30	30	30
RWS-4A	364053.7	2491878	1	13.3	24	24	22.5	28	25	30	25
RWC-2	364067.5	2491842	3	28.2	40	40	32.1	40	42	40	40

Notes:
Northing and easting values are given in NAD 1983 HARN North Carolina State Plane FIPS 3200 (US Feet)
gpm = gallons per minute

Table 3. Monitoring Wells Included in Extended Simulation

Monitoring Well	Northing	Easting	Model Layer	Well Completion Date	Borehole Depth (ft)	Finished Well Depth (ft)	Well Type
C1	365285.0	2490460.1	3	4/4/1992	104	100	Monitoring Well
C2	364895.7	2490794.3	3	4/8/1992	87	84.5	Monitoring Well
C3	364338.9	2491496.9	3	4/9/1992	90.5	89.4	Monitoring Well
C4	363971.9	2492116.1	5	4/3/1992	200	130	Monitoring Well
C5	364012.1	2491285.3	3	4/7/1992	92.5	90.5	Monitoring Well
C9	364864.6	2491760.5	3	9/10/1993	76.5	76	Monitoring Well
C10	364321.6	2491468.6	5	9/28/1993	80	0	Monitoring Well
C12	363867.4	2491961.7	3	11/6/2001	84	70	Monitoring Well
C13	363886.1	2492264.8	3	11/6/2001	83	76	Monitoring Well
C14	363787.1	2492503.0	3	5/12/2005	87	84.9	Monitoring Well
C15-D	363596.3	2492817.1	3	2/9/2007	110	110	Monitoring Well
C15-S	363596.3	2492816.1	3	2/9/2007	110	89	Monitoring Well
C16	363501.3	2492790.7	3	2/13/2007	95	94	Monitoring Well
C17-D	363306.6	2493125.4	3	2/13/2007	117	95	Monitoring Well
C17-S	363306.6	2493124.4	3	2/13/2007	117	85	Monitoring Well
C18	363226.0	2491968.6	3	2/15/2007	87	84	Monitoring Well
FWC-11	363884.0	2491523.5	3	--	89	88.6	--
FWS-12	364070.4	2491748.5	1	--	40	39.6	Monitoring Well
FWS-13	363912.7	2491653.1	1	--	38.5	38.2	Monitoring Well
RWC-1	364140.6	2491654.6	3	1/3-4/1998	91.5	--	Recovery Well
RWC-2	364067.5	2491944.6	3	1/5-6/1998	90	--	Recovery Well
RWS-1A	364445.7	2491125.4	1	--	55.5	55.5	Recovery Well
RWS-2A	364357.4	2491359.9	1	--	56	48.5	Recovery Well
RWS-3A	364146.8	2491620.4	1	--	60	55	Recovery Well
RWS-4A	364053.7	2491877.8	1	--	58.2	53	Recovery Well
S1	365289.2	2490457.3	1	3/22/1992	28	25.5	Monitor Well
S2	364889.0	2490792.7	1	3/26/1992	39.7	39.7	Monitor Well
S3	364343.6	2491482.1	1	4/2/1992	39.5	39.5	Monitor Well
S4	363976.4	2492109.4	1	4/3/1992	34	34	Monitor Well
S5	364016.2	2491275.9	1	4/1/1992	28	28	Monitor Well
S6	364962.4	2490607.3	1	3/26/1992	40.5	40.5	Monitor Well
S7	364677.4	2490707.9	1	4/5/1992	30.3	30.3	Monitor Well
S8	364951.7	2491380.5	1	4/4/1992	28	28	Monitor Well
S9	364555.9	2491748.8	1	3/21/1992	40	28.3	Monitor Well
S10	363597.3	2491992.8	1	3/20/1992	40	35	Monitor Well
S11	365440.7	2489784.3	1	9/11/1993	31	--	Monitor Well
S14	363788.1	2492499.8	1	5/10/2005	87	29	Monitor Well

Notes:

Northing and easting values are given in NAD 1983 HARN North Carolina State Plane FIPS 3200 (US Feet).

-- = information not available

[a] Estimated value

Table 4. Observed PCE Concentrations at Monitoring Wells, 1995 to 2008

Monitoring Well	Model Layer	PCE Concentration (µg/L)											
		6/1/1997	2/1/2000	1/1/2002	5/1/2002	8/1/2002	11/1/2002	3/1/2003	3/1/2004	3/1/2005	3/1/2006	2/1/2007	3/1/2008
C1	3	--	<DL	--	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL
C2	3	<DL	<DL	–	1	<DL	<DL	<DL	<DL	<DL	1.4	<DL	<DL
C3	3	580	410	–	270	140	100	150	58	37	38	23	22
C4	5	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	0.51	<DL	<DL
C5	3	<DL	<DL	–	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL
C9	3	<DL	<DL	–	1	<DL	0.48	<DL	1.9	7.4	18	20	18
C10	5	<DL	<DL	–	<DL	<DL	0.16	<DL	<DL	<DL	<DL	0.48	<DL
C12	3	–	--	15	7	1.7	<DL	<DL	<DL	<DL	<DL	<DL	<DL
C13	3	–	--	5,400	140	68	44	6	3	2.8	2.5	2.7	7.8
C14	3	–	--	–	--	–	--	–	--	1,800	1,300	320	120
C15-D	3	–	--	–	--	–	--	–	--	–	--	1.9	0.27
C15-S	3	–	--	–	--	–	--	–	--	–	--	3.8	3.8
C16	3	–	--	–	--	–	--	–	--	–	--	0.36	<DL
C17-D	3	–	--	–	--	–	--	–	--	–	--	0.77	<DL
C17-S	3	–	--	–	--	–	--	–	--	–	--	1.2	0.19
C18	3	–	--	–	--	–	--	–	--	–	--	0.41	0.84
FWC-11	3	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL
FWS-12	1	230	190	100	92	90	67	96	100	64	30	26	12
FWS-13	1	<DL	<DL	1	3	1.2	2.9	2	<DL	1.9	4.2	1.5	0.86
RWC-1	3	–	--	–	155	360	29	22	17	5	1.9	12	9.1
RWC-2	3	–	1,800	1,350	1,700	2,300	2,000	2,000	2,200	1,400	1,800	2,300	2,100
RWS-1A	1	–	--		8	<DL	5	6	2.6	2	1.8	2.7	2.1
RWS-2A	1	–	--	17	79	290	98	170	40	42	50	15	16
RWS-3A	1	–	--	760	920	970	500	810	280	560	280	260	160
RWS-4A	1	–	--	280	6,900	3,700	3,100	1,100	<DL	1,000	92	1,600	1,900
S1	1	5.6	<DL	–	<DL	<DL	0.32	<DL	<DL	<DL	<DL	<DL	<DL
S2	1	0	520	–	340	110	67	100	50	35	38	22	20
S3	1	77	12	–	23	54	60	48	53	47	23	85	94
S4	1	<DL	<DL	–	--	–	--	–	<DL	<DL	<DL	<DL	<DL
S5	1	<DL	<DL	–	<DL	<DL	1	<DL	<DL	<DL	<DL	<DL	<DL
S6	1	<DL	<DL	–	--	<DL	0.2	<DL	<DL	<DL	<DL	<DL	<DL
S7	1	<DL	--	–	--	<DL	<DL	0.5	<DL	<DL	1.9	<DL	<DL
S8	1	<DL	<DL	–	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL
S9	1	<DL	<DL	–	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL

Table 4. Observed PCE Concentrations at Monitoring Wells, 1995 to 2008

Monitoring Well	Model Layer	PCE Concentration (µg/L)											
		6/1/1997	2/1/2000	1/1/2002	5/1/2002	8/1/2002	11/1/2002	3/1/2003	3/1/2004	3/1/2005	3/1/2006	2/1/2007	3/1/2008
S10	1	<DL	<DL	<DL	<DL	<DL	0.16	<DL	<DL	<DL	<DL	0.74	<DL
S11	1	<DL	<DL	–	--	–	--	–	--	–	--	–	--
S14	1	–	--	–	--	–	--	–	--	<DL	<DL	0.47	<DL

Notes:
-- = no sample collected
<DL = sample result reported below the detection limit
PCE = tetrachloroethene

Table 5. Observed and Simulated PCE Concentrations at Monitoring Well Locations

Date	Monitoring Well	PCE Observed Concentration (µg/L)	PCE Simulated Concentration (µg/L)	Error	Abs(Error)
2/1/2000	C1	<DL	<DL	0	0
5/1/2002		<DL	<DL	0	0
8/1/2002		<DL	<DL	0	0
11/1/2002		<DL	<DL	0	0
3/1/2003		<DL	<DL	0	0
3/1/2004		<DL	<DL	0	0
3/1/2005		<DL	<DL	0	0
3/1/2006		<DL	<DL	0	0
2/1/2007		<DL	<DL	0	0
3/1/2008		<DL	<DL	0	0
6/1/1997	C2	<DL	1095	1095	1095
2/1/2000		<DL	742	742	742
5/1/2002		1	459	458	458
8/1/2002		<DL	459	459	459
11/1/2002		<DL	424	424	424
3/1/2003		<DL	388	388	388
3/1/2004		<DL	318	318	318
3/1/2005		<DL	247	247	247
3/1/2006		1.4	212	210	210
2/1/2007		<DL	177	177	177
3/1/2008		<DL	141	141	141
6/1/1997	C3	580	388	-192	192
2/1/2000		410	388	-22	22
5/1/2002		270	283	13	13
8/1/2002		140	247	107	107
11/1/2002		100	247	147	147
3/1/2003		150	247	97	97
3/1/2004		58	212	154	154
3/1/2005		37	177	140	140
3/1/2006		38	177	139	139
2/1/2007		23	141	118	118
3/1/2008		22	141	119	119
6/1/1997	C4	<DL	<DL	0	0
2/1/2000		<DL	<DL	0	0
1/1/2002		<DL	<DL	0	0
5/1/2002		<DL	<DL	0	0
8/1/2002		<DL	<DL	0	0
11/1/2002		<DL	<DL	0	0
3/1/2003		<DL	<DL	0	0
3/1/2004		<DL	<DL	0	0
3/1/2005		<DL	<DL	0	0
3/1/2006		0.51	<DL	-1	1
2/1/2007		<DL	<DL	0	0
3/1/2008		<DL	<DL	0	0

Table 5. Observed and Simulated PCE Concentrations at Monitoring Well Locations

Date	Monitoring Well	PCE Observed Concentration (µg/L)	PCE Simulated Concentration (µg/L)	Error	Abs(Error)
6/1/1997	C5	<DL	1307	1307	1307
2/1/2000		<DL	1165	1165	1165
5/1/2002		<DL	989	989	989
8/1/2002		<DL	989	989	989
11/1/2002		<DL	953	953	953
3/1/2003		<DL	918	918	918
3/1/2004		<DL	812	812	812
3/1/2005		<DL	777	777	777
3/1/2006		<DL	671	671	671
2/1/2007		<DL	600	600	600
3/1/2008		<DL	530	530	530
6/1/1997	C9	<DL	<DL	0	0
2/1/2000		<DL	<DL	0	0
5/1/2002		1	<DL	-1	1
8/1/2002		<DL	<DL	0	0
11/1/2002		0.48	<DL	0	0
3/1/2003		<DL	<DL	0	0
3/1/2004		1.9	<DL	-2	2
3/1/2005		7.4	<DL	-7	7
3/1/2006		18	<DL	-18	18
2/1/2007		20	<DL	-20	20
3/1/2008		18	<DL	-18	18
6/1/1997	C10	<DL	212	212	212
2/1/2000		<DL	177	177	177
5/1/2002		<DL	71	71	71
8/1/2002		<DL	71	71	71
11/1/2002		0.16	71	70	70
3/1/2003		<DL	71	71	71
3/1/2004		<DL	35	35	35
3/1/2005		<DL	35	35	35
3/1/2006		<DL	35	35	35
2/1/2007		0.48	35	35	35
3/1/2008		<DL	35	35	35
1/1/2002	C12	15	177	162	162
5/1/2002		7	177	170	170
8/1/2002		1.7	177	175	175
11/1/2002		<DL	177	177	177
3/1/2003		<DL	177	177	177
3/1/2004		<DL	177	177	177
3/1/2005		<DL	177	177	177
3/1/2006		<DL	177	177	177
2/1/2007		<DL	177	177	177
3/1/2008		<DL	141	141	141

Table 5. Observed and Simulated PCE Concentrations at Monitoring Well Locations

Date	Monitoring Well	PCE Observed Concentration (µg/L)	PCE Simulated Concentration (µg/L)	Error	Abs(Error)
1/1/2002	C13	5400	<DL	-5400	5400
5/1/2002		140	<DL	-140	140
8/1/2002		68	<DL	-68	68
11/1/2002		44	<DL	-44	44
3/1/2003		6	<DL	-6	6
3/1/2004		3	<DL	-3	3
3/1/2005		2.8	<DL	-3	3
3/1/2006		2.5	<DL	-3	3
2/1/2007		2.7	<DL	-3	3
3/1/2008		7.8	<DL	-8	8
3/1/2005	C14	1800	<DL	-1800	1800
3/1/2006		1300	<DL	-1300	1300
2/1/2007		320	<DL	-320	320
3/1/2008		120	<DL	-120	120
2/1/2007	C15-D	1.9	<DL	-2	2
3/1/2008		0.27	<DL	0	0
2/1/2007	C15-S	3.8	<DL	-4	4
3/1/2008		3.8	<DL	-4	4
2/1/2007	C16	0.36	<DL	0	0
3/1/2008		<DL	<DL	0	0
2/1/2007	C17-D	0.77	<DL	-1	1
3/1/2008		<DL	<DL	0	0
2/1/2007	C17-S	1.2	<DL	-1	1
3/1/2008		0.19	<DL	0	0
2/1/2007	C18	0.41	71	70	70
3/1/2008		0.84	71	70	70
6/1/1997	FWC-11	<DL	848	848	848
2/1/2000		<DL	812	812	812
1/1/2002		<DL	742	742	742
5/1/2002		<DL	742	742	742
8/1/2002		<DL	742	742	742
11/1/2002		<DL	706	706	706
3/1/2003		<DL	706	706	706
3/1/2004		<DL	671	671	671
3/1/2005		<DL	636	636	636
3/1/2006		<DL	600	600	600
2/1/2007		<DL	565	565	565
3/1/2008		<DL	494	494	494

Table 5. Observed and Simulated PCE Concentrations at Monitoring Well Locations

Date	Monitoring Well	PCE Observed Concentration (µg/L)	PCE Simulated Concentration (µg/L)	Error	Abs(Error)
6/1/1997	FWS-12	230	565	335	335
2/1/2000		190	530	340	340
1/1/2002		100	318	218	218
5/1/2002		92	283	191	191
8/1/2002		90	283	193	193
11/1/2002		67	247	180	180
3/1/2003		96	247	151	151
3/1/2004		100	212	112	112
3/1/2005		64	177	113	113
3/1/2006		30	177	147	147
2/1/2007		26	106	80	80
3/1/2008		12	71	59	59
6/1/1997	FWS-13	<DL	1201	1201	1201
2/1/2000		<DL	1024	1024	1024
1/1/2002		1	883	882	882
5/1/2002		3	848	845	845
8/1/2002		1.2	812	811	811
11/1/2002		2.9	777	774	774
3/1/2003		2	742	740	740
3/1/2004		<DL	600	600	600
3/1/2005		1.9	494	493	493
3/1/2006		4.2	388	384	384
2/1/2007		1.5	318	316	316
3/1/2008		0.86	247	246	246
5/1/2002	RWC-1	155	353	198	198
8/1/2002		360	353	-7	7
11/1/2002		29	353	324	324
3/1/2003		22	318	296	296
3/1/2004		17	318	301	301
3/1/2005		5	318	313	313
3/1/2006		1.9	283	281	281
2/1/2007		12	247	235	235
3/1/2008		9.1	247	238	238
2/1/2000	RWC-2	1800	106	-1694	1694
1/1/2002		1350	106	-1244	1244
5/1/2002		1700	106	-1594	1594
8/1/2002		2300	106	-2194	2194
11/1/2002		2000	106	-1894	1894
3/1/2003		2000	71	-1929	1929
3/1/2004		2200	71	-2129	2129
3/1/2005		1400	71	-1329	1329
3/1/2006		1800	71	-1729	1729
2/1/2007		2300	71	-2229	2229
3/1/2008		2100	71	-2029	2029

Table 5. Observed and Simulated PCE Concentrations at Monitoring Well Locations

Date	Monitoring Well	PCE Observed Concentration (µg/L)	PCE Simulated Concentration (µg/L)	Error	Abs(Error)
5/1/2002	RWS-1A	8	247	239	239
8/1/2002		<DL	247	247	247
11/1/2002		5	212	207	207
3/1/2003		6	177	171	171
3/1/2004		2.6	141	139	139
3/1/2005		2	106	104	104
3/1/2006		1.8	71	69	69
2/1/2007		2.7	71	68	68
3/1/2008		2.1	35	33	33
5/1/2002	RWS-2A	79	424	345	345
1/1/2002		17	459	442	442
8/1/2002		290	388	98	98
11/1/2002		98	353	255	255
3/1/2003		170	318	148	148
3/1/2004		40	247	207	207
3/1/2005		42	177	135	135
3/1/2006		50	141	91	91
2/1/2007		15	141	126	126
3/1/2008		16	71	55	55
1/1/2002	RWS-3A	760	565	-195	195
5/1/2002		920	530	-390	390
8/1/2002		970	494	-476	476
11/1/2002		500	494	-6	6
3/1/2003		810	459	-351	351
3/1/2004		280	353	73	73
3/1/2005		560	283	-277	277
3/1/2006		280	212	-68	68
2/1/2007		260	177	-83	83
3/1/2008		160	141	-19	19
1/1/2002	RWS-4A	280	388	108	108
5/1/2002		6900	353	-6547	6547
8/1/2002		3700	353	-3347	3347
11/1/2002		3100	353	-2747	2747
3/1/2003		1100	353	-747	747
3/1/2004		<DL	318	318	318
3/1/2005		1000	247	-753	753
3/1/2006		92	212	120	120
2/1/2007		1600	177	-1423	1423
3/1/2008		1900	141	-1759	1759

Table 5. Observed and Simulated PCE Concentrations at Monitoring Well Locations

Date	Monitoring Well	PCE Observed Concentration (µg/L)	PCE Simulated Concentration (µg/L)	Error	Abs(Error)
6/1/1997	S1	5.6	<DL	-6	6
2/1/2000		<DL	<DL	0	0
5/1/2002		<DL	<DL	0	0
8/1/2002		<DL	<DL	0	0
11/1/2002		0.32	<DL	0	0
3/1/2003		<DL	<DL	0	0
3/1/2004		<DL	<DL	0	0
3/1/2005		<DL	<DL	0	0
3/1/2006		<DL	<DL	0	0
2/1/2007		<DL	<DL	0	0
3/1/2008		<DL	<DL	0	0
6/1/1997	S2	<DL	141	141	141
2/1/2000		520	71	-449	449
5/1/2002		340	35	-305	305
8/1/2002		110	35	-75	75
11/1/2002		67	35	-32	32
3/1/2003		100	35	-65	65
3/1/2004		50	<DL	-50	50
3/1/2005		35	<DL	-35	35
3/1/2006		38	<DL	-38	38
2/1/2007		22	<DL	-22	22
3/1/2008		20	<DL	-20	20
6/1/1997	S3	77	1024	947	947
2/1/2000		12	706	694	694
5/1/2002		23	318	295	295
8/1/2002		54	283	229	229
11/1/2002		60	247	187	187
3/1/2003		48	212	164	164
3/1/2004		53	141	88	88
3/1/2005		47	106	59	59
3/1/2006		23	106	83	83
2/1/2007		85	71	-14	14
3/1/2008		94	71	-23	23
6/1/1997	S4	<DL	106	106	106
2/1/2000		<DL	106	106	106
3/1/2004		<DL	35	35	35
3/1/2005		<DL	35	35	35
3/1/2006		<DL	<DL	0	0
2/1/2007		<DL	<DL	0	0
3/1/2008		<DL	<DL	0	0

Table 5. Observed and Simulated PCE Concentrations at Monitoring Well Locations

Date	Monitoring Well	PCE Observed Concentration (µg/L)	PCE Simulated Concentration (µg/L)	Error	Abs(Error)
6/1/1997	S5	<DL	1624	1624	1624
2/1/2000		<DL	989	989	989
5/1/2002		<DL	494	494	494
8/1/2002		<DL	459	459	459
11/1/2002		1	424	423	423
3/1/2003		<DL	353	353	353
3/1/2004		<DL	247	247	247
3/1/2005		<DL	177	177	177
3/1/2006		<DL	141	141	141
2/1/2007		<DL	106	106	106
3/1/2008		<DL	71	71	71
6/1/1997	S6	<DL	<DL	0	0
2/1/2000		<DL	<DL	0	0
8/1/2002		<DL	<DL	0	0
11/1/2002		0.2	<DL	0	0
3/1/2003		<DL	<DL	0	0
3/1/2004		<DL	<DL	0	0
3/1/2005		<DL	<DL	0	0
3/1/2006		<DL	<DL	0	0
2/1/2007		<DL	<DL	0	0
3/1/2008		<DL	<DL	0	0
6/1/1997	S7	<DL	71	71	71
8/1/2002		<DL	<DL	0	0
11/1/2002		<DL	<DL	0	0
3/1/2003		0.5	<DL	-1	1
3/1/2004		<DL	<DL	0	0
3/1/2005		<DL	<DL	0	0
3/1/2006		1.9	<DL	-2	2
2/1/2007		<DL	<DL	0	0
3/1/2008		<DL	<DL	0	0
6/1/1997	S8	<DL	<DL	0	0
2/1/2000		<DL	<DL	0	0
5/1/2002		<DL	<DL	0	0
8/1/2002		<DL	<DL	0	0
11/1/2002		<DL	<DL	0	0
3/1/2003		<DL	<DL	0	0
3/1/2004		<DL	<DL	0	0
3/1/2005		<DL	<DL	0	0
3/1/2006		<DL	<DL	0	0
2/1/2007		<DL	<DL	0	0
3/1/2008		<DL	<DL	0	0

Table 5. Observed and Simulated PCE Concentrations at Monitoring Well Locations

Date	Monitoring Well	PCE Observed Concentration (µg/L)	PCE Simulated Concentration (µg/L)	Error	Abs(Error)
6/1/1997	S9	<DL	35	35	35
2/1/2000		<DL	35	35	35
5/1/2002		<DL	35	35	35
8/1/2002		<DL	35	35	35
11/1/2002		<DL	35	35	35
3/1/2003		<DL	<DL	0	0
3/1/2004		<DL	<DL	0	0
3/1/2005		<DL	<DL	0	0
3/1/2006		<DL	<DL	0	0
2/1/2007		<DL	<DL	0	0
3/1/2008		<DL	<DL	0	0
6/1/1997	S10	<DL	494	494	494
2/1/2000		<DL	494	494	494
1/1/2002		<DL	494	494	494
5/1/2002		<DL	459	459	459
8/1/2002		<DL	459	459	459
11/1/2002		0.16	459	459	459
3/1/2003		<DL	459	459	459
3/1/2004		<DL	424	424	424
3/1/2005		<DL	424	424	424
3/1/2006		<DL	388	388	388
2/1/2007		0.74	353	352	352
3/1/2008		<DL	318	318	318
6/1/1997	S11	<DL	<DL	0	0
2/1/2000		<DL	<DL	0	0
3/1/2005	S14	<DL	<DL	0	0
3/1/2006		<DL	<DL	0	0
2/1/2007		0.47	<DL	0	0
3/1/2008		<DL	<DL	0	0

Notes:
<DL = sample result reported below the detection limit
PCE = tetrachloroethene

Table 6. Mean Error and Mean Absolute Error for Monitoring Wells

Monitoring Well	Model Layer	Mean Error	Mean Absolute Error	Mean Absolute Error Category
C1	3	0	0	0-200
C2	3	423.6	423.6	200-500
C3	3	74.6	113.3	0-200
C4	5	0	0	0-200
C5	3	882.9	882.9	500-2,000
C9	3	-6.1	6.1	0-200
C10	5	77	77	0-200
C12	3	170.7	170.7	0-200
C13	3	-567.7	567.7	500-2,000
C14	3	-885	885	500-2,000
C15-D	3	-1.1	1.1	0-200
C15-S	3	-3.8	3.8	0-200
C16	3	-0.2	0.2	0-200
C17-D	3	-0.4	0.4	0-200
C17-S	3	-0.7	0.7	0-200
C18	3	70	70	0-200
FWC-11	3	688.6	688.6	500-2,000
FWS-12	1	176.4	176.4	0-200
FWS-13	1	693	693	500-2,000
RWC-1	3	242.1	243.6	200-500
RWC-2	3	-1817.9	1817.9	500-2,000
RWS-1A	1	141.8	141.8	0-200
RWS-2A	1	190.2	190.2	0-200
RWS-3A	1	-179.2	193.8	0-200
RWS-4A	1	-1677.6	1786.9	500-2,000
S1	1	-0.5	0.5	0-200
S2	1	-86.3	111.9	0-200
S3	1	246.2	253.1	200-500
S4	1	40.4	40.4	0-200
S5	1	462.2	462.2	200-500
S6	1	0	0	0-200
S7	1	7.6	8.1	0-200
S8	1	0	0	0-200
S9	1	16.1	16.1	0-200
S10	1	435.5	435.5	200-500
S11	1	0	0	0-200
S14	1	-0.1	0.1	0-200

Notes:

Northing and easting values are given in NAD 1983 HARN North Carolina State Plane FIPS 3200 (US Feet).

Exhibit 1

Resume for R. Jeffrey Davis



R. Jeffrey Davis, P.E., CGWP

Principal, Water Resources

(385) 955-5184
Salt Lake City, UT
jdavis@integral-corp.com

Mr. Jeff Davis is a licensed civil and environmental engineer, hydrogeologist, and certified groundwater professional with almost 30 years of global experience working on every continent except Antarctica. He currently serves on the Board of Directors for the National Ground Water Association. Mr. Davis has supported numerous litigation cases involving groundwater impacts and has experience as an expert witness. He has spent much of his career solving complicated water problems involving mining, oil and gas, and water resources. These projects include the clean water supply side as well as the remediation of contaminated sites. The contaminated sites include coal combustion residual (CCR) landfills and other waste impoundments, mining remediation sites, and industrial cleanup sites—both RCRA and CERCLA sites. In working with per- and polyfluoroalkyl substance (PFAS) compounds, MTBE, chlorinated solvents, hydrocarbons, nitrates, and road salt, he has developed and used numerous groundwater models for the mining, energy, chemical, and agricultural industries. Other projects have involved environmental impact statements, environmental assessments, water management, groundwater–surface water contamination, dewatering, and water supply and treatment. He has extensive knowledge of groundwater flow-and-transport principles and has taught numerous workshops and classes in the U.S. and around the world. His current focus is on water and groundwater sustainability and drought resiliency. Mr. Davis has extensive experience in the design and implementation of aquifer storage and recovery (ASR) projects across the country.

Education & Credentials

M.S., Civil & Environmental Engineering, Brigham Young University, Provo, Utah, 1998

B.S., Civil & Environmental Engineering, Brigham Young University, Provo, Utah, 1993

Professional Engineer, Utah (License No. 189690-2202), Texas (License No. 125406), Florida (License No. 74838), Colorado (License No. 0051575), Alabama (License No. PE52096), Idaho (License No. P-21839), Oregon (License No. 104270PE)

Certified Groundwater Professional, NGWA (2023)

Continuing Education

Certificate of Specialization in Leadership and Management, Harvard Business School Online (2023)

MSHA certified (2020)

First Aid and CPR certified (2020)

Professional Affiliations

National Ground Water Association

Utah Groundwater Association

Groundwater Resources Association of California

Relevant Experience

WATER MANAGEMENT

ASR Feasibility, Utah County, Utah — Served as principal investigator for a feasibility study for an ASR project. During the spring runoff of 2023, the team measured the runoff in several rivers, creeks, and ditches, and constructed a new infiltration basin, all in an effort to advance aquifer storage projects within the county.

ASR Feasibility, Utah County, Utah — Served as principal for a feasibility study for an ASR project. Former agricultural water rights were converted for industrial use and the effluent was being considered for aquifer replenishment. Both infiltration and direct injection of the treated water were considered as part of the feasibility study.

Provo ASR, Provo, Utah — Served as the project manager and engineer of record for the current Provo ASR project. Five sites (three infiltration and two direct injection) are currently permitted

for pilot studies that have been ongoing since 2020. Final engineering design and permitting have been completed for all five sites.

Water Reuse and Aquifer Sustainability, Eagle Mountain, Utah — Served as the client manager and engineer of record for the current Eagle Mountain City, Utah, water-reuse planning and aquifer sustainability project. Water rights for Eagle Mountain were evaluated along with the groundwater system to understand aquifer sustainability for the city, which is expecting tremendous future growth, including large industrial water demands.

ASR Evaluation, Weber County, Utah — Served as the project manager and engineer of record for the current evaluation of the Weber Basin Water Conservancy District, Utah, ASR project. This project has been actively operating for more than 10 years. Hired to evaluate the storage capacity of the program and obtain greater recovery volumes from the system, working with the Utah Division of Water Rights.

Drainage Reuse Initiative, Harris County, Texas — Served as part of a team for the development of the Drainage Reuse Initiative for Harris County Flood Control District in Harris County, Texas. The project investigated the feasibility of alternative methods of flood mitigation by conveying stormwater to the subsurface, including natural infiltration to groundwater, enhanced infiltration or injection into aquifers, and mechanical injection to deep aquifers.

Roseville ASR, Roseville, California — Served as one of the groundwater leads for the development of an ASR program for the city of Roseville, California. Initial efforts involved developing a regional- scale conceptualization for the major portion of the Central Valley area. Developed a subsequent regional multilayer groundwater model, followed by a number of local-scale transport models to simulate pilot tests and understand the ASR process.

COAL COMBUSTION FACILITIES

Coal Combustion Residual Waste and Disposal, Bonanza, Utah — Served as the engineer of record for a coal power plant. Oversaw all efforts related to the monitoring and compliance of the facility's CCR waste and disposal. This included semiannual reporting, development of alternative source demonstrations, and annual groundwater monitoring reports.

Hexavalent Chromium Investigation, United States — Served as the principal investigator for a study to understand and evaluate the proposed EPA changes to hexavalent chromium (Cr(VI)) as it would apply to the monitoring and management of CCR landfill facilities. The work included examining potential regulatory levels from a human health perspective.

Alternate Water Sources Investigation, United States — Served as the principal investigator for a study to understand and evaluate differences at CCR facilities between upgradient and downgradient sources, and locate potential evidence of alternate sources using isotopes and microbial fingerprinting. After development of a sampling and analysis plan, advanced statistical and multivariate methods were used to document analyses that show potential for distinguishing source water from alternate sources.

OIL AND GAS WASTE MANAGEMENT

Oil and Gas Waste Facility, De Beque, Colorado — Served as the principal engineer for the permitting and operating of an 800-acre oil-and-gas waste-disposal facility southeast of De Beque, Colorado. Involved in several aspects of the permitting process, including the hydrogeological study and groundwater investigations; stormwater design; pond liner design and construction; closure certification; and submittal of the revised engineering design and operation plan.

Remedial Investigation, Billings, Montana — Served as the groundwater lead for the Yale Oil of South Dakota Facility in Billings, Montana. The Superfund site facility is in the remedial investigation phase; the risk-assessment work plan has been submitted to the Montana Department of Environmental Quality, and the client is waiting for comments before proceeding with the risk assessment.

EPA Study, Washington, DC — Served as participant and technical reviewer for EPA's "Study of Hydraulic Fracturing for Oil and Gas and Its Potential Impact on Drinking Water Resources." Participated in technical roundtables and technical workshops and completed a peer review of the EPA's five retrospective case studies.

Fate and Transport Modeling, Texas — Served as groundwater lead for fate-and-transport modeling and analysis of chloride contamination in southern Texas near the Gulf of Mexico. As part of the site mitigation phase, modeling was used to determine the potential migration of the chloride through the shallow aquifer system and nearby receptors.

Lockwood Solvent Groundwater Plume Site, Billings, Montana — Served as one of the groundwater leads performing groundwater modeling for the Lockwood Solvent Groundwater Plume site, an EPA Superfund site in Billings, Montana. The site spans 580 acres, and much of the groundwater there is contaminated with volatile organic compounds, including tetrachloroethene, trichloroethene, cis-1,2- dichloroethene, and vinyl chloride.

PLANNING AND PERMITTING

Beverage Can Manufacturing and Filling, Salt Lake City, Utah — Served as principal investigator for wastewater, stormwater, and Utah Pollutant Discharge Elimination System permitting, monitoring, and compliance for an aluminum can manufacturing and filling facility. Worked closely with the client, its operations team, and state and municipal regulators to regularly monitor and report all discharges from the facility.

Ely Energy Center EIS, White Pine County, Nevada — Served as principal lead for the development of a regional groundwater model for Steptoe Valley in White Pine County, Nevada. The investigation and model were part of the EIS for construction of the Ely Energy Center.

Haile Gold Mine EIS, Kershaw, South Carolina — Served as groundwater lead as the third-party contractor developing an EIS for the proposed Haile Gold Mine near Kershaw, South Carolina. The EIS analyzed the potential direct, indirect, and cumulative environmental effects of the proposed project and its alternatives. Work included project-team coordination for geology, groundwater, and surface water resources areas; review of applicant-supplied information; agency coordination; and public involvement.



Four Corners Power Plant EIS, Farmington, New Mexico — Served as groundwater lead as the third- party contractor in developing an EIS for the Four Corners Power Plant and Navajo coal mine in Farmington, New Mexico. The EIS analyzed the potential direct, indirect, and cumulative environmental effects of the proposed project and its alternatives. The groundwater portion included analyzing field investigations, pump tests, conceptual and numerical modeling of the project and surrounding area, and remediation and reclamation activities.

Iron Ore Operations Cumulative Impact Assessment, Pilbara, Western Australia — Served as one of the groundwater leads for a cumulative impact assessment for a proposed expansion of iron ore operations in the Pilbara in Western Australia. Work included identifying the methodology and developing the conceptual models to perform the assessment. The groundwater modeling included both quantitative and qualitative approaches.

LITIGATION SUPPORT

Expert Witness for PFAS Litigation, Martin County, Florida — Served as the groundwater expert witness for a litigation case in Martin County. The multidistrict litigation bellwether case involved PFAS contamination of groundwater affecting public drinking water. Opinions were given regarding PFAS sourcing, and fate and transport in groundwater, and regarding public water supply planning.

Water Resources Litigation, Grand County, Colorado — Served as principal investigator for a litigation case involving flooding damages caused by a canal breach. Surface water modeling was used to determine amount and extent of erosion and sedimentation from the flooding.

Water Resources Litigation, Northwest Minnesota — Served as principal investigator and expert witness for a litigation case involving agricultural water rights and pumping near tribal lands. Developed a conceptual model to understand the hydrogeological conditions and constructed a groundwater model to determine possible impacts due to the agriculture activities.

Groundwater Litigation, Ventura County, California — Served as the groundwater expert for a litigation case in Ventura County. The case includes the development of a basin-wide groundwater- surface water model, not only for purposes of litigation but also for compliance with Sustainable Groundwater Management Act requirements. The groundwater basin in question is currently listed as a priority basin by the State of California.

Pipeline Spill Litigation, Williston, North Dakota — Provided litigation services for groundwater and surface water contamination from a pipeline spill in North Dakota. A large spill of produced water (brine) impacted surface streams as well as the shallow aquifer system. Work included groundwater modeling, field investigations, and remedial strategies.

Road Salt Contamination Litigation, Vandalia, Ohio — Performed fate-and-transport modeling and analysis of sodium chloride contamination of an aquifer in Vandalia, Ohio. Stored road salt caused limited contamination of a shallow aquifer that supplied drinking water to nearby residential homes. The groundwater model included the local domestic pumping wells, which helped determine the possible extent of chloride impacts. Largely due to the conceptual site model and transport modeling results, litigation was settled out of court to the satisfaction of the client.

GROUNDWATER MODELING

Subsidence Monitoring/Modeling, Fort Bend and Harris Counties, Texas — Served as the groundwater lead and engineer on several groundwater development projects in Fort Bend and Harris counties. Groundwater withdrawals are strictly curtailed due to historical subsidence. The Subsidence Districts have installed GPS Port-A-Measure (PAM) units and used InSAR mapping. Using this data plus the output from the models PRESS and MODFLOW-SUB to measure subsidence impacts.

Groundwater Model Development, New Jersey — Led a team of hydrogeologists to construct a groundwater flow and fate and transport model of perfluorononanoic acid and other contaminants. The model will be used to design a pump and treat system and possible aquifer replenishment with the treated groundwater.

Hydrogeological Services, Montgomery County, Texas — Provided modeling and hydrogeological consulting services for the Lone Star Ground-water Conservation District's (Montgomery County, Texas) update of its desired future conditions and groundwater management plans. Also provided litigation services for the district.

Groundwater Model Development, Havana, Florida — Provided consulting services for Northwest Florida Water Management District as it updated its regional groundwater model—an integrated groundwater-surface water model that provides regulatory control of the groundwater withdrawals and manages saltwater intrusion in the Floridan aquifer due to pumping.

Crop Production Services, Various Locations, U.S. — Served as the groundwater lead to provide modeling and hydrogeological consulting services for a number of crop production services legacy sites. The groundwater at the sites was contaminated with nitrates from long-term fertilizer use. Groundwater modeling was used to determine the fate and transport of the nitrates and to develop a remedial strategy for cleanup.

Legacy Way Tunnel Design, Brisbane, Australia — Provided senior oversight and technical review for all hydrogeologic assessments related to the Legacy Way tunnel design project, a 4.6 km underground tunnel in northern Brisbane, Australia. Work included evaluating field tests, preparing geotechnical and environmental reports, and modeling the entire project area.

Mercury Fate and Transport, Cincinnati, Ohio — Served as the groundwater lead for performing fate and transport modeling and analysis of a mercury spill at a municipal landfill in Cincinnati, Ohio. As part of the project management phase, modeling was used to determine the potential migration of mercury through the landfill to the leachate collection system. Modeling efforts examined both the spatial distribution and the temporal component of the mercury transport.

Due Diligence Environmental Review, Pascagoula, Mississippi — Served as the environmental lead for performing an environmental assessment at a chemical plant in Pascagoula, Mississippi, as part of a due diligence effort. A number of groundwater and surface water contamination issues due to spills, leaks, and storage of hazardous materials were addressed. The location of the plant on the Gulf of Mexico makes possible environmental impacts from operation of the chemical plant a sensitive issue.



MINING

Bingham Canyon Mine Closure Planning, Copperton, Utah — Completed an independent third-party audit for a closure-plan pit-lake study for Bingham Canyon Mine. Reviewed the consultant scope of work for the pit-lake study and discussed the study, methodology, and pathway to completion with consultant staff. An independent audit report was compiled and submitted to the client.

Hooker Prairie Mine, Bartow, Florida — Served as the model expert to develop a contaminant and water budget and management model for the Hookers Prairie Mine in Florida using the GoldSim modeling software. The purpose of the model was to evaluate the probabilities of the mine meeting its current and future nutrient NPDES loading limits for certain contaminants. The project also included an evaluation of current monitoring data within the mine operations and at discharge locations, and the development of a complete monitoring plan integrated into a GIS as part of the model calibration and validation.

Bridger Coal Mine Investigation, Rock Springs, Wyoming — Served on a technical team to reevaluate groundwater conditions, and treatment and discharge alternatives at the Bridger coal mine in southwest Wyoming. Previous studies' predicted maximum flows into the mine had been exceeded. Reassessed the situation and provided solutions.

EMERGENCY RESPONSE

Emergency Response to Battery Fire, Confidential Location — Served as the principal in charge leading a team of multidisciplinary scientists, engineers, toxicologists, and risk assessors for an environmental emergency response at a large-scale battery power storage unit at a solar farm. A thermal incident where several cargo container boxes caught fire and burned required immediate action to assess the environmental and human health impacts.

ECOLOGICAL RESTORATION

Ecological Restoration, Northeast Idaho — Serves as the principal in charge leading a team of scientists, engineers, and ecologists for an ecological restoration effort in northeast Idaho. The project has involved restoring flow to a creek and working with a number of state and federal agencies to develop and implement a conceptual restoration plan and a mitigation and monitoring plan. The project will also include obtaining the necessary permits and overseeing the restoration in an area of critical habitat.

PROJECT MANAGEMENT

GMS Software Development, Utah — Served as chief engineer for the original development of the software Groundwater Modeling System (GMS) at the Environmental Modeling Research Laboratory at Brigham Young University. A sophisticated graphical environment for groundwater model pre- and post-processing, 3-dimensional site characterization, and geostatistics, GMS is the official groundwater application of the U.S. Department of Defense and is also used by the U.S. Department of Energy, EPA, and thousands of users across the world.

NATURAL RESOURCE DAMAGE ASSESSMENT

Natural Resources Damage Assessment, Southeastern Idaho — Served as the groundwater expert determining groundwater damages in southeastern Idaho due to decades of phosphate



mining. Led a team of hydrogeologists evaluating the impacts of selenium and other contaminants and changes in natural groundwater flows across the entire region. The damage assessment included a number of mining areas as well as the facilities where the phosphate material was processed.

Presentations / Posters

Davis, R.J. 2023. Challenges limiting managed aquifer recharge (MAR) adoption in the West. National Ground Water Association Groundwater Summit. December 5–7. Las Vegas, NV.

Davis, R.J. 2023. Water, AI, and us: What does the future hold for solving Utah's water challenges. Hint: It can't be solved without you and me. Salt Lake County Watershed Symposium. November 15–16. Salt Lake City, UT.

Davis, R.J. 2023. Building climate resilience through sustainable remediation in the western region. Groundwater Resources Association of California Western Groundwater Congress. September 12–14. Burbank, CA.

Davis, R.J. 2023. Water in Utah: Navigating the present and shaping the future. American Groundwater Trust. August 14–15. Provo, Utah.

Davis, R.J. 2023. More managed aquifer recharge and saving the Great Salt Lake—A balancing act. Idaho Water Users Association. June 12–13. Sun Valley, ID.

Davis, R.J. 2023. More managed aquifer recharge: Deliberate resiliency to combat droughts and climate change in the West. Association for Environmental Health of Soils. March 20–23. San Diego, CA.

Davis, R.J. 2023. Resilient and sustainable remediation. ESG|Climate Resilient & Sustainable Remediation Symposium. Groundwater Resources Association of California Western Groundwater Congress. February 6–7. San Diego, CA.

Davis, R.J. 2022. More managed aquifer recharge: Solutions to combat droughts and climate change in the West. National Ground Water Association Groundwater Summit. December 6–8. Las Vegas, NV.

Davis, R.J. 2022. Saving our aquifers: Climate change and managed aquifer recharge. Salt Lake County Watershed Symposium. November 16–17. Salt Lake City, UT.

Davis, R.J. 2022. More managed aquifer recharge—A solution to combat droughts and climate change in the West. Groundwater Resources Association of California Western Groundwater Congress. September 21–23. Sacramento, CA.

Davis, R.J. 2022. Saving our aquifers—Climate change, sustainability, and managed aquifer recharge. International Water Holdings. August 24–25. Salt Lake City, UT.

Davis, R.J. 2022. More managed aquifer recharge (MMAR) a solution to combat droughts and climate change in the West. Groundwater Protection Council Annual Forum. June 21–23. Salt Lake City, UT.

Davis, R.J. 2022. Aquifer storage and recovery—Hydrogeologic considerations. American Water Resources Association. May 17. Salt Lake City, UT.

Davis, R.J. 2022. Utah hydrology—What you do and don't know about Utah hydrogeology. National Ground Water Association. May 4, 2022. Virtual.

Davis, R.J. and B. Lemon. 2022. Provo, Utah: From planning to pilot to a final aquifer storage and recovery (ASR) program. Utah Water Users Workshop. March 21–23. St. George, UT.

Davis, R.J. 2021. Provo, Utah, from planning to pilot to a final managed aquifer recharge (MAR) program. National Ground Water Association Groundwater Summit. December 7–8. Virtual.

Davis, R.J. 2021. Provo City aquifer storage and recovery project. Ground Water Protection Council Annual Forum, September 27–29. Virtual.

Davis, R.J. 2021. Provo, Utah, from planning to pilot to a final managed aquifer recharge (MAR) program. American Public Works Association Utah Section Annual Conference. September 21–22. Sandy, UT.

Davis, R.J. 2021. Provo City aquifer storage and recovery project. Utah Water Users Workshop. May 17–19. St. George, UT.

Davis, R.J. 2021. Provo, Utah: From planning to pilot to a final managed aquifer recharge (MAR) program. ASR for Texas, Virtual Webinar. May 4–5.

Davis, R.J. 2021. Provo aquifer storage and recovery—From planning to pilot. American Water Works Association Virtual Summit on Sustainable Water, PFAS, Waterborne Pathogens. February 10–11.

Davis, R.J. 2020. Update on Provo's aquifer storage and recovery program. American Water Works Association Virtual Intermountain Section Annual Conference. October 21–23. Sun Valley, ID.

Davis, R.J. 2020. Are you prepared for the new federal permit process for CCR facilities? Second Annual Coal Ash and Combustion Residual Management Webinar, October 7–8. Virtual.

Invited Participant, Expert Panels, and Workshops

Bulk Water Innovation Partnership (BWIP): More managed aquifer recharge: Deliberate resiliency to combat droughts and climate change in the West. December 6, 2023. Virtual.

Rocky Mountain Association of Environmental Professionals (RMAEP): Great Salt Lake of Utah: watershed, legislative, and community issues surrounding it. September 20, 2023.

Salt Lake Chamber: Utah Water Outlook. April 13, 2022.



EDCUtah Webinar: Water: Constraints and Opportunities for Development in Utah panel. June 11, 2021.

ULI Utah: Trends Conference—Water: Constraints and Opportunities for Development in Utah panel. October 27, 2021.



Exhibit 2

Resume for Norman L. Jones

Norman L. Jones, Ph.D.
Professor
Department of Civil & Construction Engineering
Brigham Young University

Education

Ph.D.	Civil Engineering, University of Texas at Austin, 1990
M.S.	Civil Engineering, University of Texas at Austin, 1988
B.S.	Civil Engineering, Brigham Young University, 1986

Academic Experience

Department Chair, Civil & Construction Engineering, Brigham Young University (BYU), 2018-2024
Professor, Civil & Construction Engineering, BYU, 2002–present
Associate Professor, Civil & Environmental Engineering, BYU, 1997–2002
Assistant Professor, Civil & Environmental Engineering, BYU, 1991–1996

Current Membership in Professional Organizations

American Society of Civil Engineers (ASCE)
American Water Resources Association (AWRA)
National Ground Water Association (NGWA)
American Geophysical Union (AGU)

Professional Committees

AWRA 2014 GIS in Water Resources Technical Program Chair
NGWA Groundwater Modeling Interest Group Committee
American Society of Civil Engineers
EWRI Groundwater Management Committee
EWRI Emerging Technologies Committee
International Editorial Board for the Journal of HydroInformatics
Editor of AQUAmundi Journal
Great Salt Lake Basin Integrated Plan - Groundwater Technical Advisory Team
Tethys Geoscience Foundation - Board Member

Selected Honors and Awards

2001 Walter L. Huber Civil Engineering Research Prize
2002 College of Engineering & Technology Special Commendation Award
2003 Brigham Young University Technology Transfer Award
2007 Utah Engineering Educator of the Year – ACEC
2012 Brigham Young University Karl G. Maeser Research and Creative Arts Award
2016 AWRA Educator of the Year – Utah Section
2021 NGWA John Hem Award for Science and Engineering
2023 Brigham Young University Sponsored Research Award

University Courses Taught

CE En 101 - Introduction to Civil and Environmental Engineering
CE En 201 - Infrastructure
CE En 270 – Computer Methods in Civil Engineering
CE En 341 – Elementary Soil Mechanics
CE En 540 – Geo-Environmental Engineering
CE EN 544 - Seepage and Slope Stability Analysis
CCE 547 – Ground Water Modeling

CE En 641 – Advanced Soil Mechanics

Software

Led the development of the Groundwater Modeling System (GMS) software. GMS is a state-of-the-art three-dimensional environment for ground water model construction and visualization. It includes tools for site characterization including geostatistics and solid modeling of soil stratigraphy. GMS is the most comprehensive and sophisticated groundwater modeling software available and is used by over 10,000 organizations in over 100 countries. Currently managed and distributed by Aquaveo, LLC, a company I co-founded in 2007.

External Research Grants

1. Automated Mesh Generation For the TABS-2 System, $19,000, 2/90 - 11/90, U.S. Army Engineer Waterways Experiment Station
2. A Geometry Pre-Processor for HEC-1 Employing Triangulated Irregular Networks, $20,048, 3/91 - 10/91, U.S. Army Engineer Waterways Experiment Station
3. Real-Time Visualization for the TABS-2 Modelling System, $14,123, 4/91 - 8/91, U.S. Army Engineer Waterways Experiment Station
4. An Investigation of X-Windows Interface Tools, $49,556, 1/92 - 8/92, U.S. Army Engineer Waterways Experiment Station
5. Descriptive Geometry and Solid Rendering, $24,000, 1/92 - 10/92, U.S. Army Engineer Waterways Experiment Station
6. An Investigation of Automated Pre-processing Schemes for TIN-Based Drainage Analysis, $34,750, 4/92-10/92, U.S. Army Engineer Waterways Experiment Station
7. A Comprehensive Graphical User Environment for Groundwater Flow and Transport Modeling, $246,526, 6/93-9/94, U.S. Army Engineer Waterways Experiment Station
8. An Integrated Surface Flow Modeling System, $131,848, 1/94-1/95, U.S. Army Engineer Waterways Experiment Station
9. Productivity and Management Tools for Groundwater Flow and Transport Modeling, $207,404, 5/94-4/95, U.S. Army Engineer Waterways Experiment Station
10. Enhanced Tools for Quality Control in Automated Groundwater Transport Modeling, $246,553, 1/95-12/95, U.S. Army Engineer Waterways Experiment Station
11. Visualization for Two-Dimensional Surface Runoff Modeling, $98,221, 1/95-10/95, U.S. Army Engineer Waterways Experiment Station
12. Visualization Tools for Two-Dimensional Finite Element Hydrologic Modeling, $93,933, 11/95-10/96, U.S. Army Engineer Waterways Experiment Station
13. A Graphical Environment for Multi-Dimensional Surface Water Modeling, $49,789, 3/96-9/96, U.S. Army Engineer Waterways Experiment Station
14. A Conceptual Modeling Approach to Pre-processing of Groundwater Models, $475,743, 11/95-11/97, U.S. Army Engineer Waterways Experiment Station
15. Hydrosystems Modeling, $2,458,083, 5/97-4/02, U.S. Army Engineer Waterways Experiment Station
16. Second Generation Hydroinformatics Research, $4,958,127. U.S. Army Engineer Research and Development Center.
17. Flux Calculations and 3D Visualization for the SCAPS Piezocone and GeoViz System, $34,931, U.S. Navy.
18. Development of modeling methods and tools for predicting coupled reactive transport processes in porous media under multiple scales. $949,000. US Dept. of Energy. 1/07-12/09.
19. CI-WATER: Cyberinfrastructure to Advance High Performance Water Resource Modeling, $3,435,873. National Science Foundation - EPSCoR. 9/11-8/14.

20. Comprehensive Streamflow Prediction and Visualization to Support Integrated Water Managment, $599,823. NASA SERVIR, 8/16-8/19.
21. Daniel P. Ames, E. James Nelson, Norman L. Jones, An AmeriGEOSS Cloud-based Platform for Rapid Deployment of GEOGLOWS Water and Food Security Decision Support Apps, $540,658, NASA GEO, 1/2018-12/2020
22. Geospatial Information Tools That Use Machine-Learning to Enable Sustainable Groundwater Management in West Africa, $657,232. NASA SERVIR, 11/19-11/22.
23. Advancing the NASA GEOGloWS Toolbox for Regional Water Resources Management and Decision Support. $1.2M. NASA GEOGLOWS. 2022-2025. Dan Ames, Jim Nelson, Gus Williams, Norm Jones.
24. CIROH: National Cyberinfrastructure Framework for Engaging the Hydrologic Community (NCF). $1,822,418. National Oceanographic and Atmospheric Administration. 2022-2025. Dan Ames, Jim Nelson, Gus Williams, Norm Jones.
25. CIROH: Advancing Science to Better Characterize Drought and Groundwater-Driven Low-Flow Conditions in NOAA and USGS National-Scale Models. $801,221. 2023-2025. Norm Jones, Gus Williams, T. Prabhakar Clement, Donna Rizzo.
26. Improved Hydrologic Prediction Services for Resilience with GEOGLOWS, $1,889,627, National Oceanic and Atmospheric Administration (NOAA), 4/1/2024-3/31/2027. Norm Jones, Jim Nelson, Andrew South.

Summary: PI or Co-PI on 26 projects totaling $22,026,639.

Peer-Reviewed Publications in the Past 10 Years

1. Jones, N., Nelson, J., Swain, N., Christensen, S., Tarboton, D. Dash, P. Tethys: A Software Framework for Web-Based Modeling and Decision Support Applications. In: Ames, D.P., Quinn, N.W.T., Rizzoli, A.E. (Eds.), Proceedings of the 7th International Congress on Environmental Modelling and Software, June 15-19, San Diego, California, USA. ISBN: 978-88-9035-744-2
2. Jones, N., Griffiths, T., Lemon, A., Kudlas, S. Automated Well Permitting in Virginia's Coastal Plain Using SEAWAT and GIS Geoprocessing Tools. In: Ames, D.P., Quinn, N.W.T., Rizzoli, A.E. (Eds.), Proceedings of the 7th International Congress on Environmental Modelling and Software, June 15-19, San Diego, California, USA. ISBN: 978-88-9035-744-2
3. Y. Fan, S. Richard, R. S. Bristol, S. E. Peters, S. E. Ingebritsen, N. Moosdorf, A. Packman, T. Gleeson, I. Zaslavsky, S. Peckham, L. Murdoch, M. Fienen, M. Cardiff, D. Tarboton, N. Jones, R. Hooper, J. Arrigo, D. Gochis, J. Olson and D. Wolock (2014), DigitalCrust – a 4D data system of material properties for transforming research on crustal fluid flow, *GeoFluids*, Article first published online: 7 OCT 2014 | DOI: 10.1111/gfl.12114.
4. Swain, N.R., K. Latu, S.D. Christensen, N.L. Jones, E.J. Nelson, D.P. Ames, G.P. Williams (2015). "A review of open source software solutions for developing water resources web applications." Environmental Modeling & Software 67: 108-117.
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7. Fatichi, S., Vivoni, E.R., Ogden, F.L., Ivanov, V.Y., Mirus, B., Gochis, D., Downer, C.W., Camporese, M., Davidson, J.H., Ebel, B., Jones, N., Kim, J., Mascaro, G., Niswonger, R., Restrepo, P., Rigon, R., Shen, C., Sulis, M., and Tarboton, D. (2016). *An Overview of Challenges, Current Applications and Future Trends of Distributed Process-based Models in Hydrology.*

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9. Perez, J. Fidel, Nathan R. Swain, Herman G. Dolder, Scott D. Christensen, Alan D. Snow, E. James Nelson, and Norman L. Jones, 2016. *From Global to Local: Providing Actionable Flood Forecast Information in a Cloud-Based Computing Environment.* Journal of the American Water Resources Association (JAWRA) 52(4):965–978. DOI: 10.1111/1752-1688.12392
10. Swain, N. R., S. D. Christensen, A. D. Snow, H. Dolder, G. Espinoza-Dávalos, E. Goharian, N. L. Jones, E. J. Nelson, D. P. Ames and S. J. Burian (2016). "A new open source platform for lowering the barrier for environmental web app development." Environmental Modelling & Software 85: 11-26.
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15. Purdy, A. J., David, C. H., Sikder, M. S., Reager, J. T., Chandanpurkar, H. A., Jones, N. L., & Matin, M. A. (2019). An Open-Source Tool to Facilitate the Processing of GRACE Observations and GLDAS Outputs: An Evaluation in Bangladesh. *Frontiers in Environmental Science,* 7. https://doi.org/10.3389/fenvs.2019.00155
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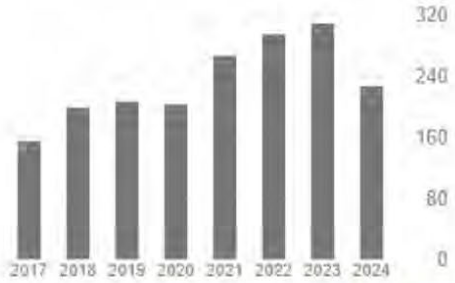
Summary: 88 total peer-reviewed publications.

Books

Strassberg, G., Jones, N., Maidment, D. (2011). Arc Hydro Groundwater: GIS for Hydrology. ESRI Press, Redlands, California, 250 pp.

Google Scholar Metrics

	All	Since 2019
Citations	3287	1507
h-index	27	19
i10-index	51	30



Complete CV: https://www.et.byu.edu/~njones/vita/

Appendix P — Reliance Materials

1. The literature, publications, and documents identified in the References section of this report (Section 8).

2. The documents, information and data identified in Appendix A2 ("Information sources used to extract model-specific data for historical reconstruction analyses, U.S. Marine Corps Base Camp Lejeune, North Carolina") to Maslia et al., 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, ATSDR 2013, and included with this report in **Appendix E**.

3. Maslia, M.L. et al. 2007. "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." ATSDR, July 2007.

4. Faye, R.E. et al. 2007. "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 B: Geohydrologic Framework of the Castle Hayne Aquifer System." ATSDR, September 2007.

5. Faye, R.E. et al. 2007. "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 C: Simulation of Groundwater Flow." ATSDR, November 2007.

6. Lawrence, S.J. et al. 2007. "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 D: Properties and Degredation Pathways of Common Organic Compounds in Groundwater." ATSDR, September 2007.

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9. Jang, W. et al. 2008. "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

G: Simulation of Three-Dimensional Multispecies, Multiphase Mass Transport of Tetrachloroethylene (PCE) and Associated Degredation By-Products." ATSDR, April 2008.

10. Jang, W. and Aral, M.M.. 2008. "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." ATSDR, February 2008.

11. Maslia, M.L. et al. 2009(a). "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 I: Parameter Sensitivity, Uncertainty, and Variability Associated with Model Simulations of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water." ATSDR, February 2009.

12. Maslia, M.L. et al. 2013. "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." ATSDR, March 2013.

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21. Faye, R.E. et al. 2012. “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 B: Geohydrologic Framework of the Brewster Boulevard and Castle Hayne Aquifer Systems and the Tarawa Terrace Aquifer.” ATSDR, January 2012.

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24. Maslia, M.L. (Editor). 2005. "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." ATSDR, Meeting March 28-29, 2005, published October 2005.

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26. March 28, 2005 Expert Peer Review Panel Meeting Transcript, available at https://www.atsdr.cdc.gov/sites/lejeune/panel_report_groundwater.html

27. March 29. 2005 Expert Peer Review Panel Meeting Transcript, available at https://www.atsdr.cdc.gov/sites/lejeune/panel_report_groundwater.html

28. April 29, 2009 Expert Peer Review Panel Meeting Transcript, available at https://www.atsdr.cdc.gov/sites/lejeune/expertpanels.html

29. April 30, 2009 Expert Peer Review Panel Meeting Transcript, available at https://www.atsdr.cdc.gov/sites/lejeune/expertpanels.html

30. February 8, 2012 Deposition of Elizabeth Ann Betz

31. June 30, 2010 Deposition of Morris Maslia

32. May 28, 2024 Deposition of General Anthony Zinni; Zinni Deposition Exhibits 1-8

33. August 5, 2024 Deposition of Kim Henderson; Henderson Deposition Exhibits 1-18

34. August 6, 2024 Deposition of Dan Waddill; Waddill Deposition Exhibits 1-20

35. August 14, 2024 Deposition of Jason Barry Sautner; Sautner Deposition Exhibits 1-10

36. August 15, 2024 Deposition of Rene Suarez-Soto; Suarez-Soto Deposition Exhibits 1-5

37. August 22, 2024 Deposition of Dr. Chris Rennix; Rennix Deposition Exhibits 1-6

38. September 26, 2024 Deposition of Morris Maslia; Maslia Deposition Exhibits 1-22

39. ATSDR Camp Lejeune Project File: CLJA_ATSDRWM01-0000000001-CLJA_ATSDRWM01-0000189563; CLJA_WATERMODELING-0000000001-CLJA_WATERMODELING-0000209307; CLJA_WATERMODELING_01-0000000001-CLJA_WATERMODELING_01-0000854197; ATSDR_WATERMODELING_01-0000854198-ATSDR_WATERMODELING_01-0000936235; CLJA_WATERMODELING_01-0000936236-CLJA_WATERMODELING_01-0001118025; CLJA_WATERMODELING_04-0000000001-CLJA_WATERMODELING_04-0000117996; CLJA_WATERMODELING_05-0000000001-CLJA_WATERMODELING_05-0001394405; ATSDR_WATERMODELING_05-0001394406-ATSDR_WATERMODELING_05-0001394413; CLJA_WATERMODELING_07-0000000001-CLJA_WATERMODELING_07-0002316354; CLJA_WATERMODELING_08-0000000001-CLJA_WATERMODELING_08-0000193508; CLJA_WATERMODELING_09-0000000001-CLJA_WATERMODELING_09-0000547124; ATSDR_WATERMODELING_09-0000547125-ATSDR_WATERMODELING_09-0000568329; CLJA_WATERMODELIING_09-0000568330-CLJA_WATERMODELIING_09-0000615612; CLJA_WATERMODELING_09-0000615613-CLJA_WATERMODELING_09-0000745917

40. 00897_PLG_0000067113-00897_PLG_0000067132

41. 00897_PLG_0000339484-00897_PLG_0000339588

42. 00897_PLG_0000063393-00897_PLG_0000063594

43. 00897_PLG_0000065633-00897_PLG_0000065659

44. CLJA_ATSDR_BOVE-0000006959-CLJA_ATSDR_BOVE-0000006960

45. September 25, 2024 Tarawa Terrace Flow and Transport Model Post-Audit by N.L. jones and R.J. Davis, Integral Consulting, Inc.

46. The forthcoming depositions of Frank Bove, Susan Martel, and Scott Williams, including any accompanying deposition exhibits