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

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

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

[Signature page to follow.]

Dated: April 29, 2025

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CERTIFICATE OF SERVICE

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

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Groundwater Engineering
Hydrology
Civil Engineering

THE HANDBOOK OF GROUNDWATER ENGINEERING

This resource covers the field of groundwater from an engineering perspective, comprehensively addressing the range of subjects related to subsurface hydrology. It provides a practical treatment of the flow of groundwater, the transport of substances, the construction of wells and well fields, the production of groundwater, and site characterization and remediation of groundwater pollution.

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Editor-in-Chief
Jacques W. Delleur

Library of Congress Cataloging-in-Publication Data

The handbook of groundwater engineering / edited by Jacques Delleur.
p. cm.
Includes bibliographical references and index.
ISBN 0-8493-2698-2 (alk. paper)
1. Groundwater flow. 2. Groundwater--Pollution. 3. Groundwater-
-Management. I. Delleur, J. W. (Jacques Willy)
TC176.H35 1998
628.1'14--dc21 97-46941
CIP

No claim to original U.S. Government works
International Standard Book Number 0-8493-2698-2
Library of Congress Card Number 97-46941
Printed in the United States of America 1 2 3 4 5 6 7 8 9 0
Printed on acid-free paper

Editor

Jacques W. Delleur received his Doctor of Engineering Science degree at Columbia University in 1955, his M.S.C.E. degree at Rensselaer Polytechnic Institute in Troy, New York, in 1950, and his Civil and Mining Engineer degree at the Universidad Nacional de Colombia (National University of Colombia) in 1949. In 1955, he joined Purdue University where he currently is Professor Emeritus of Environmental and Hydraulic Engineering and was Head of the Hydraulic and Systems Engineering Area in the School of Civil Engineering. Dr. Delleur taught intermediate and advanced graduate courses in subsurface hydrology, surface hydrology, statistical hydrology, and hydraulics. He founded the graduate program in Hydrology and Hydraulics in the School of Civil Engineering at Purdue. He is author or co-author of two books on hydrologic time series analysis. He is author or co-author of more than 60 papers in refereed journals, 70 papers in conference proceedings, and 60 technical reports. These cover the areas of subsurface hydrology, hydrologic modeling, stochastic hydrology, urban hydrology, and hydraulics. The most recent research publications related to groundwater co-authored by J.W. Delleur are concerned with the flow and transport of dissolved substances in groundwater and how they are affected by geologic heterogeneity.

Dr. Delleur's research has been supported by the U.S. Department of the Interior, the National Science Foundation, the U.S. Department of Transportation and the U.S. Department of Agriculture. He has served as an advisor to the U.S. Geological Survey, is a member of the international board of advisors of the American Society of Civil Engineers (ASCE) *Journal of Hydrologic Engineering* and is a member of the scientific council of the *Revue des Sciences de l'Eau / Journal of Water Science.* He served as a reviewer for the National Science Foundation, and for the scientific journals *Water Resources Research, Journal of Hydrology, Journal of the American Water Resources Association,* and the *Journal of Hydraulics.* He is a fellow of the Indiana Academy of Sciences, received the 1961 Freeman Fellow Award of the ASCE, in 1983 received an NSF/CNRS US-France Senior Scientist Exchange Award, and in 1992 received the Charles Harold Bechert Award of the Indiana Water Resources Association for significant contribution to the water resources profession in Indiana. While on sabbatical leave, Dr. Delleur did research in hydrology at the French National Hydraulics Laboratory (1968-69 and 1976-77), at the University of Grenoble, France (1961-62 and 1983-84) and at the Vrije Universiteit Brussel (Free University of Brussels), Belgium (1991). He has been a guest lecturer at the Ecole Polytechnique Fédérale de Lausanne (Federal Polytechnic School of Lausanne), Switzerland, at the Free University of Brussels, Belgium, at Imperial College in London, at the University of Tokushima, Japan, at the Indian Institute of Technology in Kanpur, India, at the Mahommadia School of Engineering in Rabat, Morocco, at the Taiwan National University in Taipei, Taiwan, and at the Universidad de los Andes (University of the Andes) in Bogota, Colombia.

marching algorithms. A correction can then be implemented in the next step depending on the deviation of the interacting variables. Furthermore, this simulation-based approach offers the only way to address the promising avenues of merging different treatment technologies into integrated treatment systems that achieve enhanced productivity and efficiency (treatment time, cost, and clean up level).

Specific steps for an efficient implementation of the macroengineering approach are:

- Better coordinate soil data collection with simulation of interaction processes for prediction needs.
- Hierarchically organize space and time scales of field measurements of interaction phenomena and corresponding media properties and attendant models
- Place more emphasis on the scientific understanding (prediction) of physicochemical processes rather than relying solely on data collection
- Use integrated simulation tools to better identify combinations of treatment processes as they interact with the soil media

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Groundwater Modeling

Leonard F. Konikow and Thomas E. Reilly
U.S. Geological Survey

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20.1 Introduction

Effective management of groundwater requires the ability to predict subsurface flow and transport of solutes, and the response of fluid and solute flux to changes in natural or human-induced stresses. One popular type of tool that has been evolving since the mid-1960s is the deterministic, distributed-parameter, computer simulation model for analyzing flow and solute-transport in groundwater systems. The development of the computer simulation model has somewhat paralleled the development and increasing availability of faster, larger memory, more capable, yet less expensive computer systems.

The purpose of this chapter is to review the state of the art in deterministic modeling of groundwater flow and transport processes. This chapter, based largely on Konikow (1996), is aimed at practitioners and is intended to describe the types of models that are available and how they may be applied to complex field problems. It will discuss the philosophy and theoretical basis of deterministic modeling, the advantages and limitations of models, the use and misuse of models, how to select a model, and how to calibrate and evaluate a model. However, as this chapter is only a review, it cannot offer comprehensive and in-depth coverage of this complex topic; instead, it guides the reader to references that provide more details.

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20.2 Models

The word *model* has so many definitions and is so overused that it is sometimes difficult to discern its meaning (Konikow and Bredehoeft, 1992). A model is perhaps most simply defined as a representation of a real system or process. A *conceptual model* is a hypothesis for how a system or process operates. This hypothesis can be expressed quantitatively as a mathematical model. *Mathematical models* are abstractions that represent processes as equations, physical properties as constants or coefficients in the equations, and measures of state or potential in the system as variables.

Most groundwater models in use today are deterministic mathematical models. *Deterministic models* are based on conservation of mass, momentum, and energy and describe cause and effect relations. The underlying assumption is that given a high degree of understanding of the processes by which stresses on a system produce subsequent responses in that system, the system's response to any set of stresses can be predetermined, even if the magnitude of the new stresses falls outside the range of historically observed stresses.

Deterministic groundwater models generally require the solution of partial differential equations. Exact solutions can often be obtained analytically, but *analytical models* require that the parameters and boundaries be highly idealized. Some deterministic models treat the properties of porous media as lumped parameters (essentially, as a black box), but this precludes the representation of heterogeneous hydraulic properties in the model. Heterogeneity, or variability in aquifer properties, is characteristic of all geologic systems and is now recognized as playing a key role in influencing groundwater flow and solute transport. Thus, it is often preferable to apply distributed-parameter models, which allow the representation of more realistic distributions of system properties. Numerical methods yield approximate solutions to the governing equation (or equations) through the discretization of space and time. Within the discretized problem domain, the variable internal properties, boundaries, and stresses of the system are approximated. Deterministic, distributed-parameter, *numerical models* can relax the rigid idealized conditions of analytical models or lumped-parameter models, and they can therefore be more realistic and flexible for simulating field conditions (if applied properly).

The number and types of equations to be solved are determined by the concepts of the dominant governing processes. The coefficients of the equations are the parameters that are measures of the properties, boundaries, and stresses of the system; the dependent variables of the equations are the measures of the state of the system and are mathematically determined by the solution of the equations. When a numerical algorithm is implemented in a computer code to solve one or more partial differential equations, the resulting computer code can be considered a *generic model*. When the grid dimensions, boundary conditions, and other parameters (such as hydraulic conductivity and storativity), are specified in an application of a generic model to represent a particular geographic area, the resulting computer program is a *site-specific model*. The ability of generic models to solve the governing equations accurately is typically demonstrated by example applications to simplified problems. This does not guarantee a similar level of accuracy when the model is applied to a complex field problem.

If the user of a model is unaware of or ignores the details of the numerical method, including the derivative approximations, the scale of discretization, and the matrix solution techniques, significant errors can be introduced and remain undetected. For example, if the groundwater flow equation is solved iteratively, but the convergence criterion is relatively too coarse, then the numerical solution may converge, but to a poor solution. The inaccuracy of the solution may or may not be reflected in the mass-balance error. The mass-balance error itself may not be readily observed by inexperienced model users. Unrecognized errors in numerical groundwater models are becoming more possible as user-friendly graphic interfaces make it easier for models to be used (and misused). These interfaces effectively place more distance between the modeler and the numerical method that lies at the core of the model.

20.3 Flow and Transport Processes

The process of groundwater flow is generally assumed to be governed by the relations expressed in Darcy's law (see Chapter 2) and the conservation of mass. However, Darcy's law does have limits on its range of applicability, and these limits must be evaluated in any application.

The purpose of a model that simulates solute transport in groundwater is to compute the concentration of a dissolved chemical species in an aquifer at any specified time and place. The theoretical basis for the equation describing solute transport has been well documented in the literature (e.g., Bear, 1979; Domenico and Schwartz, 1990). Reilly et al. (1987) provide a conceptual framework for analyzing and modeling physical solute-transport processes in groundwater. Changes in chemical concentration occur within a dynamic groundwater system primarily due to four distinct processes: (1) advective transport, in which dissolved chemicals are moving with the flowing groundwater; (2) hydrodynamic dispersion, in which molecular and ionic diffusion and small-scale variations in the flow velocity through the porous media cause the paths of dissolved molecules and ions to diverge or spread from the average direction of groundwater flow; (3) fluid sources, where water of one composition is introduced into and mixed with water of a different composition; and (4) reactions, in which some amount of a particular dissolved chemical species may be added to or removed from the groundwater as a result of chemical, biological, and physical reactions in the water or between the water and the solid aquifer materials or other separate liquid phases.

The subsurface environment constitutes a complex, three-dimensional, heterogeneous hydrogeologic setting. This variability strongly influences groundwater flow and transport, and such a reality can be described accurately only through careful hydrogeologic practice in the field. However, regardless of how much data are collected, uncertainty always remains about the properties and boundaries of the groundwater system of interest. Stochastic approaches have resulted in many significant advances in characterizing subsurface heterogeneity and dealing with uncertainty (see Gelhar, 1993).

20.4 Governing Equations

The mathematical equations that describe groundwater flow (see Chapter 3) and transport processes (see Chapters 14 and 15 and the summary in Chapter 2) may be developed from the fundamental principle of conservation of mass of fluid or of solute. Given a representative elementary volume (REV) of porous medium, a general equation for conservation of mass for the volume may be expressed as:

$$\text{rate of mass inflow} - \text{rate of mass outflow} + \text{rate of mass production/consumption} = \text{rate of mass accumulation} \quad (1)$$

This statement of conservation of mass (or continuity equation) may be combined with a mathematical expression of the relevant process to obtain a differential equation that describes flow or transport.

20.4.1 Groundwater Flow Equation

The rate of flow of water through a porous media is related to the properties of the water, the properties of the porous media, and the gradient of the hydraulic head, as represented by Darcy's law, which can be written as:

$$q_i = -K_{ij}\frac{\partial h}{\partial x_j} \quad (2)$$

where q_i is the specific discharge, LT^{-1}; K_{ij} is the hydraulic conductivity of the porous medium (a second-order tensor), LT^{-1}; and h is the hydraulic head, L.

A general form of the equation describing the transient flow of a compressible fluid in a nonhomogeneous anisotropic aquifer may be derived by combining Darcy's law with the continuity equation. A general groundwater flow equation may be written in Cartesian tensor notation as:

$$\frac{\partial}{\partial x_i}\left(K_{ij}\frac{\partial h}{\partial x_i}\right)=S_S\frac{\partial h}{\partial t}+W^* \tag{3}$$

where S_S is the specific storage, L^{-1}; t is time, T; W^* is the volumetric flux per unit volume (positive for outflow and negative for inflow), T^{-1}; and x_i are the Cartesian coordinates, L. The summation convention of Cartesian tensor analysis is implied in Equations (2) and (3). Equation (3) can generally be applied if isothermal conditions prevail, the porous medium only deforms vertically, the volume of individual grains remains constant during deformation, Darcy's law applies (and gradients of hydraulic head are the only driving force), and fluid properties (density and viscosity) are homogeneous and constant. Aquifer properties can vary spatially, and fluid stresses (W^*) can vary in space and time.

If the aquifer is relatively thin compared to its lateral extent, it may be appropriate to assume that groundwater flow is areally two-dimensional. This allows the three-dimensional flow equation to be reduced to the case of two-dimensional areal flow, for which several additional simplifications are possible. The advantages of reducing the dimensionality of the equation include less stringent data requirements, smaller computer memory requirements, and shorter computer execution times to achieve numerical solutions.

An expression similar to Equation (3) may be derived for the two-dimensional areal flow of a homogeneous fluid in a confined aquifer and written as:

$$\frac{\partial}{\partial x_i}\left(T_{ij}\frac{\partial h}{\partial x_i}\right)=S\frac{\partial h}{\partial t}+W \tag{4}$$

where T_{ij} is the transmissivity, L^2T^{-1}; and $T_{ij} = K_{ij}\,b$; b is the saturated thickness of the aquifer, L; S is the storage coefficient (dimensionless); and $W = W^*b$ is the volume flux per unit area, LT^{-1}.

When Equation (4) is applied to an unconfined (water-table) aquifer system, it must be assumed that flow is horizontal and equipotential lines are vertical, that the horizontal hydraulic gradient equals the slope of the water table, and that the storage coefficient is equal to the specific yield (S_y) (Anderson and Woessner, 1992). Note that in an unconfined system, the saturated thickness changes as the water-table elevation (or head) changes. Thus, the transmissivity also can change over space and time (that is, $T_{ij} = K_{ij}b$, where $b(x,y,t) = h - h_b$, and h_b is the elevation of the bottom of the aquifer).

The cross-product terms of the hydraulic conductivity tensor drop out when the coordinate axes are aligned with the principal axes of the tensor; that is, $K_{ij} = 0$ when $i \neq j$. Therefore, the only hydraulic conductivity terms with possible nonzero values are K_{xx} and K_{yy}. Under this assumption, Equation (4) may be simplified to:

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right)=S\frac{\partial h}{\partial t}+W \tag{5}$$

for two-dimensional flow.

In some field situations, fluid properties such as density and viscosity may vary significantly in space or time. This may occur where water temperature or dissolved-solids concentration changes significantly. When the water properties are heterogeneous and (or) transient, the relations among water levels, hydraulic heads, fluid pressures, and flow velocities are neither simple nor straightforward. In such cases, the flow equation is written and solved in terms of fluid pressures, fluid densities, and the intrinsic permeability of the porous media (see Konikow and Grove, 1977).

20.4.2 Seepage Velocity

The migration and mixing of chemicals dissolved in groundwater will obviously be affected by the velocity of the flowing groundwater. The specific discharge calculated from Equation (2) is sometimes called the Darcy velocity. However, this nomenclature can be misleading because q_i does not actually represent the speed of water movement. Rather, q_i represents a volumetric flux per unit cross-sectional area. Thus, to calculate the actual seepage velocity of groundwater, one must account for the actual cross-sectional area through which flow is occurring, as follows:

$$V_i=\frac{q_i}{\varepsilon}=-\frac{K_{ij}}{\varepsilon}\frac{\partial h}{\partial x_j} \tag{6}$$

where V_i is the seepage velocity (also commonly called average linear velocity or average interstitial velocity), LT^{-1}; and ε is the effective porosity of the porous medium.

20.4.3 Solute Transport Equation

An equation describing the transport and dispersion of a dissolved chemical in flowing groundwater may be derived from the principle of conservation of mass by considering all fluxes into and out of a representative elementary volume (REV), as described by Bear (1979, p. 29). A generalized form of the solute-transport equation is presented by Grove (1976), in which terms are incorporated to represent chemical reactions and solute concentration both in the pore fluid and on the solid surface, as:

$$\frac{\partial(\varepsilon C)}{\partial t}=\frac{\partial}{\partial x_i}\left(\varepsilon D_{ij}\frac{\partial C}{\partial x_j}\right)-\frac{\partial}{\partial x_i}\left(\varepsilon C V_i\right)-C'W^*+CHEM \tag{7}$$

where *CHEM* equals one or more of the following:

$-\rho_b\dfrac{\partial \overline{C}}{\partial t}$ for linear equilibrium controlled sorption or ion-exchange reactions,

$\displaystyle\sum_{k=1}^{s} R_k$ for s chemical rate-controlled reactions, and (or)

$-\lambda\left(\varepsilon C+\rho_b\overline{C}\right)$ for decay,

and where D_{ij} is the coefficient of hydrodynamic dispersion (a second-order tensor), L^2T^{-1}, C' is the concentration of the solute in the source or sink fluid, $\overline{C}$ is the concentration of the species adsorbed on the solid (mass of solute/mass of solid), ρ_b is the bulk density of the sediment, ML^{-3}, R_k is the rate of production of the solute in reaction k, $ML^{-3}T^{-1}$, and λ is the decay constant (equal to ln2/half life), T^{-1} (Grove, 1976).

The first term on the right side of Equation (7) represents the change in concentration due to hydrodynamic dispersion. This expression is analogous to Fick's law describing diffusive flux. This Fickian model assumes that the driving force is the concentration gradient and that the dispersive flux occurs in a direction from higher toward lower concentrations. However, this assumption is not always consistent with field observations and is the subject of much ongoing research and field study (see, for example, Gelhar et al., 1992). The coefficient of hydrodynamic dispersion is defined as the sum of mechanical dispersion and molecular diffusion (Bear, 1979). The mechanical dispersion is a function both of the

intrinsic properties of the porous medium (such as heterogeneities in hydraulic conductivity and porosity) and of the fluid flow. Molecular diffusion in a porous medium will differ from that in free water because of the effects of tortuous paths of fluid connectivity in porous media. These relations are commonly expressed as:

$$D_{ij} = \alpha_{ijmn} \frac{V_m V_n}{|V|} + D_m \qquad i, j, m, n = 1,2,3 \tag{8}$$

where α_{ijmn} is the dispersivity of the porous medium (a fourth-order tensor), L; V_m and V_n are the components of the flow velocity of the fluid in the m and n directions, respectively, LT^{-1}; D_m is the effective coefficient of molecular diffusion, L^2T^{-1}; and $|V|$ is the magnitude of the velocity vector, LT^{-1}, defined as $|V| = \sqrt{V_x^2 + V_y^2 + V_z^2}$ (Bear, 1979; Domenico and Schwartz, 1990). The dispersivity of an isotropic porous medium can be defined by two constants. These are the longitudinal dispersivity of the medium, α_L, and the transverse dispersivity of the medium, α_T. These are related to the longitudinal and transverse dispersion coefficients by $D_L = \alpha_L|V|$ and $D_T = \alpha_T|V|$. Most documented applications of transport models to groundwater problems have been based on this conventional formulation, even for cases in which the hydraulic conductivity is assumed to be anisotropic (despite the conceptual inconsistency). However, some models (for example, Voss, 1984) incorporate an additional level of complexity by allowing α_L and (or) α_T to vary with direction.

Although conventional theory holds that α_L is generally an intrinsic property of the aquifer, it is found in practice to be dependent on and proportional to the scale of the measurement. Most reported values of α_L fall in a range from 0.01 to 1.0 times the scale of the measurement, although the ratio of α_L to scale of measurement tends to decrease at larger scales (see Anderson, 1984; Gelhar et al., 1992). Field-scale dispersion (commonly called macrodispersion) results from large-scale spatial variations in hydraulic properties. Consequently, the use of relatively large values of dispersivity together with uniform hydraulic properties (K_{ij} and ε) is inappropriate for describing transport in geological systems (Smith and Schwartz, 1980). Part of the scale dependence of dispersivity may be explained as an artifact of the models used, in that a scaling up of dispersivity will occur whenever an (n-1)-dimensional model is calibrated or used to describe an n-dimensional system (Domenico and Robbins, 1984). Furthermore, if a model applied to a system having variable hydraulic conductivity uses mean values and thereby does not explicitly represent the variability, the model calibration will likely yield values for the dispersivity coefficients that are larger than would be measured locally in the field area. Similarly, representing a transient flow field by a mean steady-state flow field, as is commonly done, inherently ignores some of the variability in velocity and must be compensated for by using increased values of dispersivity (primarily transverse dispersivity) (Goode and Konikow, 1990). Overall, the more accurately a model can represent or simulate the true velocity distribution in space and time, the less of a problem will be the uncertainty concerning representation of dispersion processes.

The mathematical solute-transport model requires at least two partial differential equations. One is the equation of flow, from which groundwater flow velocities are obtained, and the second is the solute-transport equation, whose solution gives the chemical concentration in groundwater. If the properties of the water are affected significantly by changes in solute concentration, as in a saltwater intrusion problem, then the flow and transport equations should be solved simultaneously (or at least iteratively). If the properties of the water remain constant, then the flow and transport equations can be decoupled and solved sequentially, which is simpler numerically.

20.5 Numerical Methods To Solve Equations

The partial differential equations describing groundwater flow and transport can be solved mathematically using either analytical solutions or numerical solutions. The advantages of an analytical solution, when it is possible to apply one, are that it usually provides an exact solution to the governing equation and is often relatively simple and efficient to use. Many analytical solutions have been developed for the flow equation; however, most applications are limited to well hydraulics problems involving radial symmetry. The familiar Theis type curve represents the solution of one such analytical model. Analytical solutions are also available to solve the solute-transport equation (e.g., Bear, 1979; Javandel et al., 1984; Wexler, 1992). In general, obtaining the exact analytical solution to the partial differential equation requires that the properties and boundaries of the flow system be highly and perhaps unrealistically idealized. For simulating most field problems, the mathematical benefits of obtaining an exact analytical solution are probably outweighed by the errors introduced by the simplifying assumptions about the complex field environment that are required to apply the analytical approach.

Alternatively, for problems where the simplified analytical models no longer describe the physics of the situation, the partial differential equations can be approximated numerically. In so doing, the continuous variables are replaced with discrete variables that are defined at grid blocks or nodes. Thus, the continuous differential equation, which defines hydraulic head or solute concentration everywhere in the system, is replaced by a finite number of algebraic equations that defines the hydraulic head or concentration at specific points. This system of algebraic equations generally is solved using matrix techniques. This approach constitutes a numerical model.

Two major classes of numerical methods have come to be well accepted for solving the groundwater flow equation. These are the finite-difference methods and the finite-element methods. Each of these two major classes of numerical methods includes a variety of subclasses and implementation alternatives. Comprehensive treatments of the application of these numerical methods to groundwater problems are presented by Remson et al. (1971) and Wang and Anderson (1982). Both of these numerical approaches require that the area of interest be subdivided by a grid into a number of smaller subareas (cells or elements) that are associated with nodal points (either at the centers or peripheries of the subareas).

In addition to finite-difference and finite-element methods, boundary integral equation methods and analytical element methods can also be applied to solve the flow equation (for example, see Haitjema, 1995). Their main advantage is that, for homogeneous regions, they can provide precise solutions without discretization. Thus, if a system's heterogeneity can be adequately represented by using only a few very large elements, the methods can be very efficient in terms of computer time. If heterogeneities are such that a large number of elements are required to describe them adequately, then finite-difference or finite-element methods may be preferable. To date, finite-difference and finite-element methods have been more widely used than other numerical methods in simulating groundwater flow problems.

Finite-difference methods approximate the first derivatives in the partial differential equations as difference quotients (the differences between values of the independent variable at adjacent nodes with respect to the distance between the nodes, and at two successive time levels with respect to the duration of the time-step increment). Finite-element methods use assumed functions of the dependent variable and parameters to evaluate equivalent integral formulations of the partial differential equations. Huyakorn and Pinder (1983) present a comprehensive analysis of the application of finite-element methods to groundwater problems. In both numerical approaches, the discretization of the space and time dimensions allows the continuous boundary-value problem for the solution of the partial differential equation to be reduced to the simultaneous solution of a set of algebraic equations. These equations can then be solved using either iterative or direct matrix methods.

Each approach has advantages and disadvantages, but there are very few groundwater problems for which either is clearly superior. In general, the finite-difference methods are simpler conceptually and mathematically, and are easier to program. They are typically keyed to a relatively simple, rectangular

grid, which also eases data entry. Finite-element methods generally require the use of more sophisticated mathematics but, for some problems, may be more accurate numerically than standard finite-difference methods. A major advantage of the finite-element methods is the flexibility of the finite-element grid, which allows a close spatial approximation of irregular boundaries of the aquifer and (or) of parameter zones within the aquifer when they are considered. However, the construction and specification of an input data set are much more difficult for an irregular finite-element grid than for a regular rectangular finite-difference grid. Thus, the use of a model preprocessor, which includes a mesh generator and a scheme to number the nodes and elements of the mesh and to specify the spatial coordinates of each node, is recommended. Figure 20.1 illustrates a hypothetical aquifer system, which has impermeable boundaries and a well field (Figure 20.1A), which has been discretized using finite-difference (Figure 20.1B) and finite-element (Figure 20.1C) grids. Figures 20.1B and 20.1C illustrate conceptually how their respective grids can be adjusted to use a finer mesh spacing in selected areas of interest. The rectangular finite-difference grid approximates the aquifer boundaries in a stepwise manner, resulting in some nodes or cells outside the aquifer, whereas sides of the triangular elements of the finite-element grid can closely follow the outer boundary using a minimal number of nodes.

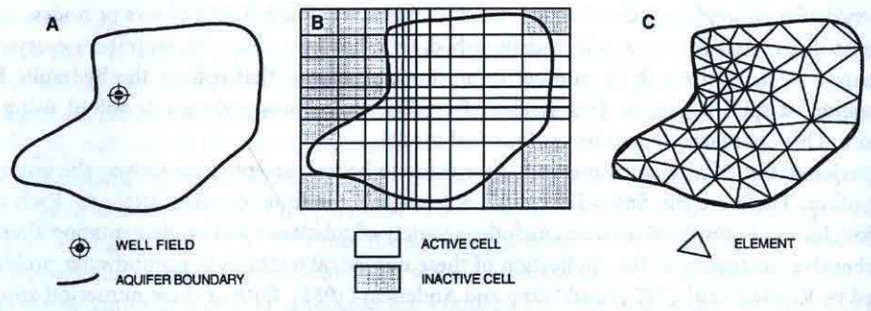


FIGURE 20.1 Hypothetical application to (A) an irregularly bounded aquifer of (B) finite-difference and (C) finite-element grids. (From Konikow, L. F. 1996. Numerical models of groundwater flow and transport, in *Manual on Mathematical Models in Isotope Hydrogeology.* International Atomic Energy Agency, Vienna.)

The solute-transport equation is more difficult to solve numerically than the groundwater flow equation, largely because the mathematical properties of the transport equation vary depending upon which terms in the equation are dominant in a particular situation. When solute transport is dominated by advective transport, as is common in many field problems, then Equation (7) approximates a hyperbolic type of equation (similar to equations describing the propagation of a wave or of a shock front). But if a system is dominated by dispersive fluxes, such as might occur where fluid velocities are relatively low and aquifer dispersivities are relatively high, then Equation (7) becomes more parabolic in nature (similar to the transient groundwater flow equation).

The numerical methods that work best for parabolic partial differential equations are not best for solving hyperbolic equations, and vice versa. Thus, no one numerical method or simulation model will be ideal for the entire spectrum of groundwater transport problems likely to be encountered in the field. Further compounding this difficulty is the fact that in the field, the seepage velocity of groundwater is highly variable, even if aquifer properties are relatively homogeneous because of the effects of complex boundary conditions. Thus, in low permeability zones or near stagnation points, the velocity may be close to zero and the transport processes will be dominated by dispersion processes; in high permeability zones or near stress points (such as pumping wells), the velocity may be several meters per day and the transport processes will be advection dominated. In other words, for the same system, the governing equation may be more hyperbolic in one area (or at one time) and more parabolic in another area (or at another time). Therefore, regardless of which numerical method is chosen as the basis for a simulation model, it will not be ideal or optimal over the entire domain of the problem, and significant numerical

errors may be introduced somewhere in the solution. The transport modeling effort must recognize this inherent difficulty and strive to minimize and control the numerical errors.

Additional complications arise when the solutes of interest are reactive. The reaction terms included in Equation (7) are mathematically simple ones. They do not necessarily represent the true complexities of many reactions. Also, particularly difficult numerical problems arise when reaction terms are highly nonlinear, or if the concentration of the solute of interest is strongly dependent on the concentration of other chemical constituents. In reality, isotherms may not be linear and may not be equilibrium controlled. For field problems in which reactions significantly affect solute concentrations, simulation accuracy is less limited by mathematical constraints than by data constraints. That is, the types and rates of reactions for the specific solutes and minerals in the particular groundwater system of interest are rarely known and require an extensive amount of data to assess accurately.

Finite-difference and finite-element methods also can be applied to solve the transport equation, particularly when dispersive transport is large compared to advective transport. However, numerical errors, such as numerical dispersion and oscillations, may be significant for some problems. The numerical errors can generally be reduced by using a finer discretization (either shorter time steps or finer spatial grid). An example of a documented three-dimensional, transient, finite-difference model that simultaneously solves the fluid pressure, energy-transport, and solute-transport equations for nonhomogeneous miscible fluids is HST3D (Kipp, 1987). An example of a two-dimensional finite-element transport model is SUTRA, documented by Voss (1984).

Although finite-difference and finite-element models are commonly applied to transport problems, other types of numerical methods have also been applied to transport problems, including the method of characteristics, random walk, Eulerian-Lagrangian methods, and adaptive grid methods. All of these methods have the ability to track sharp fronts accurately with a minimum of numerical dispersion. Documented models based on variants of these approaches include Konikow and Bredehoeft (1978), Sanford and Konikow (1985), Prickett et al. (1981), and Zheng (1990).

No single one of the standard numerical methods is ideal for a wide range of transport problems and conditions. Thus, there is currently still much research on developing better mixed or adaptive methods that aim to minimize numerical errors and combine the best features of alternative standard numerical approaches.

20.5.1 Basics of Finite-Difference Methods

The partial differential equations describing the flow and transport processes in groundwater include terms representing derivatives of continuous variables in space and time. Finite-difference methods are based on the approximation of these derivatives (or slopes of curves) by discrete linear changes over discrete intervals of space or time. If the intervals are sufficiently small, then all of the linear increments will represent a good approximation of the true curvilinear surface or hydrograph.

If we consider the observation wells in a confined aquifer, as illustrated in Figure 20.2A, Bennett (1976) shows that a reasonable approximation for the derivative of head, $\partial h/\partial x$, at a point (d) midway between wells 1 and 0 is:

$$\left(\frac{\partial h}{\partial x}\right)_d \approx \frac{h_0 - h_1}{\Delta x} \tag{9}$$

Note that the observation wells are spaced an equal distance apart. Similarly, a reasonable approximation for the second derivative, $\partial^2 h/\partial x^2$, at point 0 (the location of the center well) can be given as:

$$\left(\frac{\partial^2 h}{\partial x^2}\right)_0 \approx \frac{\left(\frac{\partial h}{\partial x}\right)_e - \left(\frac{\partial h}{\partial x}\right)_d}{\Delta x} \approx \frac{\frac{h_2 - h_0}{\Delta x} - \frac{h_0 - h_1}{\Delta x}}{\Delta x} = \frac{h_1 + h_2 - 2h_0}{(\Delta x)^2} \tag{10}$$

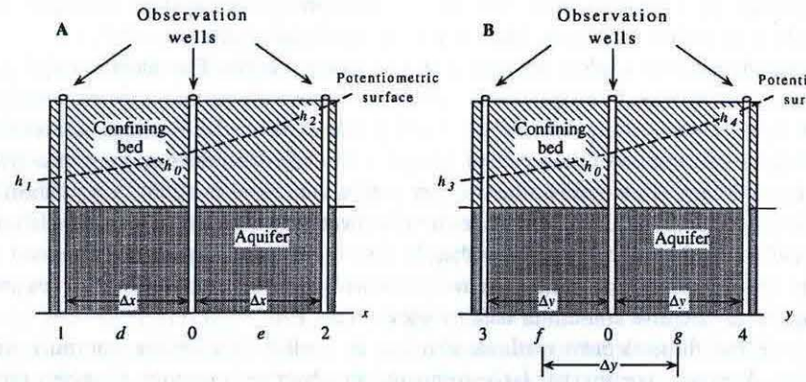


FIGURE 20.2 Schematic cross section through confined aquifer to illustrate numerical approximation to derivatives of head, (A) ∂h/∂x and (B) ∂h/∂y. (Adapted from Bennett, G. D. 1976. *Introduction to Ground-Water Hydraulics: A Programmed Text for Self-Instruction.* Techniques of Water-Res. Invests. of the U.S. Geol. Survey, Book 3, Ch. B2.)

If we also consider wells 3 and 4 shown in Figure 20.2B, located on a line parallel to the y-axis, we can similarly approximate $\partial^2 h/\partial y^2$ at point 0 (the same point 0 as in Figure 20.2A) as (Bennett, 1976):

$$\left(\frac{\partial^2 h}{\partial y^2}\right)_0 \approx \frac{h_3 + h_4 - 2h_0}{(\Delta y)^2} \tag{11}$$

If the spacing of the wells in Figure 20.2B is uniform (that is, $\Delta x = \Delta y = a$), then we can develop the following approximation:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} \approx \frac{h_1 + h_2 + h_3 + h_4 - 4h_0}{a^2} \tag{12}$$

These approximations can also be obtained through the use of Taylor series expansions. A certain error is involved in approximating the derivatives by finite-differences, but this error will generally decrease as a (or Δx and Δy) is given smaller and smaller values. This error is called a "truncation error" because the replacement of a derivative by a difference quotient is equivalent to using a truncated Taylor series, so that the exact solution of a difference equation differs from the solution of the corresponding differential equation (Peaceman, 1977). Also, it may not be possible to achieve an "exact" solution of the difference equation because of limits of precision in storing numbers in a digital computer. In solving a large set of difference equations, many arithmetic operations are performed, and round-off errors may sometimes accumulate.

Next consider the construction of a rectangular finite-difference grid. Two possible modes of grid construction are illustrated in two dimensions in Figures 20.3A and 3B. In Figure 20.3A, the calculation points (or nodes) are located at the centers of the blocks (or cells) formed by the grid lines. This type of grid is commonly called a block-centered grid. In the second type (Figure 20.3B), the nodes are considered to be located at the intersections of the grid lines. This type has been variously called a point-centered, node-centered, mesh-centered, or lattice-centered grid. Although there is no overall inherent advantage of one type over the other, there will be some operational differences between the two approaches in the treatment of boundaries and in areas of influence around nodes. Most, but not all, finite-difference groundwater models are based on the use of block-centered grids. Double indexing is normally used to identify functions and variables within the two-dimensional region. For example, $h_{i,j}$

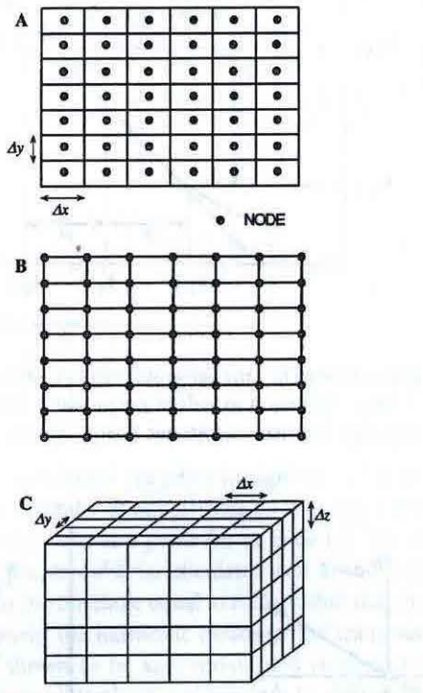


FIGURE 20.3 Examples of finite-difference grids: (A) two-dimensional block-centered grid, (B) two-dimensional node-centered grid, and (C) three-dimensional block-centered grid. (A and B from Konikow, L. F. 1996. Numerical models of groundwater flow and transport, in *Manual on Mathematical Models in Isotope Hydrogeology.* International Atomic Energy Agency, Vienna. C from Konikow, L. F., Goode, D. J., and Hornberger, G. Z. 1996. A three-dimensional method-of-characteristics solute-transport model (MOC3D). U.S. Geol. Survey Water-Res. Inv. Rept. 96-4267).

is the head at node i,j, where i and j are the row and column locations in the finite-difference grid. This procedure is easily extended to three dimensions, as illustrated in Figure 20.3C. Here the vertical dimension (or z-direction) is indexed by the subscript k and $h_{i,j,k}$ would represent the head at node i,j,k.

We must also consider the discretization of time, which may be viewed as another dimension, and hence represented by another index. If we consider a representative segment of a hydrograph (see Figure 20.4), in which head is plotted against time for a transient flow system, n is the index or subscript used to denote the time at which a given head value is observed. The slope of the hydrograph at any point is the derivative of head with respect to time, and it can be approximated as $\partial h/\partial t = \Delta h/\Delta t$. In terms of the heads calculated at specific time increments (or time nodes), the slope of the hydrograph at time n can be approximated by:

$$\left(\frac{\partial h}{\partial t}\right)_{n\Delta t} \approx \frac{h_{n+1} - h_n}{\Delta t} \tag{13}$$

or

$$\left(\frac{\partial h}{\partial t}\right)_{n\Delta t} \approx \frac{h_n - h_{n-1}}{\Delta t} \tag{14}$$

We are calculating the derivative at $t = n\Delta t$ in Equation (13) by taking a "forward difference" from time n to time $n+1$, and by taking a "backward difference" in Equation (14). In terms of solving the

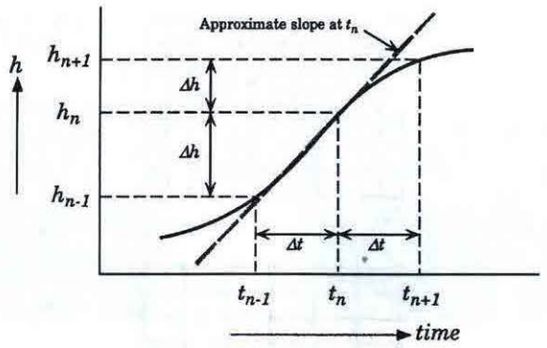


FIGURE 20.4 Part of a hydrograph showing that the derivative (or slope, ∂h/∂t) at time node t_n may be approximated by Δh/Δt. (From Konikow, L. F. 1996. Numerical models of groundwater flow and transport, in *Manual on Mathematical Models in Isotope Hydrogeology.* International Atomic Energy Agency, Vienna.)

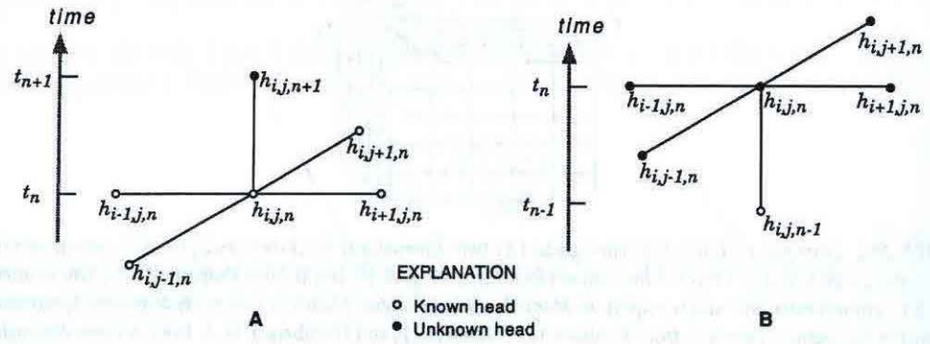


FIGURE 20.5 Grid stencil showing discretization of time at node (i,j) in two-dimensional finite-difference grid: (A) explicit (forward-difference) formulation and (B) implicit (backward-difference) formulation. (From Konikow, L. F. 1996. Numerical models of groundwater flow and transport, in *Manual on Mathematical Models in Isotope Hydrogeology.* International Atomic Energy Agency, Vienna.)

groundwater flow equation for a node (*i,j*) of a finite-difference grid, we have to consider heads at five nodes and at two time levels, as illustrated in Figure 20.5. In Figure 20.5A, we have expressed the spatial derivatives of head at time level n, where all values are known, and the time derivative as a forward difference to the unknown head at time step n+1. Then for every node of the grid we will have a separate difference equation, each of which contains only one unknown variable. Thus, these equations can be solved explicitly. Explicit finite-difference equations are thus simple and straightforward to solve, but they may have associated stability criteria. That is, if time increments are too large, small numerical errors or perturbations may propagate into larger errors at later stages of the computations.

In Figure 20.5B, we have expressed the time derivative as a backward difference from the heads at time level n, which are thereby the unknown heads, whereas the heads at the previous time level, n-1, are known (either from specified initial conditions for the first time step or from subsequent solutions at later time steps). The spatial derivatives of head are written at time level n, where all values are unknown, so for every node of the grid we will have one difference equation that contains five unknowns, which cannot be solved directly. However, for the entire grid, which contains N nodes, we would have a system of N equations containing a total of N unknowns. Such a system of simultaneous equations, together with specified boundary conditions, can be solved implicitly. Although implicit solutions are more complicated, they also have the advantage of generally being unconditionally stable. This implies that a solution will be obtained, although not necessarily that the estimate of the derivative that is calculated

will be accurate, if the time steps are large relative to the rate of change of head. Most available groundwater flow models solve an implicit finite-difference approximation to the flow equation.

We may next consider a two-dimensional groundwater flow equation for a heterogeneous, anisotropic aquifer (Equation [5]), in which the coordinate system is aligned with the major axes of the transmissivity tensor. This may be approximated by the following finite-difference equation for representative node (*i,j*) as:

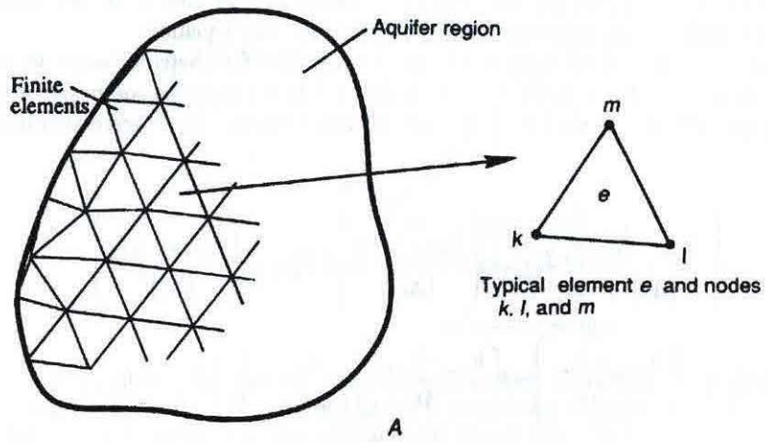
$$T_{xx[i-\frac{1}{2},j]}\left(\frac{h_{i-1,j,n}-h_{i,j,n}}{(\Delta x)^2}\right)+T_{xx[i+\frac{1}{2},j]}\left(\frac{h_{i+1,j,n}-h_{i,j,n}}{(\Delta x)^2}\right)+T_{yy[i,j-\frac{1}{2}]}\left(\frac{h_{i,j-1,n}-h_{i,j,n}}{(\Delta y)^2}\right)$$
$$+T_{yy[i,j+\frac{1}{2}]}\left(\frac{h_{i,j+1,n}-h_{i,j,n}}{(\Delta y)^2}\right)=S\left(\frac{h_{i,j,n}-h_{i,j,n-1}}{\Delta t}\right)-\frac{q_{i,j}}{\Delta x\Delta y}-\frac{K_z}{m}\left(H_{s[i,j]}-h_{i,j,n}\right) \quad (15)$$

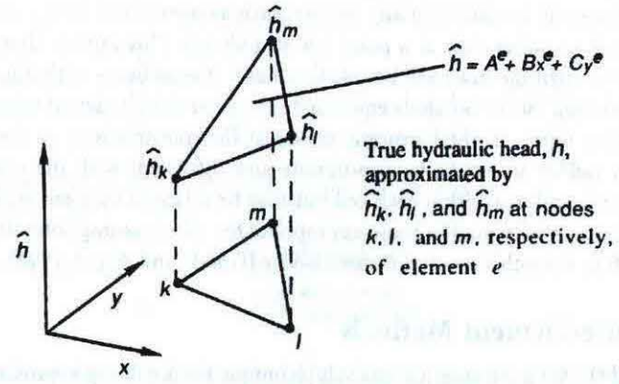
where $q_{i,j}$ is the volumetric rate of withdrawal (negative in sign) or recharge (positive) at the i,j node, L^3T^{-1}. This formulation inherently assumes that any stresses, such as represented by $q_{i,j}$, are applied over the entire surface area of cell i,j rather than at a point (or at node i,j). This implies that if a pumping well is represented at node i,j, then the head will be calculated as if it were being withdrawn from a well that had a horizontal surface area for the borehole equal to ΔxΔy rather than its actual value. In Equation (15), the transmissivity terms represent the harmonic means of the transmissivity of the two adjacent cells. The harmonic mean can be shown to be appropriate and consistent with the assumption that transmissivity is constant and uniform within each cell but may be different between cells. Other types of means for interblock transmissivity may be more appropriate for other assumptions about the transmissivity distribution, such as smoothly varying transmissivity (Goode and Appel, 1992).

20.5.2 Basics of Finite-Element Methods

The finite-element method (FEM) is a numerical analysis technique for obtaining approximate solutions to a wide variety of problems in physics and engineering. The method was originally applied to structural mechanics but is now used in all fields of continuum mechanics. Huebner (1975) describes four different approaches to formulate the finite-element method for a problem, which are: the direct approach, the variational approach, the weighted residual approach, and the energy balance approach. In groundwater problems, the approach frequently used is either the weighted residual or variational approach.

The finite-element method (FEM) uses a concept of "piecewise approximation." The domain of the problem, that is the extent of the aquifer to be simulated, is divided into a set of elements or pieces. In theory, the elements can be of different shapes and sizes. Most FEM computer programs use one shape element, most commonly either triangular or quadrilateral elements. In the groundwater model MODFE (Torak, 1993; Cooley, 1992) triangular elements are used, whereas in the groundwater model SUTRA (Voss, 1984) quadrilateral elements are used. Point values of the dependent variable (for example, head, pressure, or concentration) are calculated at nodes, which are the corners or vertices of the elements, and a simple equation is used to describe the value of the dependent variable within the element. This simple equation is called a basis function and each node that is part of an element has an associated basis function. The simplest basis functions that are usually used are linear functions. The solution to the differential equation for flow (Equation [3]) or transport (Equation [7]) is approximated by a set of elements in which the dependent variable only varies linearly within the element, but the entire set of elements approximates the complex distribution of head or concentration. Figure 20.6 shows the approximate modeled hydraulic head distribution (Figure 20.6C) comprised of a set of triangular elements (Figure 20.6A) having a linear approximation of head variation within each element (Figure 20.6B).





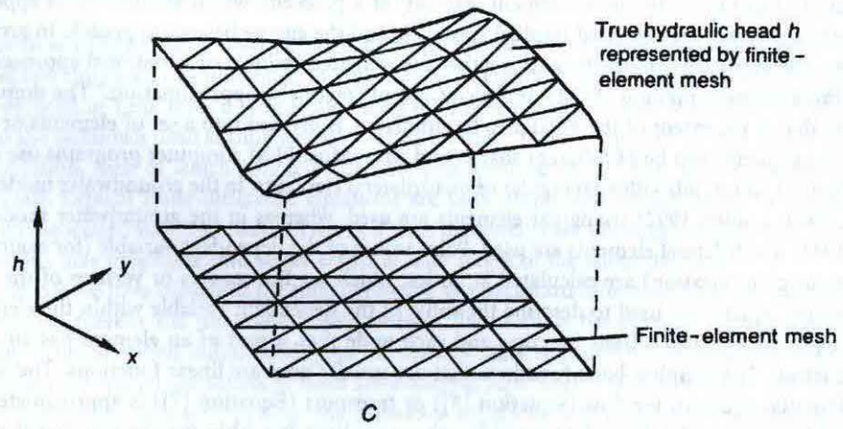


FIGURE 20.6 Diagram showing (A) aquifer region partially subdivided by finite elements and typical element e, (B) finite-element representation of hydraulic head $\hat{h}$, and (C) finite-element mesh configuration for approximating true hydraulic head. (From Torak, L. J. 1993. A modular finite-element model (MODFE) for areal and axisymmetric ground-water-flow problems, Part 1: Model description and user's manual. Techniques of Water-Res. Invests. of the U.S. Geol. Survey, Book 6, Ch. A3.)

In the method of weighted residuals, the piecewise continuous surface is obtained by minimizing the difference between the approximate surface and the continuous surface. The method of weighted residuals is summarized by Huyakorn and Pinder (1983, p. 39) as follows. Any differential equation L(h), such as the steady-state form of Equation (3) (the groundwater flow equation) can be written:

$$L(h) = 0 \tag{16}$$

over the domain of the problem *R*. The first step in obtaining the approximate solution is to define the approximate solution as the sum of all the simple basis functions as:

$$\hat{h} = \sum_{i=1}^{n} N_i Z_i \tag{17}$$

where $\hat{h}$ is the approximate solution, n is the number of linearly independent basis functions, N_i are the linearly independent basis functions defined over the entire domain, and Z_i are the unknown coefficients to be determined (there is one coefficient for each node in the finite-element mesh). The trial function $\hat{h}$ is an approximation, so that when it is substituted into Equation (16) there will be some error, ξ, defined as:

$$\xi = L(\hat{h}) \tag{18}$$

The method of weighted residuals determines the unknown coefficients by minimizing the error. This is accomplished by weighting the error, integrating the error, and setting the error equal to zero over the entire domain. A weighting function, W_i, can be specified for each basis function and the resulting integration is:

$$\int_R W_i \xi \, dR = \int_R W_i L(\hat{h}) \, dR = 0 \qquad i = 1,2 \ldots n \tag{19}$$

Equation (17) is substituted into Equation (19), and weighting functions are specified. There are then n equations and n unknowns. The selection of the weighting functions and the simplification of the integral in Equation (19) into a linear algebraic equation is mathematically straightforward, but not intuitive. In the Galerkin method, the weighting functions are chosen to be identical to the basis functions, and Equation (19) is simplified by using integration by parts. Because the basis functions and weighting functions are defined to be of a specific algebraic form (for example, linear basis functions), the modified integral is straightforward to solve and becomes a set of n simultaneous algebraic equations.

After Equation (19) is mathematically evaluated into a set of n simultaneous equations, they are solved using matrix solution techniques for the n unknown coefficients Z_i, and the approximate solution $\hat{h}$ is determined at each node. The time derivative is frequently approximated by finite differences as discussed in the previous section. Huyakorn and Pinder (1983), Huebner (1975), Zienkiewicz (1971), Wang and Anderson (1982), and Cooley (1992) provide more comprehensive explanations of the method.

20.5.3 Basics of Method-of-Characteristics Methods

The method of characteristics was developed to solve hyperbolic differential equations (advectively dominated transport equations). A major advantage is that the method minimizes numerical dispersion

(Reddell and Sunada, 1970; Garder et al., 1964; Zheng and Bennett, 1995). The approach taken by the method of characteristics is not to solve Equation (7) directly, but rather to solve an equivalent system of ordinary differential equations. A form of Equation (7), accounting for equilibrium-controlled sorption or exchange and first-order irreversible rate reactions, can be further modified for improved compatibility with this method by expanding the advection term, substituting relations from Darcy's law and the flow equation, and rearranging terms to obtain:

$$\frac{\partial C}{\partial t} = \frac{1}{R_f}\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{V_i}{R_f}\frac{\partial C}{\partial x_i} + \frac{W^*\left(C - C'\right)}{\varepsilon R_f} - \lambda C \tag{20}$$

where R_f is defined as a dimensionless retardation factor, $R_f = 1 + \frac{\rho_b K_d}{\varepsilon}$, and K_d is the distribution coefficient, L^3M^{-1}. If we consider the material derivative of concentration with respect to time, dC/dt, as describing the change in concentration of a parcel of water moving at the seepage velocity of water, it may be defined for a two-dimensional system as:

$$\frac{dC}{dt} = \frac{\partial C}{\partial t} + \frac{\partial C}{\partial x}\frac{dx}{dt} + \frac{\partial C}{\partial y}\frac{dy}{dt} \tag{21}$$

The second and third terms on the right side include the material derivatives of position, which are defined by the velocity in the x and y directions. We then have:

$$\frac{dx}{dt} = \frac{V_x}{R_f} \tag{22}$$

$$\frac{dy}{dt} = \frac{V_y}{R_f} \tag{23}$$

and

$$\frac{dC}{dt} = \frac{1}{R_f}\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right) + \frac{W^*\left(C - C'\right)}{\varepsilon R_f} - \lambda C \tag{24}$$

The solutions of the system of equations comprising Equations (22) through (24) may be given as $x = x(t)$, $y = y(t)$, and $C = C(t)$, and are called the characteristic curves of Equation (20). Given solutions to Equations (22) through (24), a solution to the partial differential equation may be obtained by following the characteristic curves, which are defined by the particle pathlines. This may be accomplished by introducing a set of moving points (or reference particles) that can be traced within the stationary coordinates of a finite-difference grid. Each particle corresponds to one characteristic curve, and values of x, y, and C are obtained as functions of t for each characteristic (Garder et al., 1964). Each point has a concentration and position associated with it and is moved through the flow field in proportion to the flow velocity at its location (see Figure 20.7). The concentrations at the nodes of the fixed finite-difference grid may then be estimated as an arithmetic or weighted mean of the concentrations of all particles contained within the cell area for that node.

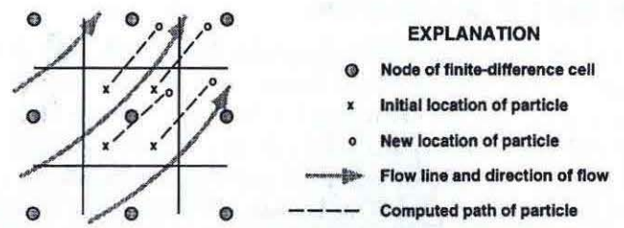


FIGURE 20.7 Part of a hypothetical finite-difference grid showing relation of flow field to movement of points (or particles) in method-of-characteristics model for simulating solute transport. (Adapted from Konikow, L. F. and Bredehoeft, J. D. 1978. *Computer Model of Two-Dimensional Solute Transport and Dispersion in Ground Water.* Techniques of Water-Res. Invests. of the U.S. Geol. Survey, Book 7, Ch. C2.)

20.5.4 Matrix Solution Techniques

As indicated, the finite-difference and finite-element approximations lead to an algebraic equation for each node point. The set of algebraic equations may be solved numerically by one of two basic methods: direct or iterative. In direct methods, a sequence of operations is performed only once to solve the matrix equation, providing a solution that is exact, except for machine round-off error. Iterative methods arrive at a solution by a process of successive approximation. They involve making an initial guess at the solution, then improving this guess by some iterative process until an error criterion is satisfied. Therefore, in these techniques, convergence and the rate of convergence are of concern.

Direct methods can be further subdivided into: (1) solution by determinants, (2) solution by successive elimination of the unknowns, and (3) solution by matrix inversion. Direct methods have two main disadvantages. The first problem is one of computer resource requirements, including large storage (memory) requirements and long computation times for large problems. The matrix is sparse (contains many zero values) and to minimize computational effort, several techniques have been proposed. However, for finite-difference and finite-element methods, storage requirements may still prove to be unavoidably large for three-dimensional problems. The second problem with direct methods is round-off error. Because many arithmetic operations are performed, round-off errors can accumulate for certain types of matrices.

Iterative schemes avoid the need for storing large matrices, which make them attractive for solving problems with many unknowns. Numerous schemes have been developed; a few of the more commonly used ones include successive over-relaxation methods, iterative alternating-direction implicit procedure, and the strongly implicit procedure.

Because iterative methods start with an initial estimate for the solution, the efficiency of the method depends somewhat on this initial guess. To speed up the iterative process, relaxation and acceleration factors are used. Unfortunately, the definition of best values for these factors commonly is problem dependent. In addition, iterative approaches require that an error tolerance be specified to stop the iterative process. An optimal value for the tolerance, which is used to evaluate when the iterative calculations have converged on a solution, may also be problem dependent. If the tolerance is set too large, then the iterations may stop before adequate numerical accuracy is achieved. If the tolerance is set too small, then the iterative process may consume excessive computational resources in striving for numerical precision that may be orders of magnitude smaller than the precision of the field data, or the iterative process may even fail to converge.

More recently, a semi-iterative method, or class of methods, known as conjugate-gradient methods, has gained popularity. One advantage of the conjugate-gradient method is that it does not require the use or specification of iteration parameters, thereby eliminating this partly subjective procedure.

20.5.5 Boundary and Initial Conditions

To obtain a unique solution of a partial differential equation corresponding to a given physical process, additional information about the physical state of the process is required. This information is supplied by boundary and initial conditions. For steady-state problems, only boundary conditions are required, whereas for transient problems, boundary and initial conditions must be specified.

Mathematically, the boundary conditions include the geometry of the boundary and the values of the dependent variable or its derivative normal to the boundary. In physical terms, for groundwater model applications, the boundary conditions are generally of three types: (1) specified value (head or concentration), (2) specified flux (corresponding to a specified gradient of head or concentration), or (3) value-dependent flux (or mixed boundary condition, in which the flux across a boundary is related to both the normal derivative and the value) (Mercer and Faust, 1981; Franke et al., 1987). The third type of boundary condition might be used, for example, to represent leakage or exchange between a stream and an adjacent aquifer, in which the leakage may change over time as the head in the aquifer changes, even though the head in the stream might remain fixed. A no-flow boundary is a special case of the second type of boundary condition. The types of boundaries appropriate to a particular field problem require careful consideration.

The initial conditions are simply the values of the dependent variable specified everywhere inside the boundary at the start of the simulation. Normally, the initial conditions are specified to be a steady-state solution. If, however, initial conditions are specified so that transient flow is occurring in the system at the start of the simulation, it should be recognized that heads will change during the simulation, not only in response to the new pumping stress, but also due to the initial conditions (Franke et al., 1987).

20.6 Model Design, Development, and Application

The first step in model design and application is to define the nature of the problem and the purpose of the model. Although this may seem obvious, it is an important first step that is sometimes overlooked in a hasty effort to take action. This step is closely linked with the formulation of a conceptual model, which again is required prior to development of a mathematical model. A possible outcome of such a preliminary assessment might even be that a deterministic simulation model is not needed. In formulating a conceptual model, the analyst must evaluate which processes are significant in the system being investigated for the particular problem at hand. Some processes may be important to consider at one scale of study, but negligible or irrelevant at another scale of investigation. The analyst must similarly decide on the appropriate dimensionality for the numerical model. Good judgment is required to evaluate and balance the trade-offs between accuracy and cost, with respect to model development, model use, and data requirements. The key to efficiency and accuracy in modeling a system probably is more affected by the formulation of a proper and appropriate conceptual model than by the choice of a particular numerical method or code.

Once a decision to develop a model has been made, a code (or generic model) must be selected (or modified or constructed) that is appropriate for the given problem. Next, the generic code must be adapted to the specific site or region being simulated. Development of a numerical deterministic, distributed-parameter, simulation model involves selecting or designing spatial grids and time increments that will yield an accurate solution for the given system and problem. The analyst must then specify the properties of the system (and their distributions), stresses on the system (such as recharge and pumping rates), boundary conditions, initial conditions (for transient problems), and geochemical processes/reactions (if appropriate). All of the parameter specifications and boundary conditions are really part of the overall conceptual model of the system, and the initial numerical model reflects the analyst's conceptual model of the system.

It must always be remembered that a model is an approximation of a very complex reality, and a model is used to simplify that reality in a manner that captures or represents the essential features and processes relative to the problem at hand. In the development of a deterministic groundwater model for a specific

area and purpose, an appropriate level of model complexity (or, rather, simplicity) must be selected. One may be inclined to believe that finer resolution in a model will yield greater accuracy, and there is a legitimate basis for this. However, there also exists the practical constraint that even when appropriate data are available, a finely discretized three-dimensional numerical model may be too large to run on available computers, especially if transport processes are included. The selection of the appropriate model and appropriate level of model complexity remains subjective and dependent on the judgment and experience of the analysts, the objectives of the study, the level of prior information available for the system of interest, and the complexity of the system being modeled. The trade-off between model accuracy and model cost will always be a difficult one to resolve, but will always have to be made. In any case, water managers and other users of model results must be made aware that these trade-offs and judgments have been made and may affect the reliability of the model.

In general, it is more difficult to calibrate a solute-transport model of an aquifer than it is to calibrate a groundwater flow model. Fewer parameters need to be defined to compute the head distribution with a flow model than are required to compute concentration changes with similar confidence using a solute-transport model. Also, in typical field problems, defining the source term for a solute-transport model is especially difficult for point-source contamination problems because the timing and strength of releases of solute mass into an aquifer system are rarely known or reported accurately (and, in fact, are commonly the very point of contention in litigation).

Because the groundwater seepage velocity is determined from the head distribution, and because both advective transport and hydrodynamic dispersion are functions of the seepage velocity, a model of groundwater flow is typically calibrated before a solute-transport model is developed. In fact, in a field environment perhaps the single most important key to understanding a solute-transport problem is the development of an accurate definition (or model) of the flow system. This is particularly relevant to transport in fractured rocks, where simulation is commonly based on porous-media concepts. In highly heterogeneous systems, the potential (or head) field can often be simulated fairly accurately, whereas the calculated velocity field may still be greatly in error, resulting in considerable errors in simulations of transport.

20.6.1 Generic Model Verification

One of the first things that must be demonstrated is that the generic model accurately solves the governing equations for various boundary value problems, an evaluation that is often called model "verification." This is checked by demonstrating that the code gives good results for problems having known solutions. This test is usually done by comparing the numerical model results to that of an analytical solution. Numerical accuracy is rarely a problem for the solution to the flow equation, but may sometimes be a significant problem in transport modeling.

It must be remembered that numerical solutions are sensitive to spatial and temporal discretization. Therefore, even a perfect agreement for test cases only proves that the numerical code can accurately solve the governing equations, not that it will accurately solve problems under any and all circumstances.

Analytical solutions generally require simple geometry, uniform properties, and idealized boundary and initial conditions. The power of the numerical methods is that they are not constrained by the simplification imposed by analytical methods and allow the introduction of nonhomogeneous, anisotropic parameter sets, irregular geometry, mixed boundary conditions, and even nonlinearities into the boundary value problems. Usually, analytical solutions approximating these complexities are unavailable for comparison. Therefore, once these complexities are introduced there is no definitive basis for verifying the numerical model.

One approach that improves confidence for complex heterogeneous problems is to compare the model results to experimental data, to results of other well-accepted models, or to some other accepted standard. Such evaluations might best be termed benchmarking. The HYDROCOIN Project used standardized problem definitions as a basis for intercode comparisons (Swedish Nuclear Power Inspectorate, 1987). While this type of benchmarking helps assure consistency, it does not guarantee or measure accuracy. A

collection and detailed discussion of a number of classical groundwater problems that have been used historically as a basis of model evaluation are presented and documented by Ségol (1994).

20.6.2 Grid Design

The dimensionality of the model (i.e., one, two, or three dimensions) should be selected during the formulation of the conceptual model. If a one- or two-dimensional model is selected, then it is important that the grid be aligned with the flow system so that there is no unaccounted flux into or out of the line or plane of the grid. For example, if a two-dimensional areal model is applied, then there should be no significant vertical components of flow and any vertical leakage or flux must be accounted for by boundary conditions; if a two-dimensional profile model is applied, then the line of the cross section should be aligned with an areal streamline, and there should not be any significant lateral flow into or out of the plane of the cross section.

To minimize a variety of sources of numerical errors, the model grid should be designed using the finest mesh spacing and time steps that are possible, given limitations on computer memory and computational time. To the extent possible, the grid should be aligned with the fabric of the rock and with the average direction of groundwater flow. The boundaries of the grid also should be aligned, to the extent possible, with natural hydrologic and geologic boundaries of the system of interest. Where it is impractical to extend the grid to a natural boundary, then an appropriate boundary condition should be imposed at the edge of the grid to represent the net effects of the continuation of the system beyond the grid. This can typically be accomplished using head-dependent leakage (third type) boundary conditions. However, this would preclude calculating (and accounting for) any storage changes outside the active grid. These boundaries should also be placed as far as possible away from the area of interest and areas of stresses on the system, so as to minimize any impact of conceptual errors associated with these artificial boundary conditions. Note that it is possible for certain types of hydraulic boundaries, such as a groundwater divide, to change location over time if they are located near a major hydraulic stress. If this is anticipated, it might be preferable to extend the boundary of the grid some distance beyond the location of such a natural boundary.

In designing the grid, the length-to-width ratio (or aspect ratio) of cells or elements should be kept as close to one as possible. Long linear cells or elements can lead to numerical instabilities or errors, and should be avoided, particularly if the aspect ratio is greater than about five (Bear and Verruijt, 1987). However, this is a loose guideline as aspect ratios exceeding 100:1 are often used without introducing significant error. In applying this guideline to triangular finite-element methods, Torak (1993) recommends that angles less than 22.5° in a triangle should be avoided.

In specifying boundary conditions for a particular problem and grid design, care must be taken not to overconstrain the solution. That is, if dependent values are fixed at too many boundary nodes, at either internal or external nodes of a grid, the model may have too little freedom to calculate a meaningful solution. At the extreme, by manipulating boundary conditions, one can force any desired solution at any given node. While a forced solution may assure a perfect match to observed data used for calibration, such a match is, of course, not an indicator of model accuracy or reliability and, in fact, can be meaningless (Franke and Reilly, 1987).

To optimize computational resources in a model, it is sometimes advisable to use an irregular (or variably spaced) mesh in which the grid is finest in areas of point stresses, where gradients are steepest, where data are most dense, where the problem is most critical, and (or) where greatest numerical accuracy is desired. It is generally advisable to increase the mesh spacing by a factor no greater than about two between adjacent cells or elements. Similarly, time steps can often be increased geometrically during a transient simulation. At the initial times or after a change in the stress regime, very small time steps should be imposed, because that is when changes in the dependent variable over time are the greatest. As elapsed time increases, the rate of change in head typically decreases, so time steps can often be safely increased by a factor of two or more.

Because transmissivity is a property of the porous media, the cross-product terms of the transmissivity tensor drop out of the governing flow equation that is solved in a model by aligning the model grid with the major axes of the transmissivity tensor (as represented in Equation [5]). This makes the code simpler and more efficient, and, in fact, is a required assumption for most finite-difference models. However, this same simplification typically is not possible for the dispersion tensor in the transport equation because it is also related to, and depends on, the flow direction, which changes orientation over space and time. In general, it is not possible to design a fixed grid that will always be aligned with a changing flow field.

20.6.3 Model Calibration

Deterministic groundwater simulation models impose large requirements for data to define all of the parameters at all of the nodes of a grid. To determine uniquely the parameter distribution for a field problem, so much expensive field testing would be required that it is seldom feasible either economically or technically. Therefore, the model typically represents an attempt, in effect, to solve a large set of simultaneous equations having more unknowns than equations. It is inherently impossible to obtain a unique solution to such a problem.

Uncertainty in parameters logically leads to a lack of confidence in the interpretations and predictions that are based on a model analysis, unless the model can be demonstrated to be a reasonably accurate representation of the real system. To demonstrate that a deterministic groundwater simulation model is realistic, usually field observations of aquifer responses (such as changes in water levels for flow problems or changes in concentration for transport problems) are compared to corresponding values calculated by the model. The objective of this calibration procedure is to minimize differences between the observed data and calculated values. Usually, the model is considered calibrated when it reproduces historical data within some acceptable level of accuracy. The level of acceptability is, of course, determined subjectively. Although a poor match provides evidence of errors in the model, a good match in itself does not prove the validity or adequacy of the model (Konikow and Bredehoeft, 1992).

Because of the large number of variables in the set of simultaneous equations represented in a model, calibration will not yield a unique set of parameters. Where the match is poor, it suggests (1) an error in the conceptual model, (2) an error in the numerical solution, or (3) a poor set of parameter values. Even when the match to historical data is good, the model may still fail to predict future responses accurately, especially under a newer or more extended set of stresses than were experienced during the calibration period.

The calibration of a deterministic groundwater model is often accomplished through a trial and error adjustment of the model's input data (aquifer properties, sources and sinks, and boundary and initial conditions) to modify the model's output. Because a large number of interrelated factors affect the output, trial and error adjustment may become a highly subjective and inefficient procedure. Advances in parameter estimation procedures help to eliminate some of the subjectivity inherent in model calibration (Yeh, 1986). The newer approaches generally treat model calibration as a statistical procedure using multiple regression approaches. Parameter estimation procedures allow the simultaneous construction, application, and calibration of a model using uncertain data, so that the uncertainties in model parameters and in predictions and assessments can be quantified.

However, even with regression modeling, the hydrologic experience and judgment of the modeler continues to be a major factor in calibrating a model both accurately and efficiently. In any case, the modeler should be very familiar with the specific field area being studied in order to ensure that both the data base and the numerical model adequately represent prevailing field conditions. The modeler must also recognize that uncertainty in specification of sources, sinks, and boundary and initial conditions should be evaluated during the calibration procedure in the same manner as uncertainty in aquifer properties. Failure to recognize the uncertainty inherent both in the input data and in the calibration data may lead to "fine-tuning" of the model through unjustifiably precise parameter adjustments strictly to improve the match between observed and calculated variables. This may serve only to provide a false

confidence in the model without producing an equivalent (or any) increase in the predictive accuracy of the model or any improved conceptual understanding of the real system. Freyberg (1988) illustrated this in an exercise in which several groups were given the task of modeling a particular hypothetical groundwater problem. The group that achieved the best calibration, as measured by the minimum root mean square error, was not the group that developed the model that yielded the best prediction (measured by the same criterion). Freyberg (1988, p. 360) concluded that "simple measures of the goodness of a calibrated fit to head data are inadequate to evaluate the true worth of a calibrated parameter set."

Figure 20.8 illustrates in a general manner the use and role of deterministic models in the analysis of groundwater problems. The value of the modeling approach is its capability to integrate site-specific data with equations describing the relevant processes as a quantitative basis for predicting changes or responses in a groundwater system. There must be allowances for feedback from the stage of interpreting model output both to the data collection and analysis phase and to the conceptualization and mathematical definition of the relevant governing processes. One objective of model calibration should be to improve the conceptual model of the system. Because the model quantitatively integrates the effects of the many factors that affect groundwater flow or solute transport, the calculated results should be internally consistent with all input data, and it can be determined if any element of the conceptual model should be revised. In fact, prior concepts or interpretations of aquifer parameters or variables, such as represented by potentiometric maps or the specification of boundary conditions, may be revised during the calibration procedure as a result of feedback from the model's output. In a sense, any adjustment of input data constitutes a modification of the conceptual model.

Automated parameter-estimation techniques improve the efficiency of model calibration and have two general components — one part that calculates the best fit (sometimes called automatic history matching) and a second part that evaluates the statistical properties of the fit. The objective of automatic history matching is to obtain the estimates of system parameters that yield the closest match (minimize deviations) between observed data and model calculations. Least squares deviation is usually chosen as a criterion. The minimization procedure uses sensitivity coefficients that are based on the change in calculated value divided by the change in the parameter. For groundwater flow, for example, this may

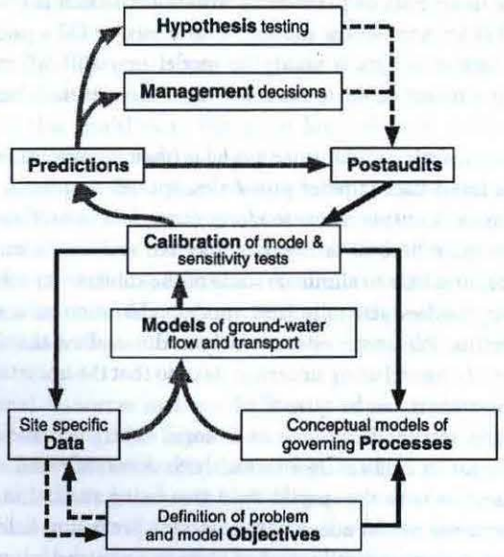


FIGURE 20.8 The use and role of models in the analysis of groundwater problems. (Adapted from Konikow, L. F. 1996. Numerical models of groundwater flow and transport, in *Manual on Mathematical Models in Isotope Hydrogeology*. International Atomic Energy Agency, Vienna.)

take the specific form of $\partial h/\partial T$; that is, the change in head with changing transmissivity. The sensitivity coefficients themselves may be useful in the consideration of additional data collection.

Parameter uncertainty is commonly addressed using a sensitivity analysis. A major objective of sensitivity analysis of simulation models is to determine the change in model results as a result of changes in the model input or system parameters. Conventional sensitivity analysis uses direct parameter sampling in which parameters are perturbed one by one and the complete set of system equations are resolved (Konikow and Mercer, 1988). Sensitivity coefficients for each of these perturbed parameters may be derived by a finite-difference approximation.

20.6.4 Model Error

Discrepancies between observed and calculated responses of a system are the manifestation of errors in the conceptual or mathematical model. In applying groundwater models to field problems, there are three sources of error, and it may not be possible to distinguish among them (Konikow and Bredehoeft, 1992). One source is conceptual errors — that is, misconceptions about the basic processes that are incorporated in the model. Conceptual errors include both neglecting relevant processes as well as inappropriate representation of processes. Examples of such errors include the use of a two-dimensional model where significant flow or transport occurs in the third dimension, or the application of a model based upon Darcy's law to media or environments where Darcy's law is inappropriate. A second source of error involves numerical errors arising in the equation-solving algorithm. These include truncation errors, round-off errors, and numerical dispersion. A third source of error arises from uncertainties and inadequacies in the input data that reflect our inability to describe comprehensively and uniquely the aquifer properties, stresses, and boundaries. In most model applications, conceptualization problems and uncertainty concerning the input data are the most common sources of error.

Numerical methods in general yield approximate solutions to the governing equations. There are a number of possible sources of numerical error in the solution. If model users are aware of the source and nature of these errors, they can control them and interpret the results in light of the presence of error. In solving advection-dominated transport problems in which a relatively sharp front (or steep concentration gradient) is moving through a system, it is numerically difficult to preserve the sharpness of the front.

Obviously, if the width of the front is narrower than the node spacing, then it is inherently impossible to calculate the correct values of concentration in the vicinity of the sharp front. However, even in situations where a front is less sharp, the numerical solution technique can calculate a greater dispersive flux than would occur by physical dispersion alone or would be indicated by an exact solution of the governing equation. That part of the calculated dispersion (or spreading of solute about the center of mass) introduced solely by the numerical solution algorithm is called numerical dispersion.

Figure 20.9 illustrates calculated breakthrough curves for a hypothetical problem of uniform flow and transport to the right, at some time and distance after a tracer having a relative concentration of 1.0 was injected at some point upstream. Curve A represents the breakthrough curve and position of a sharp front for a case having no dispersion (plug flow). Curve B represents an exact analytical solution for a nonzero dispersivity. Curve C illustrates the breakthrough curve calculated for the same conditions as B, but using a numerical method that introduces numerical dispersion. Significant differences exist between the analytical solution (B) and the numerical solution (C) in parts of the domain. Therefore, care must be taken to assess and minimize such numerical errors that would artificially add "numerical" spreading or mixing to the calculated dispersion attributable to physical and chemical processes.

Numerical dispersion can be controlled by reducing the grid spacing (Δx and Δy). However, reduction to a tolerable level may require an excessive number of nodes and render the computational costs unacceptably high. It may also be controlled in finite-element methods by using higher order basis functions or by adjusting the formulation of the equations (using different combinations of forward, backward, or centered in time and/or space, or using different weighting functions). Unfortunately, many approaches that eliminate or minimize numerical dispersion introduce oscillatory behavior, causing

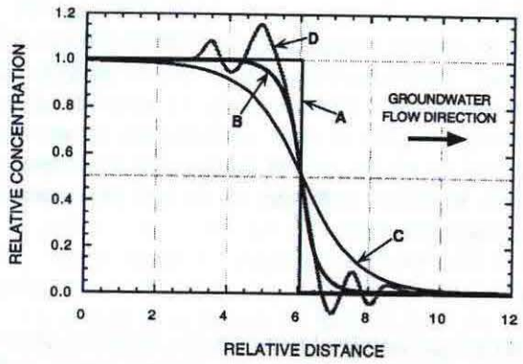


FIGURE 20.9 Representative breakthrough curves for a simple flow and transport problem to illustrate types of numerical errors that may occur in numerical solution to transport equation: (A) plug flow having no dispersion, (B) "exact" solution for transport with dispersion, (C) numerical solution for case B that exhibits effects of numerical dispersion, and (D) numerical solution for case B that exhibits oscillatory behavior. (Adapted from Konikow, L. F. 1996. Numerical models of groundwater flow and transport, in *Manual on Mathematical Models in Isotope Hydrogeology*. International Atomic Energy Agency, Vienna.)

overshoot behind a moving front and possibly undershoot ahead of the front (see curve D in Figure 20.9), and vice versa. Undershoot can result in the calculation of negative concentrations, which are obviously unrealistic. Overshoot can introduce errors of equal magnitude that may go unnoticed because the value is positive in sign (although greater than the source concentration, so still unrealistic). Oscillations generally do not introduce any mass balance errors, and often dampen out over simulation time. However, in some cases, oscillatory behavior can become unbounded, yielding an unstable solution or failure to converge numerically.

In solving the advective-dispersive transport equation, some numerical errors (mainly oscillations) can be related to two dimensionless parameter groups (or numbers). One is the Peclet number, P_e, which may be defined as $P_e = \Delta l/\alpha$, where Δl is a characteristic nodal spacing (although it should be noted that there are several alternative, though essentially equivalent, ways to define P_e). Anderson and Woessner (1992) recommend that the grid be designed so that $\Delta l < 4\alpha$ (or $P_e < 4$); Ségol (1994) recommends a criterion of $P_e \leq 2$. Similarly, time discretization can be related to the Courant number, C_o, which may be defined as $C_o = V\Delta t/\Delta l$ (Anderson and Woessner, 1992). Anderson and Woessner (1992) recommend that time steps be specified so that $\Delta t < \Delta l/V$ (or $C_o < 1.0$), which is equivalent to requiring that no solute be displaced by advection more than the distance across one grid cell or element during one time increment. Numerical error associated with the deviation of curves *C* or *D* (Figure 20.9) from the exact solution can be significant in some locations within the problem domain, although such errors tend to be minimal at the center of a front (relative concentration of 0.5).

In transport models, there may also be a grid-orientation effect in which the solute distribution, calculated for the same properties and boundary conditions, will vary somewhat depending on the angle of the flow relative to the grid. This phenomenon is largely related to the cross-product terms in the governing equation, and generally is not a serious source of error, but the model user should be aware of it.

20.6.5 Mass Balance

One measure of numerical accuracy is how well the model conserves mass. This can be measured by comparing the net fluxes calculated or specified in the model (e.g., inflow and sources minus outflow and sinks) with changes in storage (accumulation or depletion). Mass-balance calculations should always be performed and checked during the calibration procedure to help assess the numerical accuracy of the solution.

As part of these calculations, the hydraulic and chemical fluxes contributed by each distinct hydrologic component of the flow and transport model should be itemized separately to form hydrologic and chemical budgets for the system being modeled. The budgets are valuable assessment tools because they provide a measure of the relative importance of each component to the total budget.

Errors in the mass balance for flow models should generally be less than 0.1%. However, because the solute-transport equation is more difficult to solve numerically, the acceptable mass-balance error for a solute may be greater than for the fluid, but this will depend also on the nature of the numerical method implemented. Finite-difference and finite-element methods are inherently mass conservative, while some implementations of the method of characteristics and particle tracking approaches may not be (or their mass balance calculations themselves are only approximations). It must also be remembered that while a large mass-balance error provides evidence of a poor numerical solution, a perfect mass balance in itself does not and cannot prove that a true or accurate solution has been achieved or that the overall model is valid. That is, a perfect mass balance can be achieved if the model includes compensating errors. For example, the solutions C and D in Figure 20.9 that exhibit significant numerical dispersion or oscillatory behavior arise from solutions that show a near-perfect mass balance, but they are still wrong.

20.6.6 Sensitivity Tests

Assuming various values for given parameters also helps to achieve another objective of the calibration procedure, namely to determine the sensitivity of the model to factors that affect groundwater flow and transport and to errors and uncertainty in the data. Evaluating the relative importance of each factor helps determine which data must be defined most accurately and which data are already adequate or require only minimal further definition. If additional field data can be collected, such a sensitivity analysis helps in deciding which types of data are most critical and how to get the best information return on the costs of additional data collection. If additional data cannot be collected, then the sensitivity tests can help to assess the reliability of the model by demonstrating the effect of a given range of uncertainty or error in the input data on the output of the model. The relative sensitivities of the parameters that affect flow and transport will vary from problem to problem. Furthermore, the sensitivities may change over time as the stress regime imposed on a system evolves. Thus, one generalization is that a sensitivity analysis should be performed during the early stages of a model study.

The sensitivity of the solution to the grid design (or spacing), time-step criterion, nature and placement of boundary conditions, and other numerical parameters also should be evaluated, even if an inverse or regression modeling approach has been used. This step is frequently overlooked, but failure to do so may cause critical design flaws to remain undetected. For example, parameter-estimation models cannot evaluate the sensitivity to grid spacing or certain boundary conditions that are fixed in the model by the user. It is generally recommended that after a preliminary calibration has been achieved, the model should be rerun for the same stresses and properties using a finer grid, smaller time steps, and perhaps alternative boundary conditions. If such a test yields significantly different results, then the model should be recalibrated using design criteria that yield a more accurate numerical solution. If such a test yields no significant differences, then the coarser design is probably adequate for that particular problem.

20.6.7 Calibration Criteria

Model calibration may be viewed as an evolutionary process in which successive adjustments and modifications to the model are based on the results of previous simulations. The modeler must decide when sufficient adjustments have been made to the representation of parameters and processes and at some time accept the model as being adequately calibrated (or perhaps reject the model as being inadequate and seek alternative approaches). This decision is often based on a mix of subjective and objective criteria. The achievement of a best fit between values of observed and computed variables is a regression procedure and can be evaluated as such. That is, the residual errors should have a mean that approaches zero and the deviations should be minimized. Cooley (1977) discusses several statistical measures that can be used

to assess the reliability and "goodness of fit" of groundwater flow models. The accuracy tests should be applied to as many dependent variables as possible. The types of observed data that are most valuable for model calibration include head and concentration changes over space and time, and the quantity and quality of groundwater discharges from the aquifer.

While it is necessary to evaluate the accuracy of the model quantitatively, it is equally important to assure that the dependent variables that serve as a basis for the accuracy tests are reliable indicators of the computational power and accuracy of the model. For example, if a particular dependent variable was relatively insensitive to the governing parameters, then the existence of a high correlation between its observed and computed values would not necessarily be a reflection of a high level of accuracy in the overall model.

Similarly, caution must be exercised when the "observed data" contain an element of subjective interpretation. For example, matching an observed potentiometric surface or concentration distribution is sometimes used as a basis for calibrating groundwater models. However, a contoured surface is itself interpretive and can be a weak basis for model calibration because it includes a variability or error introduced by the contouring process, in addition to measurement errors present in the observed data at the specific points.

20.6.8 Predictions and Postaudits

As model calibration and parameter estimation are keyed to a set of historical data, the confidence in and reliability of the calibration process is proportional to the quality and comprehensiveness of the historical record. The time over which predictions are made with a calibrated model should also be related to, and limited by, the length of the historical record. A reasonable guideline is to predict only for a time comparable to the period that was matched.

The accuracy of a model's predictions is the best measure of its reliability. However, predictive accuracy can be evaluated only after the fact. Anderson and Woessner (1992) summarize several published studies in which the predictive accuracy of a deterministic groundwater model was evaluated several years after the prediction had been made. The results suggest that extrapolations into the future were rarely very accurate. Predictive errors often were related to having used a time period for history matching that was too short to capture an important element of the model or of the system, or to having an incomplete conceptual model. For example, processes and boundary conditions that are negligible or insignificant under the past and present stress regime may become nontrivial or even dominant under a different set of imposed stresses. Thus, a conceptual model founded on observed behavior of a groundwater system may prove to be inadequate in the future, when existing stresses are increased or new stresses are added. A major source of predictive error is sometimes attributable primarily to the uncertainty of future stresses, which is often controlled by demographic, political, economic, and (or) social factors. But if the range or probability of future stresses can be estimated, then the range or probability of future responses can be predicted. An encouraging trend is that many analysts are now attempting to place confidence bounds on predictions arising out of the uncertainty in parameter estimates. However, these confidence limits still would not bound errors arising from the selection of a wrong conceptual model or from problems in the numerical solution algorithms (Bredehoeft and Konikow, 1993).

If a model is to be used for prediction relating to a problem or system that is of continuing interest or significance to society, then field monitoring should continue and the model should be periodically postaudited, or recalibrated, to incorporate new information, such as changes in imposed stresses or revisions in the assumed conceptual model. A postaudit offers a means to evaluate the nature and magnitude of predictive errors, which may itself lead to a large increase in the understanding of the system and in the value of a subsequently revised model. Revised predictions can then be made with greater reliability.

20.6.9 Model Validation

It is natural for people who apply groundwater models, as well as those who make decisions based on model results, to want assurance that the model is valid. Groundwater models are embodiments of various scientific theories and hypotheses. Karl Popper (1959) argues that "as scientists we can never validate a hypothesis, only invalidate it." The same philosophy has been applied specifically to groundwater models (Konikow and Bredehoeft, 1992; Oreskes et al., 1994).

The criteria for labeling a model as validated are inherently subjective. In practice, validation is attempted through the same process that is typically and more correctly identified as calibration — that is, by comparing calculations with field or laboratory measurements. However, the nonuniqueness of model solutions means that a good comparison can be achieved with an inadequate or erroneous model. Also, because the definition of "good" is subjective, under the common operational definitions of validation, one competent and reasonable scientist may declare a model as validated while another may use the same data to demonstrate that the model is invalid. To the general public, proclaiming that a groundwater model is validated carries with it an aura of correctness that many modelers would not claim (Bredehoeft and Konikow, 1993). Because labeling a model as having been validated has very little objective or scientific meaning, such "certification" does little beyond instilling a false sense of confidence in such models. Konikow and Bredehoeft (1992) recommend that the term "validated" not be applied to groundwater models.

20.7 Overview of Representative Generic Models

A large number and variety of generic groundwater models are documented and available at the present time. Two widely used public domain models are explained in more detail as illustrative examples.

20.7.1 MODFLOW

One of the most popular and comprehensive deterministic groundwater models available today is the MODFLOW code of McDonald and Harbaugh (1988) and Harbaugh and McDonald (1996). This is actually a family of compatible codes that centers on an implicit finite-difference solution to the three-dimensional flow equation that was coded in FORTRAN in a modular style to allow and encourage the development of additional packages or modules that can be added on or linked to the original code. The basic model uses a block-centered finite-difference grid that allows variable spacing of the grid in three dimensions. Flow can be steady or transient. Layers can be simulated as confined, unconfined, or a combination of both. Aquifer properties can vary spatially and hydraulic conductivity (or transmissivity) can be anisotropic. Flow associated with external stresses, such as wells, areally distributed recharge, evapotranspiration, drains, and streams, can also be simulated through the use of specified head, specified flux, or head-dependent flux boundary conditions. The implicit finite-difference equations can be solved using either the strongly implicit procedure (SIP) or slice-successive overrelaxation (SSOR) methods. Newer packages offer several additional solution algorithms, including a preconditioned conjugate-gradient solver (Hill, 1990) and a direct solver (Harbaugh, 1995). Although the input and output systems of the program were designed to permit maximum flexibility, usability and ease of interpretation of model results can be enhanced by using one of several commercially available preprocessing and post-processing packages; some of these operate independently of MODFLOW, whereas others are directly integrated into reprogrammed and (or) recompiled versions of the MODFLOW code.

The pathline program MODPATH (Pollock, 1989, 1994) uses the results of the MODFLOW model and determines paths and travel times of water movement under steady-state and transient conditions. MODPATH uses a semianalytical particle-tracking scheme. The method assumes that each directional velocity component varies linearly within a grid cell in its own coordinate direction. MODPATH-PLOT is a graphics interface package that visually displays the results of MODPATH (Pollock, 1994).

The parameter-estimation package, MODFLOWP, can be used to estimate parameters (such as transmissivity, storage coefficient, leakance coefficients, recharge rates, evapotranspiration, and hydraulic head at constant-head boundaries) using nonlinear regression (Hill, 1992). Parameters are estimated by minimizing a weighted least-squares objective function by either the modified Gauss-Newton method or a conjugate-direction method. Data used to estimate parameters can include independent estimates of parameter values, observed heads or drawdowns, and observed gains or losses in streamflow. The MODFLOWP output includes statistics for analyzing the reliability of the estimated parameters and of the model.

A variety of other MODFLOW accessory codes, packages, and features are available. Most of these were developed by the U.S. Geological Survey (USGS) and are summarized by Appel and Reilly (1994); examples include coupled surface-water and groundwater flow, aquifer compaction, transient leakage from confining units, rewetting of dry cells, horizontal flow barriers, alternative interblock transmissivity conceptualizations, cylindrical flow to a well, a statistical processor, a data input program, and a program that calculates water budgets. Other packages have been developed by non-USGS sources to work with MODFLOW; one example is the advective-dispersive solute-transport model MT3D (Zheng, 1990).

20.7.2 MOC

The Method of Characteristics (MOC) model developed by Konikow and Bredehoeft (1978) simulates solute transport in flowing groundwater in two dimensions. The model has been extensively used since the mid-1970s and has been evolving through updates and improvements. The model computes changes in concentration over time caused by the processes of advective transport, hydrodynamic dispersion, mixing or dilution from fluid sources, and the following types of chemical reactions: first-order irreversible-rate reaction, such as radioactive decay; reversible equilibrium-controlled sorption with linear, Freundlich, or Langmuir isotherms; and reversible equilibrium-controlled ion exchange for monovalent or divalent ions. The model couples the groundwater flow equation with the solute-transport equation. The model uses a finite-difference approximation to the groundwater flow equation and the method of characteristics to solve the solute-transport equation. The model uses a particle tracking procedure to represent advective transport and an explicit finite-difference procedure to calculate concentration changes due to hydrodynamic dispersion.

The original model of Konikow and Bredehoeft (1978) was later revised by Goode and Konikow (1989) and Konikow et al. (1994). The model has also been used as the foundation for MOCDENSE (Sanford and Konikow, 1985), a model that can simulate two constituents in a density-dependent flow system. There are public-domain and commercial preprocessors available, including PREMOC (Granato et al., 1993). A three-dimensional version of the model (MOC3D) uses MODFLOW to simulate the flow system (Konikow et al., 1996).

20.8 Case Histories

A large number of documented examples of the application of groundwater models to a variety of hydrogeologic problems are available in the literature. Two case studies have been selected to help illustrate modeling philosophy and practice, including aspects of model conceptualization, model implementation, and interpretation of results.

20.8.1 Regional-Scale Flow in a Deep Confined Aquifer

The Powder River Basin of northeastern Wyoming and southeastern Montana contains large coal reserves that have not yet been fully developed. The future development of such energy resources in the Powder River Basin will be accompanied by increased demands for water, which is not abundantly available in this semiarid area. One plan had been formulated to construct a coal-slurry pipeline to transport coal out of the area; it would have required about 0.6 to 0.8 m^3/s of water. In the mid-1970s, a plan was

proposed to supply this water from up to 40 wells drilled about 1000 m into the Mississippian age Madison Limestone in Niobrara County, Wyoming. The Madison aquifer is an areally extensive carbonate rock system that underlies an area exceeding 260,000 km^2 in the northern Great Plains.

Concern that such relatively large groundwater withdrawals might cause significant water-level declines in the Madison aquifer, perhaps extending into adjacent states, as well as possibly causing decreases in streamflow and spring discharge in or near the outcrop areas, resulted in the need to predict the effects of the proposed large groundwater withdrawals on potentiometric levels, recharge, and discharge. Because the Madison aquifer lies at such great depths (from 300 to 5000 m) in most of the area, it is relatively undeveloped, and sufficient data are not available to define the head distribution and the hydraulic properties of the aquifer accurately and precisely. In light of this uncertainty, and as a prelude to a planned subsequent 5-year hydrogeologic investigation of the Madison aquifer, a preliminary, two-dimensional, finite-difference model of the aquifer was developed (Konikow, 1976). The objectives of the preliminary model study were to: (1) improve the conceptual model of groundwater flow in the aquifer system; (2) determine deficiencies in existing data, and help set priorities for future data collection by identifying the most sensitive parameters, assuming the model is appropriate; and (3) make a preliminary estimate of the regional hydrologic effects of the proposed well field (Konikow, 1976).

The results indicated that the aquifer can probably sustain the increased groundwater withdrawals, but that they probably would significantly lower the potentiometric surface in the Madison aquifer in a large part of the basin. Because of the great uncertainty in most of the parameters needed to represent the flow system, the model study and predictions were framed in terms of a sensitivity analysis. For example, Figure 20.10 shows drawdown predictions made for an area near the proposed well field for an assumed reasonable range of values for the storage and leakance coefficients (K_Z/m), where K_Z and m are the vertical hydraulic conductivity and the thickness, respectively, of the confining layer. The curves show that the range in plausible drawdowns, even after 1 year, is extremely large. The solutions also illustrate that sensitivities vary with time. At late times (about 100 years), there is no significant difference in drawdown for different values of S (simulations A, B, and C), and at early times (up to about 0.1 years) the drawdown is about the same for all values of leakance at a given value of S (simulations B, D, E, and F).

This preliminary model analysis helped in formulating an improved conceptual model of the Madison aquifer. For example, the important influences of temperature differences and aquifer discontinuities on groundwater flow were recognized and documented (see Konikow, 1976). Because the discrepancies between observed heads and those calculated with the earliest preliminary models did not appear to be

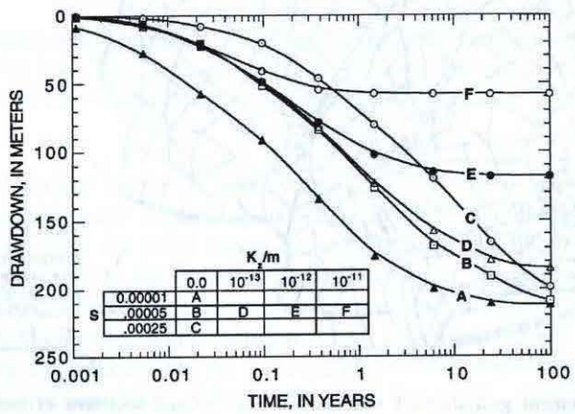


FIGURE 20.10 Time-drawdown curves for model node located near proposed well field to pump groundwater from the Madison Limestone aquifer. (Adapted from Konikow, L. F. 1976. Preliminary digital model of ground-water flow in the Madison group, Powder River basin and adjacent areas, Wyoming, Montana, South Dakota, North Dakota, and Nebraska. U.S. Geol. Survey Water-Res. Inv. 63-75.)

distributed randomly, it was thought that data uncertainty was not the only source of error. Although it could be argued that the importance of these influences could have been (or should have been) recognized on the basis of hydrogeologic principles without the use of a simulation model, the fact is that none of the earlier published studies of this aquifer system indicated that these factors were of major significance. The improvement over earlier studies arose from the quantitative hypothesis-testing role of the model; the nature of the inconsistencies between observed head distributions and those calculated using the initial estimates of model parameters helped direct the investigators toward testing hypotheses that would resolve or minimize the inconsistencies with only a small increment of added complexity. The demonstrated high sensitivity of drawdown to the leakance coefficient emphasized the need to reevaluate the system in a true three-dimensional framework so as to represent vertical components of flow more accurately, which was done in several subsequent studies (for example, see Downey and Weiss, 1980; Woodward-Clyde Consultants, 1981).

Cooley et al. (1986) applied a nonlinear-regression groundwater flow model to this same aquifer system. Their two-dimensional model was based on a Galerkin finite-element discretization scheme. The finite-element grid and boundary conditions are shown in Figure 20.11. The grid was designed to be finer where more data were available and (or) where hydraulic gradients are relatively steep. Regression analysis was used to estimate parameters, including intrinsic permeabilities of the main aquifer and separate lineament zones, discharges from eight major springs, and specified heads on the model boundaries. The regression approach also yielded statistical measures of the reliability of those parameter estimates. Analysis by Cooley et al. (1986) tends to confirm the existence of lineament zones, which appear to exert a strong influence upon the flow and head distribution in the Madison aquifer.

Thus, results from a variety of models were used to understand the sensitivity of the response of the conceptualized Madison aquifer to changes in simulated aquifer parameters. From these sensitivity analyses, improved predictions of aquifer responses were made, and the confidence in the predictions were assessed.

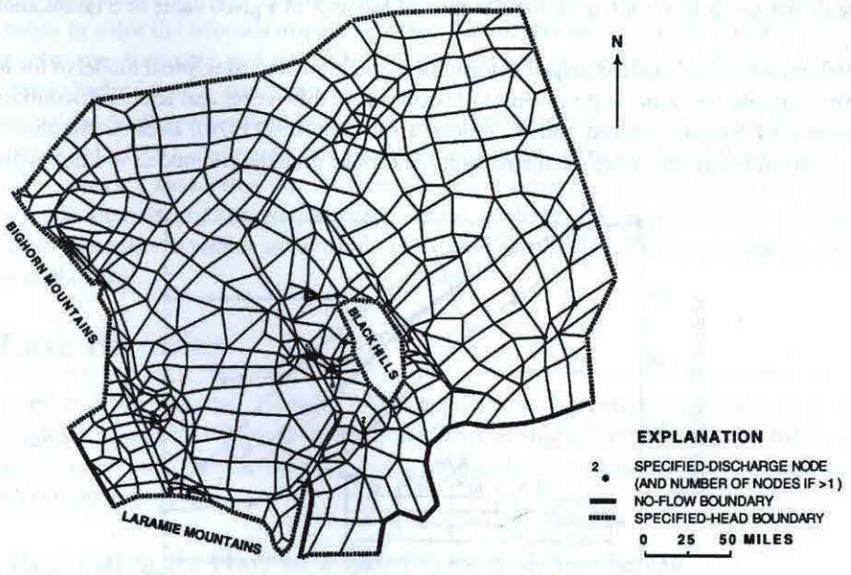


FIGURE 20.11 Finite-element grid showing boundary conditions and locations of specified-discharge points. (Adapted from Cooley, R. L., Konikow, L. F., and Naff, R. L. 1986. Nonlinear-regression groundwater flow modeling of a deep regional aquifer system. *Water Resour. Res.* 10(3):546-562.)

20.8.2 Local-Scale Flow and Transport in a Shallow Unconfined Aquifer

Reilly et al. (1994) combined the application of environmental tracers and deterministic numerical modeling to analyze and estimate recharge rates, flow rates, flow paths, and mixing properties of a shallow groundwater system near Locust Grove, in eastern Maryland. The study was undertaken as part of the U.S. Geological Survey's National Water Quality Assessment Program to provide flow paths and travel time estimates to be used in understanding and interpreting water-quality trends in monitoring wells and stream base flows. The study area encompassed about 2.6×10^7 m^2 of mostly agricultural land on the Delmarva Peninsula. The surficial aquifer includes unconsolidated permeable sands and gravel that range in thickness from less than 6 m to more than 20 m. This surficial aquifer is underlain by relatively impermeable silt and clay deposits, which form a confining unit.

In this study, chlorofluorocarbons (CFCs) and tritium were analyzed from a number of water samples collected from observation wells to estimate the age of groundwater at each sampling location and depth. Because errors and uncertainty are associated with estimates of age based on environmental tracers, just as errors and uncertainty are associated with deterministic models of groundwater flow and transport, the authors applied a feedback or iterative process based on comparisons of independent estimates of travel time. Their approach is summarized and outlined in Figure 20.12. Each task shown was designed to improve either the estimates of parameters or the conceptualization of the system.

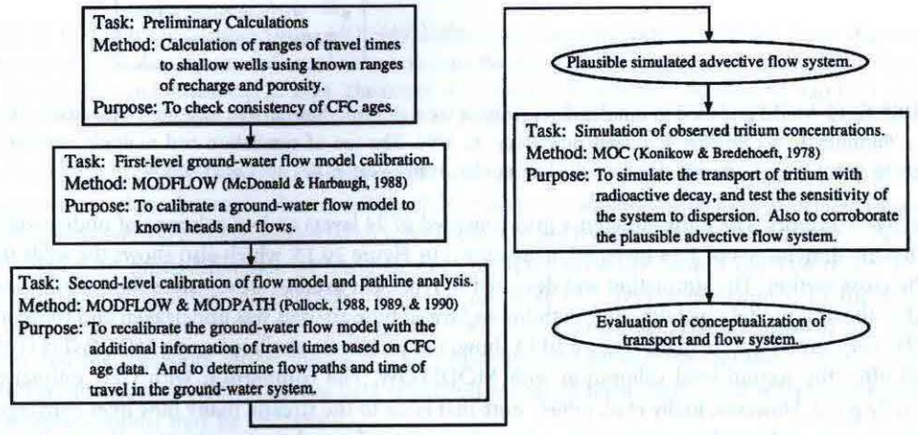


FIGURE 20.12 Flow diagram of the steps taken to quantify the flow paths in the Locust Grove, Maryland, groundwater flow system. (Adapted from Reilly, T. E., Plummer, L. N., Phillips, P. J., and Busenberg, E. 1994. The use of simulation and multiple environmental tracers to quantify groundwater flow in a shallow aquifer. *Water Resour. Res.* 30(2):421-433.)

The preliminary calculations (first task) were used to set bounds on the plausibility of the results of the more complex simulations and chemical analyses. The first-level calibration of a groundwater flow model (second task) provided the initial system conceptualization. The third task was a second-level calibration and analysis involving simulation of advective transport, which provided quantitative estimates of flow paths and time of travel to compare with those obtained from the CFC analyses. The fourth task involved the application of a solute-transport model to simulate tritium concentrations in the groundwater flow system as influenced by the processes of advection, dispersion, radioactive decay, and time-varying input (source concentration) functions.

The sampling wells were located approximately along an areal flow line, and a two-dimensional cross-sectional model was developed for the simulation of processes occurring along this flow line. The MODFLOW model (McDonald and Harbaugh, 1988) was used to simulate groundwater flow and

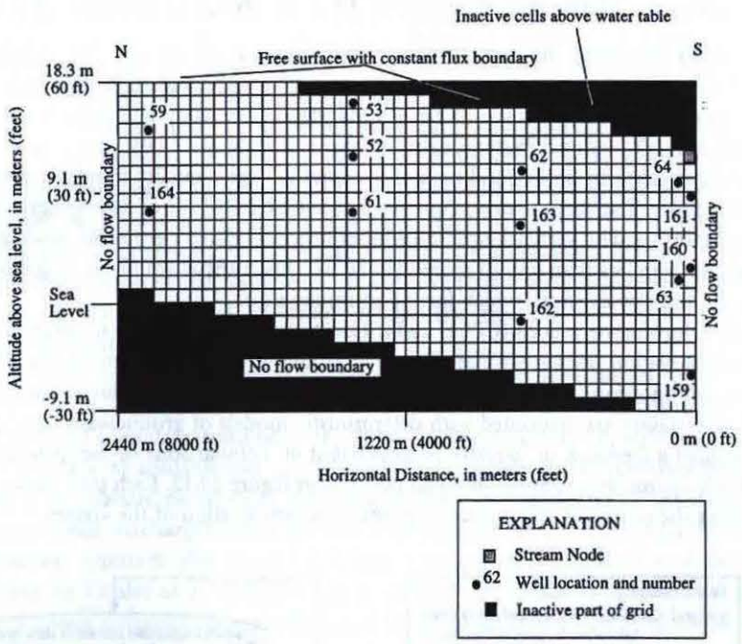


FIGURE 20.13 Model grid used to simulate Locust Grove cross section, showing well locations. (Adapted from Reilly, T. E., Plummer, L. N., Phillips, P. J., and Busenberg, E. 1994. The use of simulation and multiple environmental tracers to quantify groundwater flow in a shallow aquifer. *Water Resour. Res.* 30(2):421-433.)

advective transport. The finite-difference grid consisted of 24 layers and 48 columns of nodes, with each cell having dimensions of 1.14 by 50.80 m, as shown in Figure 20.13, which also shows the wells that lie in the cross section. The simulation was designed to represent average steady-state flow conditions.

After the flow model was calibrated, pathline and travel time analysis was undertaken and comparisons to CFC age estimates were made. Figure 20.14 shows the pathlines calculated using MODPATH (Pollock, 1989) after the second-level calibration with MODFLOW. The comparison with CFC estimates was generally good. However, Reilly et al. (1994) note that close to the stream, many flow lines converge, and the convergence of pathlines representing the entire range of travel times present in the aquifer causes waters of different ages to be relatively near each other. Thus, at the scale and grid spacing of the model, in the area near the stream the convergent flow lines cannot be readily differentiated in the model and the locations of individual well screens cannot be accurately represented directly under the stream. After the second-level calibration, the root mean squared error between the simulated ages and the CFC ages for the 10 wells farthest from the stream (i.e., excluding wells 159, 160, and 161) was 3.4 years.

Tritium concentrations of recharge waters have varied considerably over the last 40 years. Thus, the time of travel would not always be readily apparent from the tritium concentration in a water sample. Also, mixing of waters recharged during periods of these relatively sharp changes of input concentrations can make the interpretation of time of travel from tritium concentrations even more uncertain. Thus, the investigators simulated solute transport of tritium within the system using a model that accounts for mixing (dispersion), radioactive decay, and transient input functions, which also allowed a further evaluation of consistency with the results of the previous flow and advective transport model. They applied the MOC solute-transport model of Konikow and Bredehoeft (1978) and Goode and Konikow (1989) for this purpose.

The results of the simulation of the tritium distribution assuming (1) no dispersion and (2) α_L of 0.15 m and α_T of 0.015 m are shown in Figure 20.15. The limiting case simulation of no dispersion yielded acceptable results and was used as the best estimate of the tritium distribution in November

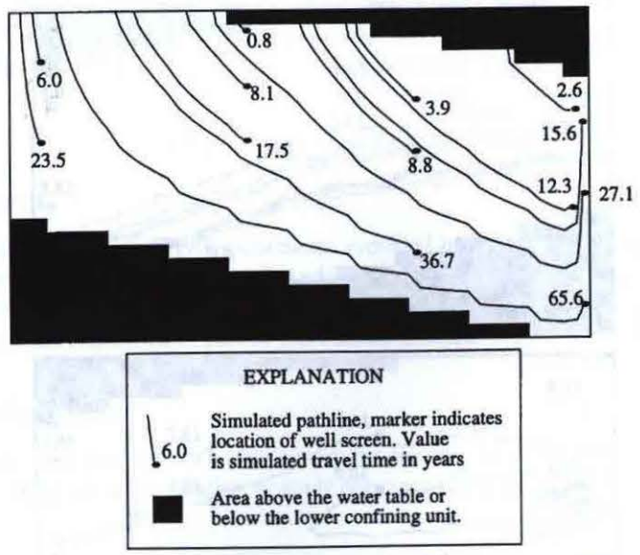


FIGURE 20.14 Pathlines (calculated using MODPATH after second-level calibration) in Locust Grove cross section to observation wells showing time of travel (in years) from the water table. (Adapted from Reilly, T. E., Plummer, L. N., Phillips, P. J., and Busenberg, E. 1994. The use of simulation and multiple environmental tracers to quantify groundwater flow in a shallow aquifer. *Water Resour. Res.* 30(2):421-433.)

1990 (Reilly et al., 1994). This case reproduces the sharp concentration gradients required to reproduce the low tritium values that were observed. The MOC model was advantageous for this problem because it minimizes numerical dispersion and it can solve the governing equations for α_L of 0.0, which transport models based on finite-difference or finite-element methods generally cannot do. The results of the solute-transport simulation are consistent with the advective flow system determined by the second-level calibration and thus strengthen the case for the conceptual model. The coupling of the tritium analyses and the transport model indicates where discrepancies between the measured and simulated concentrations occur, where additional data collection would be most useful, and where refinement of the conceptual model may be warranted.

This case study illustrates that environmental tracers and numerical simulation methods in combination are effective tools that complement each other and provide a means to estimate the flow rate and path of water moving through a groundwater system. Reilly et al. (1994) found that the environmental tracers and numerical simulation methods also provide a "feedback" that allows a more objective estimate of the uncertainties in the estimated rates and paths of movement. Together the two methods enabled a coherent explanation of the flow paths and rates of movement while identifying weaknesses in the understanding of the system that require additional data collection and refinement of conceptual models of the groundwater system.

20.9 Available Groundwater Models

A large number of generic deterministic groundwater models, based on a variety of numerical methods and a variety of conceptual models, are available. The selection of a numerical method or generic model for a particular field problem depends on several factors, including accuracy, efficiency/cost, and usability. The first two factors are related primarily to the nature of the field problem, availability of data, and scope or intensity of the investigation. The usability of a method may depend partly on the mathematical background of the modeler, as it is preferable for the model user to understand the nature of the numerical methods implemented in a code. It may be necessary to modify and adapt the program to the specific

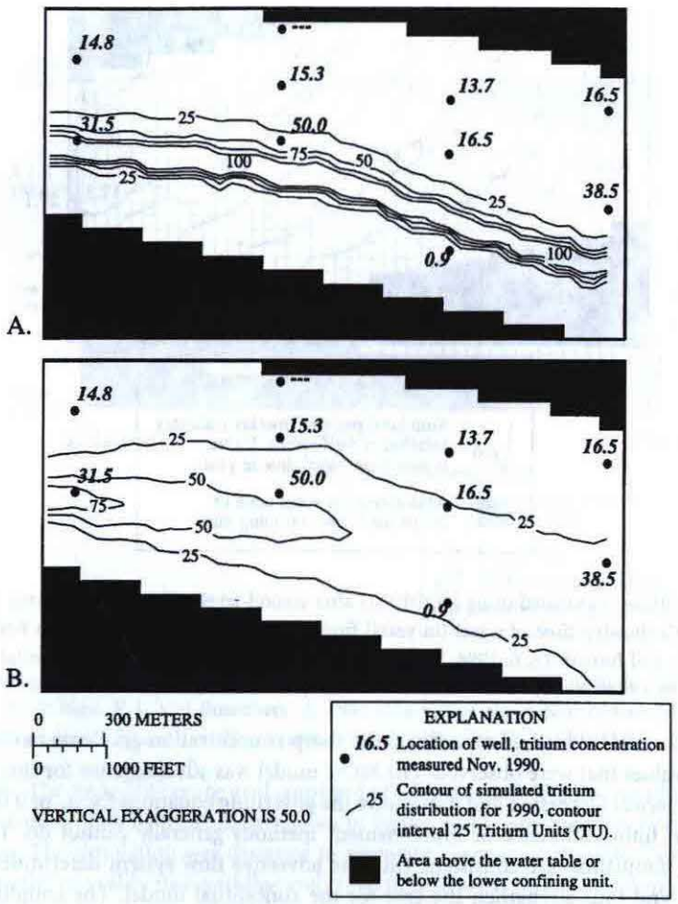


FIGURE 20.15 Simulated tritium distribution at the end of 1990: (A) with dispersivity $\alpha_L = 0.0$ m and $\alpha_T = 0.0$ m, and (B) with dispersivity $\alpha_L = 0.15$ m and $\alpha_T = 0.015$ m. Contour interval 25 tritium units (TU). Measured concentrations from samples obtained from wells in November 1990 are given for their location in bold italics. (Adapted from Reilly, T. E., Plummer, L. N., Phillips, P. J., and Busenberg, E. 1994. The use of simulation and multiple environmental tracers to quantify groundwater flow in a shallow aquifer. *Water Resour. Res.* 30(2):421-433.)

problem of interest, and this can sometimes require modifications to the source code. In selecting a model that is appropriate for a particular application, it is most important to choose one that incorporates the proper conceptual model; one must avoid force fitting an inappropriate model to a field situation solely because of the model's convenience, availability, or familiarity to the user. Usability is also enhanced by the availability of preprocessing and postprocessing programs or features, and by the availability of comprehensive yet understandable documentation.

A number of surveys of available models have been published in recent years (Appel and Reilly, 1994; Van der Heijde et al., 1985). Van der Heijde et al. (1985) report on an international survey of 399 models, of which 206 had been documented at that time. This was a significant increase from the 245 models available for a similar review 5 years earlier. Appel and Reilly (1994) summarize the nature and availability of 89 groundwater flow and quality models produced by and available from the U.S. Geological Survey. Anderson et al. (1992), in their review of groundwater models, list 19 separate software distributors and provide brief descriptions of several codes. The International Ground Water Modeling Center, Golden, CO, (see internet address in *For Further Information*) maintains a clearinghouse and distribution center for groundwater simulation models.

A large number of public and private organizations distribute public domain and (or) proprietary software for groundwater modeling. A growing availability of models is also occurring on the internet (see *For Further Information* for some examples). Some internet sites allow computer codes to be downloaded at no cost, while other sites provide catalog information, demonstrations, and pricing information.

Acknowledgment

The authors appreciate the helpful review comments provided by Robert Nicholson, Michael Planert, and Cliff Voss, all of the USGS, and by Mary P. Anderson of the University of Wisconsin–Madison. We also acknowledge Dr. Y. Yurtsever and the International Atomic Energy Agency for supporting the development of the report upon which part of this chapter is based.

For Further Information

Textbooks and examples of good reports on site-specific models are provided as starting points for readers who would like to obtain more information or study representative applications.

Textbooks

Anderson and Woessner (1992) present an overview of applied groundwater flow and advective transport modeling.

Zheng and Bennett (1995) present an overview of the theory and practice of contaminant transport modeling.

Examples of Reports on Site-Specific Models

Comprehensive reports on site-specific models provide insight into applied groundwater simulation. A few examples from the work of the U.S. Geological Survey are provided below. Obviously, this list is not inclusive, and many other reports could have been listed.

Regional Flow Models

Kernodle et al. (1995) describe a three-dimensional flow model of the Albuquerque Basin in New Mexico.

Fleck and Vroblesky (1996) describe the application of a three-dimensional groundwater flow model to a coastal plain system in the northeastern U.S.

Local Flow Model

Masterson and Barlow (1994) used a two-step approach to simulate a saltwater–freshwater system.

Local Radial-Flow Model

Lindner and Reilly (1983) used a finite-element radial flow model to analyze aquifer tests on Long Island, New York.

Local Advective-Transport Model

Barlow (1994) examined contributing areas to public-supply wells at Cape Cod, Massachusetts.

Solute-Transport Model

LeBlanc (1984) documented a two-dimensional simulation of a 6-km-long sewage plume at Cape Cod, Massachusetts.

Lambert (1996) used a three-dimensional model to simulate a contaminant plume in an approximately 480-km^2 area in Utah.

Model Calibration

Masterson et al. (1996) used particle tracking and contaminant plumes to improve calibration of a three-dimensional flow model.

Yager (1997) used a parameter-estimation model (MODFLOWP) to help calibrate a three-dimensional flow model for a fractured dolomite aquifer system.

Internet

A number of sites on the World Wide Web provide compendia of codes and sources of information about groundwater modeling, as well as providing links to other websites related to groundwater modeling. Many of these sites allow codes to be downloaded. Examples of several groundwater-oriented home page locations are: **http://www.ems.psu.edu/Hydrogeologist/**, **http://www.et.byu.edu/~asce-gw/**, **http://www.mines.edu/igwmc/**, and **http://www.ibmpcug.co.uk/~bedrock/gsd/**. Also, many of the U.S. Geological Survey public domain codes are available from the "USGS Water Resources Applications Software" link on the USGS Water Resources Information Home page at: **http://water.usgs.gov/**.

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Glossary

Analytical Model A closed-form exact mathematical solution which is continuous in space and time.
Conceptual Model A hypothesis for how a system or process operates.
Deterministic Model A mathematical model based on conservation of mass, momentum, and energy.
Discretization The process of representing a continuous system by a set of discrete blocks, cells, or elements.
Generic Model The computer code used to solve one or more partial differential equations.
Mathematical Model A set of equations, which include mathematical variables, constants, and coefficients, that represents relevant processes.
Model A representation of a real system or process.

Numerical Model An approximate solution of a differential equation obtained by replacing the continuous variables with a set of discrete variables defined at grid blocks, cells, or nodes.

Site-Specific Model A numerical model with the parameters (such as hydraulic conductivity, dispersivity, etc.), boundary conditions, and grid dimensions of the generic model specified to represent a particular geographical area.

21

The Role of Geographical Information Systems in Groundwater Engineering

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21.1 Introduction to Geographic Information Systems (GIS)

Geographic Information Systems (GIS) have become important tools in efficiently solving many problems in which spatial data are important. Natural resources and environmental concerns, including groundwater, have benefited greatly from the use of GIS. This chapter provides a brief introduction to GIS and some of its applications in addressing groundwater issues.

21.1.1 Overview of GIS

GIS have evolved rapidly in the last decade, becoming powerful computer tools for varied applications ranging from sophisticated analysis and modeling of spatial data to simple inventory and management.

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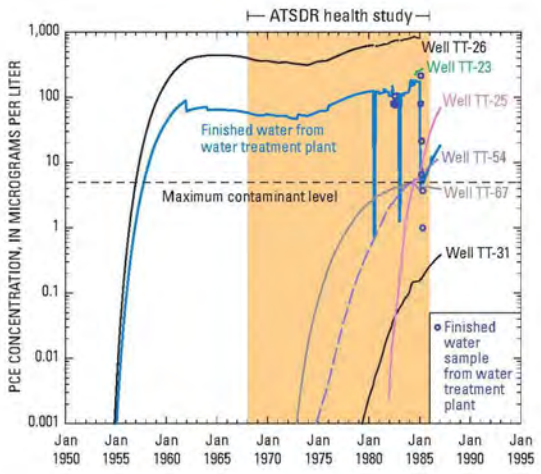
EXHIBIT 19

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



DEPARTMENT OF HEALTH & HUMAN SERVICES · USA

ATSDR
AGENCY FOR TOXIC SUBSTANCES AND DISEASE REGISTRY

Atlanta, Georgia–July 2007

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

Maps: U.S. Marine Corps Base Camp Lejeune, North Carolina; Tarawa Terrace area showing historical water-supply wells and site of ABC One-Hour Cleaners

Photographs on left: Ground storage tank STT-39 and four high-lift pumps used to deliver finished water from tank STT-39 to Tarawa Terrace water-distribution system

Photograph on right: Equipment used to measure flow and pressure at a hydrant during field test of the present-day (2004) water-distribution system

Graph: Reconstructed historical concentrations of tetrachloroethylene (PCE) at selected water-supply wells and in finished water at Tarawa Terrace water treatment plant

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

By Morris L. Maslia, Jason B. Sautner, Robert E. Faye, René J. Suárez-Soto, Mustafa M. Aral, Walter M. Grayman, Wonyong Jang, Jinjun Wang, Frank J. Bove, Perri Z. Ruckart, Claudia Valenzuela, Joseph W. Green, Jr., and Amy L. Krueger

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Suggested citation: Maslia ML, Sautner JB, Faye RE, Suárez-Soto RJ, Aral MM, Grayman WM, Jang W, Wang J, Bove FJ, Ruckart PZ, Valenzuela C, Green JW Jr, and Krueger AL. 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. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2007.

Foreword

The Agency for Toxic Substances and Disease Registry (ATSDR), an agency of the U.S. Department of Health and Human Services, is conducting an epidemiological study to evaluate whether in utero and infant (up to 1 year of age) exposures to volatile organic compounds in contaminated drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina, were associated with specific birth defects and childhood cancers. The study includes births occurring during the period 1968–1985 to women who were pregnant while they resided in family housing at the base. During 2004, the study protocol received approval from the Centers for Disease Control and Prevention Institutional Review Board and the U.S. Office of Management and Budget.

Historical exposure data needed for the epidemiological case-control study are limited. To obtain estimates of historical exposure, ATSDR is using water-modeling techniques and the process of historical reconstruction. These methods are used to quantify concentrations of particular contaminants in finished water and to compute the level and duration of human exposure to contaminated drinking water.

Final interpretive results for Tarawa Terrace and vicinity—based on information gathering, data interpretations, and water-modeling analyses—are presented as a series of ATSDR reports. These reports provide comprehensive descriptions of information, data analyses and interpretations, and modeling results used to reconstruct historical contaminant levels in drinking water at Tarawa Terrace and vicinity. Each topical subject within the water-modeling analysis and historical reconstruction process is assigned a chapter letter. Specific topics for each chapter report are listed below:

- **Chapter A**: Summary of Findings
- **Chapter B**: Geohydrologic Framework of the Castle Hayne Aquifer System
- **Chapter C**: Simulation of Groundwater Flow
- **Chapter D**: Properties and Degradation Pathways of Common Organic Compounds in Groundwater
- **Chapter E**: Occurrence of Contaminants in Groundwater
- **Chapter F**: Simulation of the Fate and Transport of Tetrachloroethylene (PCE) in Groundwater
- **Chapter G**: Simulation of Three-Dimensional Multispecies, Multiphase Mass Transport of Tetrachloroethylene (PCE) and Associated Degradation By-Products
- **Chapter H**: Effect of Groundwater Pumping Schedule Variation on Arrival of Tetrachloroethylene (PCE) at Water-Supply Wells and the Water Treatment Plant
- **Chapter I**: Parameter Sensitivity, Uncertainty, and Variability Associated with Model Simulations of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water
- **Chapter J**: Field Tests, Data Analyses, and Simulation of the Distribution of Drinking Water
- **Chapter K**: Supplemental Information

Electronic versions of these reports 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*.

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Conversion Factors

Multiply	By	To obtain
	Length	
inch	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (MG)	3,785	cubic meter (m^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
million gallons per day (MGD)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)

Concentration Conversion Factors

Unit	To convert to	Multiply by
microgram per liter (µg/L)	milligram per liter (mg/L)	0.001
microgram per liter (µg/L)	milligram per cubic meter (mg/m^3)	1
microgram per liter (µg/L)	microgram per cubic meter ($µg/m^3$)	1,000
parts per billion by volume (ppbv)	parts per million by volume (ppmv)	1,000

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Glossary and Abbreviations

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

A

aerobic conditions Conditions for growth or metabolism in which the organism is sufficiently supplied with oxygen (IUPAC 2006)

anaerobic process A biologically-mediated process or condition not requiring molecular or free oxygen (IUPAC 2006)

ATSDR Agency for Toxic Substances and Disease Registry

B

biodegradation Transformation of substances into new compounds through biochemical reactions or the actions of microorganisms, such as bacteria. Typically expressed in terms of a rate constant or half-life (USEPA 2004). The new compounds are referred to as degradation by-products (for example, TCE, 1,2-tDCE, and VC are degradation by-products of PCE)

BTEX Benzene, toluene, ethylbenzene, and xylene; a group of VOCs found in petroleum hydrocarbons, such as gasoline, and other common environmental contaminants

C

calibration *See* model calibration

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

CRWQME Continuous recording water-quality monitoring equipment; equipment that can be connected to hydraulic devices such as hydrants to continuously record water-quality parameters such as temperature, pH, and fluoride. For the Camp Lejeune analyses, the Horiba W-23XD continuous recording, dual probe ion detector data logger was used

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

degradation *See* biodegradation

degradation by-product *See* biodegradation

density The mass per unit volume of material, expressed in terms of kilograms per cubic meter or grams per cubic centimeter

direct measurement or observation A method of obtaining data that is based on measuring or observation of the parameter of interest

diurnal pattern The temporal variations in water usage for a water system that typically follow a 24-hour cycle (Haestad Methods et al. 2003)

DNAPL Dense nonaqueous phase liquids; a class of environmental contaminants that have a specific gravity greater than water (Huling and Weaver 1991). Immiscible (nonmixing)DNAPLs exit in the subsurface as a separate fluid phase in the presence of air and water. DNAPLs can vaporize into air and slowly dissolve into flowing groundwater. Examples of DNAPLs include chlorinated solvents, creosote, coal tar,
and PCBs (Kueper et al. 2003)

DVD Digital video disc

E

EPANET 2 A water-distribution system model developed by USEPA

epidemiological study A study to determine whether a relation exists between the occurrence and frequency of a disease and a specific factor such as exposure to a toxic compound found in the environment

EPS Extended period simulation; a simulation method used to analyze a water-distribution system that is characterized by time-varying demand and operating conditions

exposure Pollutants or contaminants that come in contact with the body and present a potential health threat

F

fate and transport Also known as mass transport; a process that refers to how contaminants move through, and are transformed in, the environment

finished water Groundwater that has undergone treatment at a water treatment plant and is delivered to a person's home. For this study, the concentration of treated water at the water treatment plant is considered the same as the concentration of water delivered to a person's home

ft Foot or feet

G

gal Gallon or gallons

gal/min Gallons per minute

H

historical reconstruction A diagnostic analysis used to examine historical characteristics of groundwater flow, contaminant fate and transport, water-distribution systems, and exposure

I

interconnection The continuous flow of water in a pipeline from one water-distribution system to another

inverse distance weighting A process of assigning values to unknown points by using values from known points; a method used to contour data or simulation results

IUPAC International Union of Pure and Applied Chemistry

K

K_{oc} Organic carbon partition coefficient

K_{ow} Octanol-water partition coefficient

M

MCL Maximum contaminant level; a legal threshold limit set by the USEPA on the amount of a hazardous substance that is allowed in drinking water under the Safe Drinking Water Act; usually expressed as a concentration in milligrams or micrograms per liter. Effective dates for MCLs are as follows: trichloroethylene (TCE) and vinyl chloride (VC), January 9, 1989; tetrachloroethylene (PCE) and *trans*-1,2-dichloroethylene (1,2-tDCE), July 6, 1992 (40 CFR, Section 141.60, Effective Dates, July 1, 2002, ed.)

MCS Monte Carlo simulation; *see* Monte Carlo analysis

MESL Multimedia Environmental Simulations Laboratory, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, Georgia; an ATSDR cooperative agreement partner

µg/L Microgram per liter; 1 part per billion, a unit of concentration

MG Million gallons

MGD Million gallons per day

mg/L Milligram per liter; 1 part per million (ppm), a unit of concentration

mL Milliliter; 1/1000th of a liter

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

MODFLOW-96 A three-dimensional groundwater-flow model, 1996 version, developed by the U.S. Geological Survey

MODFLOW-2K A three-dimensional groundwater-flow model, 2000 version, developed by the U.S. Geological Survey

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 (USEPA 1997)

MT3DMS A three-dimensional mass transport, multispecies model developed by C. Zheng and P. Wang on behalf of the U.S. Army Engineer Research and Development Center in Vicksburg, Mississippi

N

NPL National Priorities List; the USEPA's official list of uncontrolled hazardous waste sites which are to be cleaned up under the Superfund legislation

P

paired data point A location with observed data (for example, water level or concentration) that is associated with a model location for the purpose of comparing observed data with model results

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

PDF Probability density function; also known as the probability function or the frequency function. A mathematical function that expresses the probability of a random variable falling within some interval

PHA Public health assessment; an evaluation conducted by ATSDR of data and information on the release of hazardous substances into the environment in order to assess any past, present, or future impact on public health

potentiometric level A level to which water will rise in a tightly cased well

potentiometric surface An imaginary surface defined by the levels to which water will rise in a tightly cased wells. The water table is a particular potentiometric surface

probabilistic analysis An analysis in which frequency (or probability) distributions are assigned to represent variability (or uncertainty) in quantities. The output of a probabilistic analysis is a distribution (Cullen and Frey 1999)

pseudo-random number generator A deterministic algorithm used to generate a sequence of numbers with little or no discernable pattern in the numbers except for broad statistical properties

PSOpS A pumping schedule optimization system simulation tool used to assess impacts of unknown and uncertain historical groundwater well operations. The simulation tool was developed by the Multimedia Environmental Simulations Laboratory at the Georgia Institute of Technology, Atlanta, Georgia

Q

qualitative description A method of estimating data that is based on inference

quantitative estimate A method of estimating data that is based on the application of computational techniques

R

rank-and-assign method An optimization method uniquely developed for the pumping schedule optimization system (PSOpS) simulation tool . This procedure updates the pumping schedule for maximum and minimum contaminant concentration levels in finished water of the WTP based on derivative, pumping capacity, and total pumping demand information

RMS Root-mean-square; a statistical measure of the magnitude of a varying quantity

S

saturated zone Zone at or below the water table

SCADA Supervisory control and data acquisition; a computerized data collection system used to collect hydraulic data and information in water-distribution systems at specified time intervals such as every 1, 5, 15, etc., minutes

sensitivity analysis An analysis method used to ascertain how a given model output (for example, concentration) depends upon the input parameters (for example, pumping rate, mass loading rate). Sensitivity analysis is an important method for checking the quality of a given model, as well as a powerful tool for checking the robustness and reliability of its analysis

sequential biodegradation Degradation of a volatile organic compound as a result of a biological process that occurs in a progression, for example, the biodegradation of PCE ⟶ TCE ⟶ 1,2-tDCE ⟶ VC

SGA Small for gestational age; a term used to describe when an infant's weight is very low given their gestational week of birth

SGS Sequential Gaussian simulation; a process in which a field of values (such as hydraulic conductivity) is obtained multiple times assuming the spatially interpolated values follow a Gaussian (normal) distribution

skeletonization The reduction or aggregation of a water-distribution system network so that only the major hydraulic characteristics need be represented by a model. Skeletonization is often used to reduce the computational requirements of modeling an all-pipes network

SR Highway or state route

standard deviation Square root of the variance or the root-mean-square (RMS) deviation of values from their arithmetic mean

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

trihalomethane A chemical compound in which three of the four hydrogen atoms of methane (CH_4) are replaced by halogen atoms. Many trihalomethanes are used in industry as solvents or refrigerants. They also are environmental pollutants, and many are considered carcinogenic

U

uncertainty The lack of knowledge about specific factors, parameters, or models (for example, one is uncertain about the mean value of the concentration of PCE at the source)

unsaturated zone Zone or area above the water table; also known as the vadose zone

USEPA U.S. Environmental Protection Agency

USGS U.S. Geological Survey

V

variability Observed differences attributable to heterogeneity or diversity in a model parameter, an exposure parameter, or a population

VC Vinyl chloride or chloroethene

Venn diagram A diagram that shows the mathematical or logical relationship between different groups or sets; the diagram shows all the possible logical relations between the sets

venturi meter A device used to measure the flow rate or velocity of a fluid through a pipe

VOC Volatile organic compound; an organic chemical compound (chlorinated solvent) that has a high enough vapor pressure under normal circumstances to significantly vaporize and enter the atmosphere. VOCs are considered environmental pollutants and some may be carcinogenic

W

water-distribution system A water-conveyance network consisting of hydraulic facilities such as wells, reservoirs, storage tanks, high-service and booster pumps, and a network of pipelines for delivering drinking water

water table Also known as the phreatic surface; the surface where the water pressure is equal to atmospheric pressure

WTP Water treatment plant

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

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

By Morris L. Maslia,[1] Jason B. Sautner,[1] Robert E. Faye,[2] René J. Suárez-Soto,[1] Mustafa M. Aral,[3] Walter M. Grayman,[4] Wonyong Jang,[3] Jinjun Wang,[3] Frank J. Bove,[1] Perri Z. Ruckart,[1] Claudia Valenzuela,[5] Joseph W. Green, Jr.,[5] and Amy L. Krueger [5]

Abstract

Two of three water-distribution systems that have historically supplied drinking water to family housing at U.S. Marine Corps Base Camp Lejeune, North Carolina, were contaminated with volatile organic compounds (VOCs). Tarawa Terrace was contaminated mostly with tetrachloroethylene (PCE), and Hadnot Point was contaminated mostly with trichloroethylene (TCE). Because scientific data relating to the harmful effects of VOCs on a child or fetus are limited, the Agency for Toxic Substances and Disease Registry (ATSDR), an agency of the U.S. Department of Health and Human Services, is conducting an epidemiological study to evaluate potential associations between in utero and infant (up to 1 year of age) exposures to VOCs in contaminated drinking water at Camp Lejeune and specific birth defects and childhood cancers. The study includes births occurring during the period 1968–1985 to women who were pregnant while they resided in family housing at Camp Lejeune. Because limited measurements of contaminant and exposure data are available to support the epidemiological study, ATSDR is using modeling techniques to reconstruct historical conditions of groundwater flow, contaminant fate and transport, and the distribution of drinking water contaminated with VOCs delivered to family housing areas. The analyses and results presented in this Summary of Findings, and in reports described herein, refer solely to Tarawa Terrace and vicinity. Future analyses and reports will present information and data about contamination of the Hadnot Point water-distribution system.

Models and methods used as part of the historical reconstruction process for Tarawa Terrace and vicinity included: (1) MODFLOW-96, used for simulating steady-state (predevelopment) and transient groundwater flow; (2) MT3DMS, used for simulating three-dimensional, single-specie contaminant fate and transport; (3) a materials mass balance model (simple mixing) used to compute the flow-weighted average concentration of PCE assigned to the finished water at the Tarawa Terrace water treatment plant (WTP); (4) TechFlowMP, used for simulating three-dimensional, multispecies, multiphase mass transport; (5) PSOpS, used for simulating the impacts of unknown and uncertain historical well operations; (6) Monte Carlo simulation and sequential Gaussian simulation used to conduct probabilistic analyses to assess uncertainty and variability of concentrations

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of PCE-contaminated groundwater and drinking water; and (7) EPANET 2, used to conduct extended-period hydraulic and water-quality simulations of the Tarawa Terrace water-distribution system. Through historical reconstruction, monthly concentrations of PCE in groundwater and in finished water distributed from the Tarawa Terrace WTP to residents of Tarawa Terrace were determined.

Based on field data, modeling results, and the historical reconstruction process, the following conclusions are made:

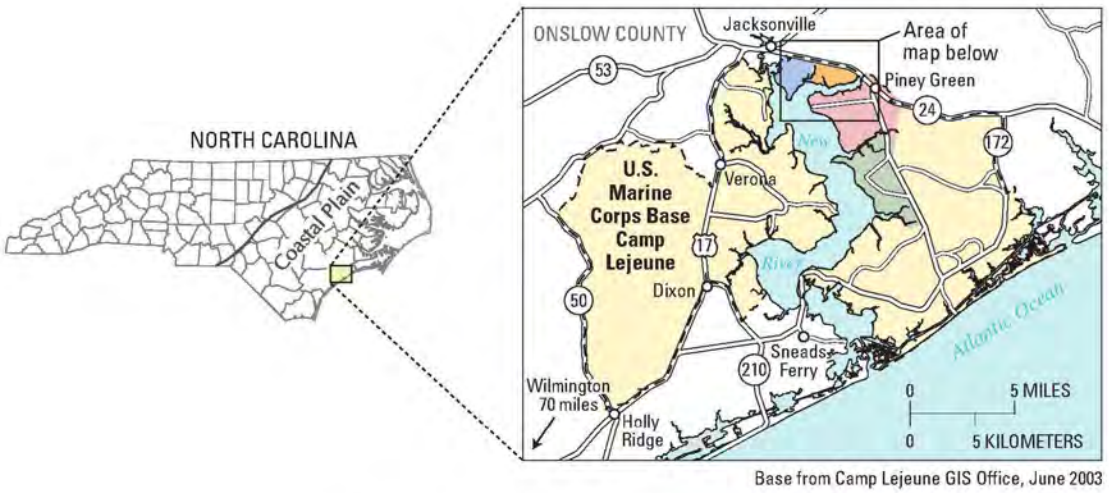
- Simulated PCE concentrations exceeded the current maximum contaminant level (MCL) of 5 micrograms per liter (µg/L) at water-supply well TT-26 for 333 months—January 1957–January 1985.
- The maximum simulated PCE concentration at well TT-26 was 851 µg/L during July 1984; the maximum measured PCE concentration was 1,580 µg/L during January 1985.
- Simulated PCE concentrations exceeded the current MCL of 5 µg/L in finished water at the Tarawa Terrace WTP for 346 months—November 1957–February 1987.
- The maximum simulated PCE concentration in finished water at the Tarawa Terrace WTP was 183 µg/L during March 1984; the maximum measured PCE concentration was 215 µg/L during February 1985.
- Simulation of PCE degradation by-products—TCE, *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride—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 degradation by-products in finished water at the Tarawa Terrace WTP 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.
- Based on water-supply well scheduling analyses, finished water exceeding the current MCL for PCE (5 µg/L) at the Tarawa Terrace WTP could have been delivered as early as December 1956 and no later than June 1960.
- Based on probabilistic analyses, the most likely dates that finished water first exceeded the current MCL for PCE ranged from October 1957 to August 1958 (95 percent probability), with an average first exceedance date of November 1957.
- Exposure to drinking water contaminated with PCE and PCE degradation by-products ceased after February 1987 when the Tarawa Terrace WTP was closed.

Introduction

The Agency for Toxic Substances and Disease Registry (ATSDR), an agency of the U.S. Department of Health and Human Services, is conducting an epidemiological study to evaluate whether in utero and infant (up to 1 year of age) exposures to drinking water contaminated with volatile organic compounds (VOCs) at U.S. Marine Corps Base Camp Lejeune, North Carolina (Plate 1), were associated with specific birth defects and childhood cancers. The study includes births occurring during the period 1968–1985 to women who resided in family housing at Camp Lejeune. The first year of the study, 1968, was chosen because North Carolina computerized its birth certificates starting that year. The last year of the study, 1985, was chosen because the most contaminated water-supply wells were removed from regular service that year. ATSDR is using water-modeling techniques to provide the epidemiological study with quantitative estimates of monthly contaminant concentrations in finished drinking water[6] because contaminant concentration data and exposure information are limited. Results obtained by using water-modeling techniques, along with information from the mother on her water use, can be used by the epidemiological study to estimate the level and duration of exposures to the mother during her pregnancy and to the infant (up to 1 year of age). Using water-modeling techniques in such a process is referred to as historical reconstruction (Maslia et al. 2001).

Three water-distribution systems have historically supplied drinking water to family housing at U.S. Marine Corps Base Camp Lejeune—Tarawa Terrace, Holcomb Boulevard, and Hadnot Point (Plate 1, Figure A1).

[6] For this study, finished drinking water is defined as groundwater that has undergone treatment at a water treatment plant and is delivered to a person's home. The concentration of contaminants in treated water at the water treatment plant is considered the same as the concentrations in the water delivered to a person's home. This assumption is tested and verified in the Chapter J report (Sautner et al. In press 2007). Hereafter, the term "finished water" will be used.



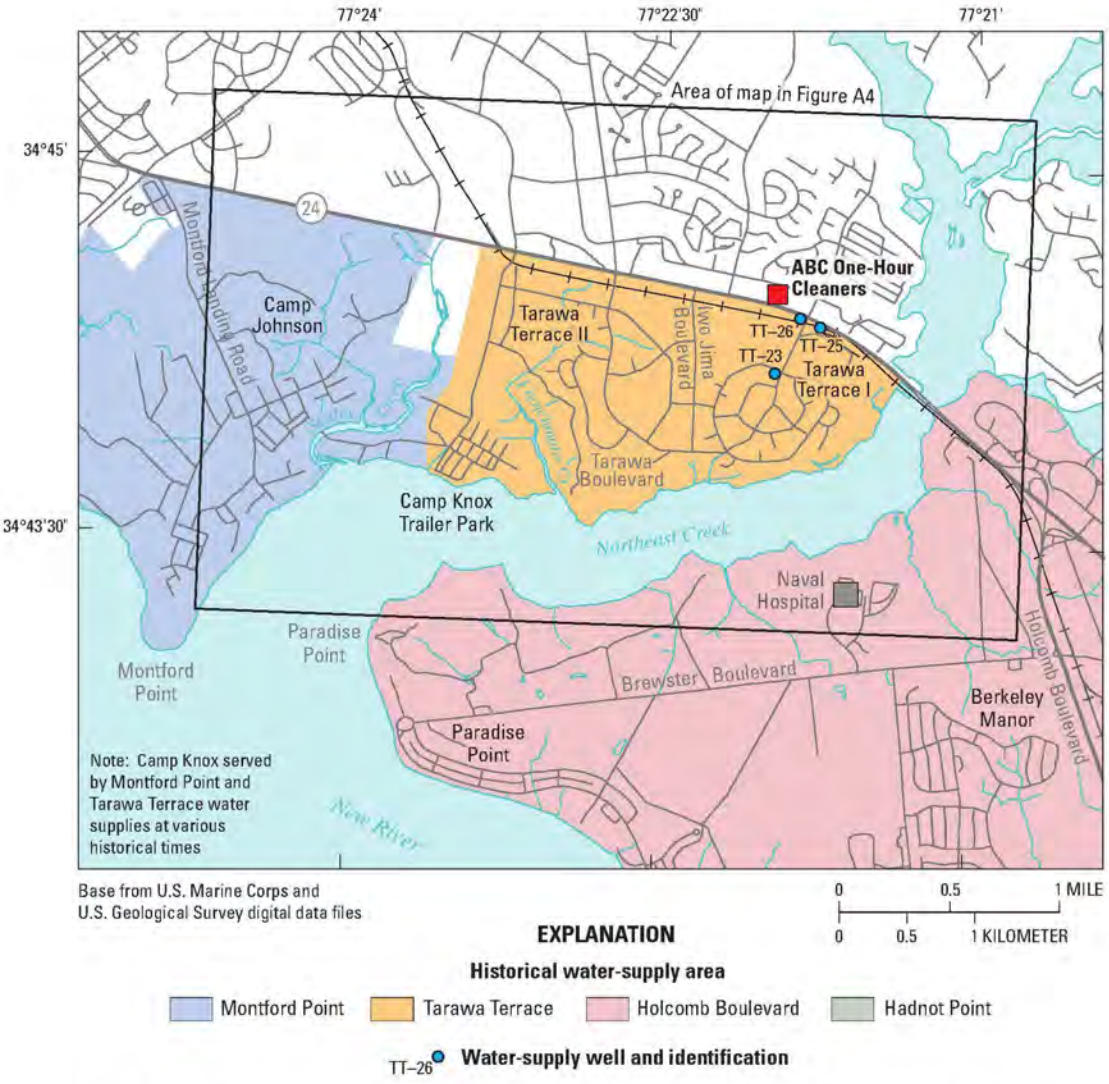


Figure A1. Selected base housing and historical water-supply areas, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Two of the water-distribution systems were contaminated with VOCs. Tarawa Terrace was contaminated mostly with tetrachloroethylene (PCE), and Hadnot Point was contaminated mostly with trichloroethylene (TCE). Historical information and data have indicated that one source of contamination—ABC One-Hour Cleaners (Figure A1)—was responsible for contaminating Tarawa Terrace water-supply wells (Shiver 1985). Water-supply data and operational information indicate that Tarawa Terrace wells supplied water solely to the Tarawa Terrace water treatment plant (WTP). Additionally, the Tarawa Terrace water-distribution system was operated independently of the other two water-distribution systems (Holcomb Boulevard and Hadnot Point). Therefore, analyses presented in this Summary of Findings and in reports described herein refer solely to Tarawa Terrace and vicinity. Future analyses and reports will present information and data about contamination of the Hadnot Point water-distribution system.

Previous Studies and Purpose of the Current Investigation

Only a small number of studies have evaluated the risk of birth defects and childhood cancers from exposures to drinking water contaminated with VOCs. These include, for example, studies by Cohn et al. (1994), Bove et al. (1995, 2002), Costas et al. (2002), Massachusetts Department of Public Health (1996), and the New Jersey Department of Health and Senior Services (2003). Five studies that have evaluated exposures to TCE and PCE in drinking water and adverse birth outcomes are summarized in Table A1. Compared to

Table A1. Summary of trichloroethylene and tetrachloroethylene study characteristics and results.[1]

[OR, odds ratio; TCE, trichloroethylene; PCE, tetrachloroethylene; SGA, small for gestational age; LBW, low birth weight; NTD, neural tube defects; MBW, mean birth weight; MBWD, mean birth weight difference; VLBW, very low birth weight; GIS, geographic information system; =, equal; ≤, less than or equal to; –, negative; g, gram; yr, year]

Study site and period	Outcome	Number of subjects	Exposure	Results (OR)[2]
Arizona 1969–1981 (Goldberg et al. 1990)	Cardiac defects	365 cases	1st trimester residence (or employment) in area of TCE contamination	Prevalence ratio = 2.58
Woburn, Massachusetts 1975–1979 (MDPH,CDC 1996)	SGA preterm birth birth defects fetal death	2,211 births 19 fetal deaths	Modeled distribution system to estimate monthly exposures; address at delivery	SGA = 1.55; LBW ≤1.0; preterm delivery ≤ 1.0; **fetal death = 2.57; NTD = 2.21; cleft palate = 2.21; heart defects = 0.40; eye defects = 4.41;** cluster of choanal atresia
1969–1979	LBW	5,347 births		
Northern New Jersey 1985–1988 (Bove et al. 1995)	SGA preterm birth birth defects fetal death	80,938 live births, 594 fetal deaths	Estimated average monthly levels of solvents based on tap water sample data and address at delivery	TCE: SGA ≤1.0; preterm birth = 1.02; NTD = 2.53; oral clefts = 2.24; heart defects = 1.24; fetal death ≤ 1.0 PCE: SGA ≤ 1.0; preterm birth ≤ 1.0; NTD = 1.16; oral clefts = 3.54; heart defects = 1.13; fetal death ≤ 1.0
Camp Lejeune, North Carolina 1968–1985 (ATSDR 1998)	MBW SGA preterm birth	31 births exposed to TCE, 997 unexposed; 6,117 births exposed to PCE, 5,681 births unexposed	Residence in a base housing area known to have received contaminated water	TCE: SGA = 1.5; MBWD = –139 g; preterm birth = 0.0; males: SGA = 3.9; MBWD = –312 g PCE: SGA = 1.2; MBWD = –24 g; preterm birth = 1.0; women > 35 yr: SGA = 4.0; MBWD = –205 g; women with ≥2 fetal losses: SGA = 2.5
Arizona 1979–1981 (high exposure) and 1983–1985 (post exposure) (Rodenbeck et al. 2000)	LBW VLBW full-term LBW	1,099 exposed births, 877 unexposed births	Maternal residence in target or comparison census tracts at delivery; GIS modeling of groundwater plume	TCE: LBW = 0.90; VLBW = 3.30; full-term LBW = 0.81

[1]Bove et al. (2002)
[2]Results in bold type indicate those that were calculated by the reviewing authors (Bove et al. 2002)

the aforementioned studies, the current study at Camp Lejeune is unique in that it will examine the associations between well-defined, quantitative levels of PCE and TCE in drinking water and the risk of developing specific birth defects—spina bifida, anencephaly, cleft lip, and cleft palate—childhood leukemia, and non-Hodgkin's lymphoma. The current study includes parent interviews conducted to obtain residential history, information on water consumption habits, and risk factors. Using model-derived drinking-water concentrations and interview data, associations between exposure to PCE and TCE during various time periods of interest—preconception, trimesters, entire pregnancy, and infancy (up to 1 year of age)—and the risk of particular health outcomes can be thoroughly examined.

The purpose of the analyses described in this report and associated chapter reports is to provide epidemiologists with historical monthly concentrations of contaminants in drinking water to facilitate the estimation of exposures. Because historical contaminant concentration data are limited, the process of historical reconstruction—which included water-modeling analyses—was used to synthesize information and quantify estimates of contaminant occurrences in groundwater and the water-distribution system at Tarawa Terrace.

Tarawa Terrace Chapter Reports

Owing to the complexity, uniqueness, and the number of topical subjects included in the historical reconstruction process, a number of reports were prepared that provide comprehensive descriptions of information, data, and methods used to conduct historical and present-day analyses at Tarawa Terrace and vicinity. Table A2 lists the 11 chapters (A–K) and chapter titles of reports that compose the complete description and details of the historical reconstruction process used for the Tarawa Terrace analyses. Also included in Table A2 are listings of the authors and a topical summary of each chapter report. Figure A2 shows the relation among the Chapter A report (Summary of Findings—this report), Chapters B–K reports, and the overall process of historical reconstruction as it relates to quantifying exposures and the ATSDR case-control epidemiological study. Reports for chapters B–K present detailed information, data, and analyses. Summaries of results from each chapter report are provided in Appendix A1. Readers interested in details of a specific topic, for example, numerical model development, model-calibration procedures, synoptic maps showing groundwater migration of PCE at Tarawa Terrace, or probabilistic analyses, should consult the appropriate chapter report (Table A2, Appendix A1). Also provided with the Chapter A report is a searchable electronic database—on digital video disc (DVD) format—of information and data sources used to conduct the historical reconstruction analysis. Electronic versions of each chapter report—summarized in Appendix A1—and 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*.

External Peer Review

Throughout this investigation, ATSDR has sought independent external expert scientific input and review of project methods, approaches, and interpretations to assure scientific credibility of the analyses described in the Tarawa Terrace reports. The review process has included convening an expert peer review panel and submitting individual chapter reports to outside experts for technical reviews. On March 28–29, 2005, ATSDR convened an external expert panel to review the approach used in conducting the historical reconstruction analysis and to provide input and recommendations on preliminary analyses and modeling results (Maslia 2005). The panel was composed of experts with professional backgrounds from government and academia, as well as the private sector. 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 the following recommendations:

- *Data discovery:* ATSDR should expend additional effort and resources in the area of conducting more rigorous data discovery activities. To the extent possible, the agency should augment, enhance, and refine data it is relying on to conduct water-modeling activities.
- *Chronology of events:* ATSDR should focus efforts on refining its understanding of chronological events. These need to include documenting periods of known contamination, times when water-distribution systems were interconnected, and the start of operations of the Holcomb Boulevard WTP.

Table A2. Summary of ATSDR chapter reports on topical subjects of water-modeling analyses and the historical reconstruction process, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[ATSDR, Agency for Toxic Substances and Disease Registry; VOC, volatile organic compound; PCE, tetrachloroethylene; WTP, water treatment plant]

Report chapter	Author(s)	Chapter title and reference citation	Topical summary
A	Maslia ML, Sautner JB, Faye RE, Suárez-Soto RJ, Aral MM, Grayman WM, Jang W, Wang J, Bove FJ, Ruckart PZ, Valenzuela C, Green JW Jr, and Krueger AL	Summary of Findings; Maslia et al. 2007 (this report)	Summary of detailed technical findings (found 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
B	Faye RE	Geohydrologic Framework of the Castle Hayne Aquifer System; Faye (In press 2007a)	Analyses of well and geohydrologic data used to develop the geohydrologic framework of the Castle Hayne aquifer system at Tarawa Terrace and vicinity
C	Faye RE, and Valenzuela C	Simulation of Groundwater Flow; Faye and Valenzuela (In press 2007)	Analyses of groundwater flow including developing a predevelopment (steady state) and transient groundwater-flow model
D	Lawrence SJ	Properties of Degradation Pathways of Common Organic Compounds in Groundwater; Lawrence (In press 2007)	Describes and summarizes the properties, degradation pathways, and degradation by-products of VOCs (non-trihalomethane) commonly detected in groundwater
E	Faye RE, and Green JW Jr	Occurrence of Contaminants in Groundwater; Faye and Green (In press 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
F	Faye RE	Simulation of the Fate and Transport of Tetrachloroethylene (PCE); Faye (In press 2007b)	Historical reconstruction of the fate and transport of PCE in groundwater from the vicinity of ABC One-Hour Cleaners to individual water-supply wells and the Tarawa Terrace WTP
G	Jang W, and Aral MM	Simulation of Three-Dimensional Multispecies, Multiphase Mass Transport of Tetrachloroethylene (PCE) and Associated Degradation By-Products; Jang and Aral (In press 2007)	Descriptions about the development and application of a model capable of simulating three-dimensional, multispecies, and multiphase transport of PCE and associated degradation by-products
H	Wang J, and Aral MM	Effect of Groundwater Pumping Schedule Variation on Arrival of Tetrachloroethylene (PCE) at Water-Supply Wells and the Water Treatment Plant; Wang and Aral (In press 2007)	Analysis of the effect of groundwater pumping schedule variation on the arrival of PCE at water-supply wells and the Tarawa Terrace WTP
I	Maslia ML, Suárez-Soto RJ, Wang J, Aral MM, Sautner JB, and Valenzuela C	Parameter Sensitivity, Uncertainty, and Variability Associated with Model Simulations of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water; Maslia et al. (In press 2007b)	Assessment of parameter sensitivity, uncertainty, and variability associated with model simulations of groundwater flow, contaminant fate and transport, and the distribution of drinking water
J	Sautner JB, Valenzuela C, Maslia ML, and Grayman WM	Field Tests, Data Analyses, and Simulation of the Distribution of Drinking Water; Sautner et al. (In press 2007)	Field tests, data analyses, and simulation of the distribution of drinking water at Tarawa Terrace and vicinity
K	Maslia ML, Sautner JB, Faye RE, Suárez-Soto RJ, Aral MM, Grayman WM, Jang W, Wang J, Bove FJ, Ruckart PZ, Valenzuela C, Green JW Jr, and Krueger AL	Supplemental Information; Maslia et al. (In press 2007a)	Additional information such as synoptic maps showing groundwater levels, directions of groundwater flow, and the distribution of PCE based on simulation; a complete list of references; and other ancillary information and data that were used as the basis of this study

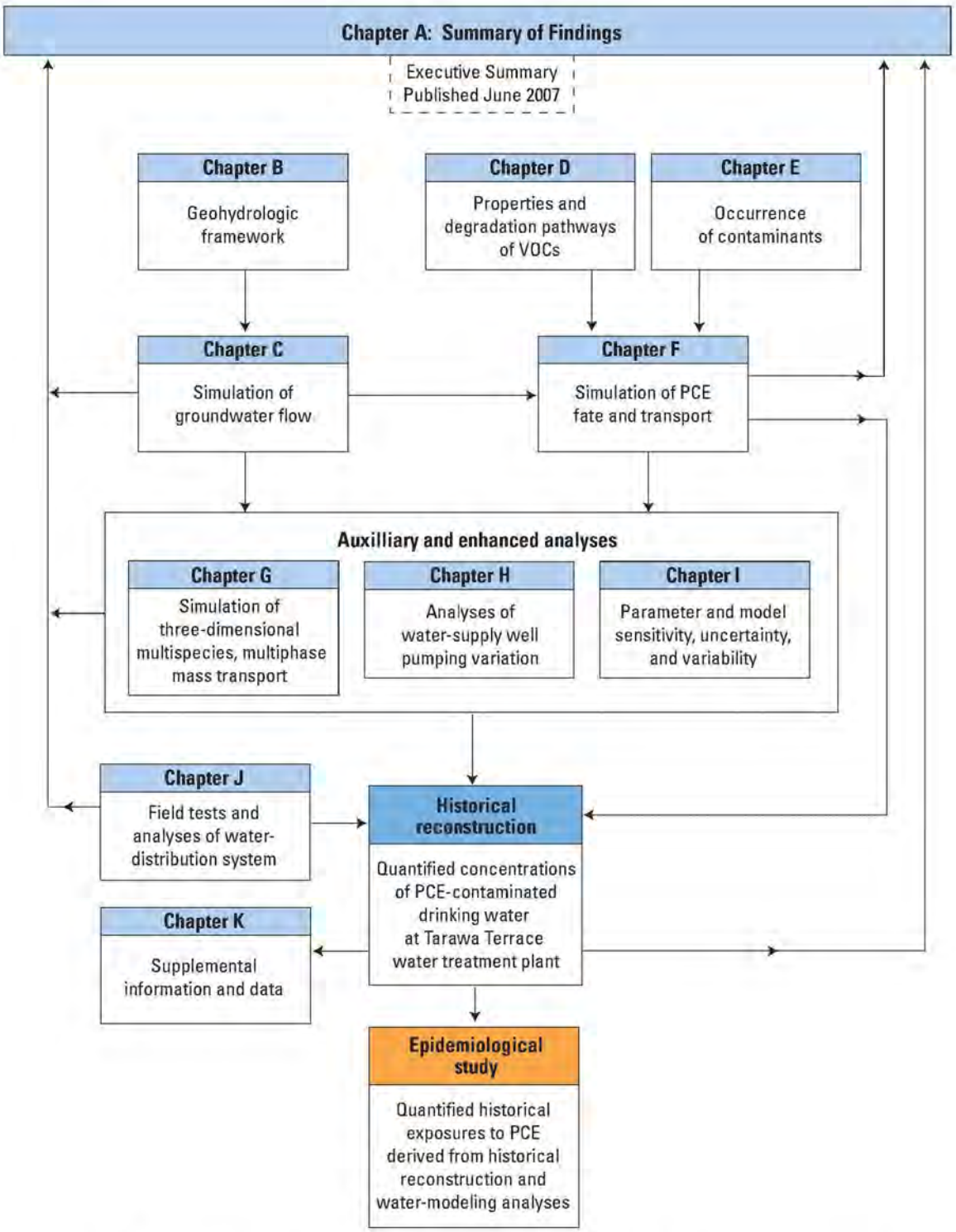


Figure A2. Relation among Chapter A report (Summary of Findings), Chapters B–K reports, historical reconstruction process, and the ATSDR epidemiological case-control study, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [VOCs, volatile organic compounds; PCE, tetrachloroethylene]

- *Groundwater modeling, Tarawa Terrace area:* Several recommendations were made with respect to groundwater modeling and associated activities for the Tarawa Terrace area, and these included: (1) refine operational schedules of water-supply wells, (2) conduct fate and dispersive transport analyses, (3) conduct sensitivity and uncertainty analyses to refine initial estimates of model parameter values, and (4) determine sensitivity of model to cell sizes and boundary conditions.[7]
- *Water-distribution system analyses:* In light of available data, the ATSDR water-modeling team should consider using more simplified mixing models (rather than complex water-distribution system models) to quantify historical exposures to drinking-water supplies. More complex modeling might be warranted only if data discovery shows that the water-distribution systems had a greater frequency of interconnectivity.

The recommendations of the external expert panel were implemented as part of the historical reconstruction analysis efforts. Results of these efforts are presented in conjunction with specific data needs, descriptions of the historical reconstruction simulations, and sensitivity analyses that are summarized in this report (Chapter A) and discussed in detail in subsequent chapter reports (B–J).

Chlorinated Solvents and Volatile Organic Compounds (VOCs)

The compounds and contaminants discussed in this report and other Tarawa Terrace chapter reports belong to a class of chemicals referred to as chlorinated solvents. The denser-than-water characteristic of liquid chlorinated solvents has led to their being called "dense nonaqueous phase liquids" (DNAPLs[8]) (Pankow and Cherry 1996). The significant volatility that characterizes chlorinated solvents also has led to these compounds being referred to as "volatile organic compounds" (VOCs). It is the property of significant volatility that has led to the greatest lack of understanding of their potential for causing groundwater contamination (Schwille 1988). Thus, VOCs are organic compounds that have a high enough vapor pressure under normal circumstances to significantly vaporize and enter the atmosphere.

In the United States, the production of chlorinated solvents, and more generally, synthetic organic chemicals, was most probably a direct result of World War I. As of 1914, PCE was manufactured as a by-product of carbon tetrachloride, and domestic production of TCE is reported to have begun during the 1920s (Doherty 2000a, b). Contamination of groundwater systems by chlorinated solvents, however, was not recognized in North America until the late 1970s.[9] The lateness of this recognition was due in part because monitoring for VOCs and nearly all other organic compounds was not common until that time. Research into the properties of chlorinated solvents and how their properties, such as density (DNAPLs) and significant volatility (VOCs), were capable of leading to severe groundwater problems was first recognized by Schwille in West Germany during the 1970s (Schwille 1988). Thus, VOCs are considered environmental pollutants, and some may be carcinogenic. Briefly described next are naming conventions used for VOCs and maximum contaminant levels (MCLs) established by the U.S. Environmental Protection Agency (USEPA) for selected VOCs.

Naming Conventions

It is common to find a confusing variety of names used to identify VOCs. For example, tetrachloroethene also is known as perchloroethylene, PCE, PERC®, and tetrachloroethylene (Table A3). The variety of different names for VOCs depends on (1) the brand name under which the product is sold, (2) the region where the compound is used, (3) the type of publication referring to the compound, (4) the popularity of the name in recently published literature, (5) the profession of the person using the name, or (6) a combination of all or part of the above. As early as the late 1800s, chemists and others recognized the need to have a consistent naming convention for chemical compounds. The International Union of Pure and Applied Chemistry (IUPAC) is an organization responsible for formal naming conventions

[7] Detailed discussions related to specific model characteristics such as geometry, cell size, boundary conditions, and more, are provided in Chapter C (Faye and Valenzuela In press 2007) and Chapter F (Faye In press 2007b) reports.

[8] Dense nonaqueous phase liquids (DNAPLs) have a specific gravity greater than water (> 1.0), and are immiscible (nonmixing) in water.

[9] Contaminants were detected in groundwater sampling by the New Jersey Department of Environmental Protection during 1978 (Cohn et al. 1994) and at Woburn, Massachusetts, during May 1979 (Massachusetts Department of Public Health 1996).

and corresponding names assigned to chemical compounds. Table A3, obtained from Lawrence (2006), lists the IUPAC names and synonyms (associated common, alternate, and other possible names) for selected VOCs detected in groundwater. The common or alternate names are used in this and all of the Tarawa Terrace reports for ease of reference to, and recognition of, previously published reports, documents, and laboratory analyses that pertain to the Tarawa Terrace area.[10]

Maximum Contaminant Levels

The maximum contaminant level or MCL is a legal threshold set by the USEPA to quantify the amount of a hazardous substance allowed in drinking water under the Safe Drinking Water Act. For example, the MCL for PCE was set at 5 micrograms per liter (µg/L) during 1992 because, given the technology at that time, 5 µg/L was the lowest level that water systems could be required to achieve. Effective dates for MCLs presented in this report are as follows: TCE and vinyl chloride (VC), January 9, 1989; PCE and *trans*-1,2-dichloroethylene (1,2-tDCE), July 6, 1992 (40 CFR, Section 141.60, Effective Dates, July 1, 2002, ed.). In this report and other Tarawa Terrace chapter reports, the current MCL for a specific VOC—for example, 5 µg/L for PCE—is used as a reference concentration to compare historically measured data and computer simulation results. These comparisons are not intended to imply (1) that the MCL was in effect at the time of sample measurement or simulated historical time or (2) that a measured or simulated concentration above an MCL was necessarily unsafe. Hereafter, the use of the term MCL should be understood to mean the current MCL associated with a particular contaminant. A complete list of MCLs for common VOCs can be found in USEPA report EPA 816-F-03-016 (2003). A complete list of effective dates for MCLs can be found in 40 CFR, Section 141.60, Effective Dates, July 1, 2002, edition.

[10]A detailed discussion and description of selected volatile organic compounds and associated degradation pathways is presented in the Chapter D report (Lawrence In press 2007).

Table A3. Names and synonyms of selected volatile organic compounds detected in groundwater.[1]

[IUPAC, International Union of Pure and Applied Chemistry; CAS, Chemical Abstract Services; —, not applicable]

IUPAC name[2]	Common or alternate name (synonym)[3]	Other possible names[3]	CAS number[2]
benzene	—	The B in BTEX, coal naptha, 1,3,5-cyclohexatriene, mineral naptha	71-43-2
1,2-dimethylbenzene	*o*-xylene	The X in BTEX, dimethyltoluene, Xylol	95-47-6
1,3-dimethylbenzene	*m*-xylene		108-38-3
1,4-dimethylbenzene	*p*-xylene		106-42-3
ethylbenzene	—	The E in BTEX, Ethylbenzol, phenylethane	100-41-4
methylbenzene	toluene	The T in BTEX, phenylmethane, Methacide, Toluol, Antisal 1A	108-88-3
chloroethene	vinyl chloride	chloroethylene, VC, monochloroethylene, monovinyl chloride, MVC	75-01-4
1,1-dichloroethene	1,1-dichloroethylene, DCE	vinylidene chloride	75-35-4
cis-1,2-dichloroethene	*cis*-1,2-dichloroethylene	1,2 DCE, Z-1,2-dichloroethene	156-59-2
trans-1,2-dichloroethene	*trans*-1,2-dichloroethylene	1,2 DCE, E-1,2-dichloroethene	156-60-2
tetrachloroethene	perchloroethylene, PCE, 1,1,2,2-tetrachloroethylene	ethylene tetrachloride, carbon dichloride, PERC®, PERK®, tetrachloroethylene	127-18-4
1,1,2-trichloroethene	1,1,2-trichloroethylene, TCE	acetylene trichloroethylene, trichloroethylene	79-01-6

[1]Lawrence (modified from 2006, In press 2007)

[2]International Union of Pure and Applied Chemistry (2006)

[3]USEPA (1995)

Historical Background

U.S. Marine Corps Base Camp Lejeune is located 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 (Figure A1). Operations began at Camp Lejeune during the 1940s. Today, nearly 150,000 people work and live on base, including active-duty personnel, dependents, retirees, and civilian employees. About two-thirds of the active-duty personnel and their dependents are less than 25 years of age.

Camp Lejeune consists of 15 different housing areas; families live in base housing for an average of 2 years. During the 1970s and 1980s, family housing areas were served by three water-distribution systems, all of which used groundwater as the source for drinking water—Hadnot Point, Tarawa Terrace, and Holcomb Boulevard (Plate 1). Hadnot Point was the original water-distribution system serving the entire base with drinking water during the 1940s. The Tarawa Terrace WTP began delivering drinking water during 1952–1953, and the Holcomb Boulevard WTP began delivering drinking water during June 1972 (S.A. Brewer, U.S. Marine Corps Base Camp Lejeune, written communication, September 29, 2005).

The Tarawa Terrace housing area was constructed during 1951 and was subdivided into housing areas I and II (Figure A1). Originally, areas I and II contained a total of 1,846 housing units and accommodated a resident population of about 6,000 persons (Sheet 3 of 18, Map of Tarawa Terrace II Quarters, June 30, 1961; Sheet 7 of 34, Tarawa Terrace I Quarters, July 31, 1984). The general area of Tarawa Terrace is bounded on the east by Northeast Creek, to the south by New River and Northeast Creek, to the west by New River, and to the north by North Carolina Highway 24 (SR 24).

The documented onset of pumping at Tarawa Terrace is unknown but is estimated to have begun during 1952. Water-supply well TT-26, located about 900 feet southeast of ABC One-Hour Cleaners (Figure A1), began operations during 1952. ABC One-Hour Cleaners—an off-base dry-cleaning facility that used PCE in the dry-cleaning process (Melts 2001)—is the only documented source of PCE contamination of groundwater resources at Tarawa Terrace (Shiver 1985). The first occurrence of PCE contamination at a Tarawa Terrace water-supply well probably occurred at well TT-26 after the onset of dry-cleaning operations at ABC One-Hour Cleaners during 1953.

The Camp Knox trailer park area was constructed during 1976 with 112 trailer spaces. An additional 75 spaces were added during 1989 allowing for a total of 187 housing units, which could accommodate a population of 629 persons (Sheet 5 of 34, Map of Knox Trailer Park Area, July 31, 1984). The Camp Knox trailer park area is located in the southwestern part of the Tarawa Terrace area and is bounded on the south by Northeast Creek (Figure A1). Camp Johnson and Montford Point are located to the west and southwest of Tarawa Terrace, respectively. Historically, the Camp Knox trailer park was served by both Tarawa Terrace and Montford Point water supplies.

During 1989, the USEPA placed U.S. Marine Corps Base Camp Lejeune and ABC One-Hour Cleaners on its National Priorities List (NPL) of sites requiring environmental investigation (also known as the list of Superfund sites). During August 1990, ATSDR conducted a public health assessment (PHA) at ABC One-Hour Cleaners. The PHA found that PCE, detected in onsite and offsite wells, was the primary contaminant of concern. Other detected contaminants included TCE, 1,2-dichloroethylene (1,2-DCE), 1,2-tDCE, 1,1-dichloroethylene (DCE), VC, benzene, and toluene (ATSDR 1990).

During 1997, ATSDR completed a PHA for Camp Lejeune which concluded that estimated exposures to VOCs in drinking water were significantly below the levels shown to be of concern in animal studies. Thus, ATSDR determined that exposure to VOCs in on-base drinking water was unlikely to result in cancer and noncancer health effects in adults. However, because scientific data relating to the harmful effects of VOCs on a child or a fetus were limited, ATSDR recommended conducting an epidemiological study to assess the risks to infants and children during in utero exposure to chlorinated solvents (for example, PCE and TCE) contained in on-base drinking water (ATSDR 1997).

Following this recommendation, during 1998 ATSDR published a study of adverse birth outcomes (ATSDR 1998). ATSDR used various databases to evaluate possible associations between maternal exposure to contaminants contained in drinking water on the base and mean birth weight deficit, preterm birth (less than 37 weeks gestational age), and small for gestational age (SGA). To identify women living in base housing when they delivered, birth certificates were collected

for live births that occurred January 1, 1968—December 31, 1985. The study found that exposure to PCE in drinking water was related to an elevated risk of SGA for mothers older than 35 years or who experienced two or more prior fetal losses (ATSDR 1998; Sonnenfeld et al. 2001). The study could not, however, evaluate childhood cancers and birth defects because the study relied solely on birth certificates to ascertain adverse birth outcomes.[11] However, because this study used incorrect information on the start-up date for the Holcomb Boulevard WTP,[12] errors were made in assigning exposures to the mothers. Therefore, this study is being re-analyzed using the results from the historical reconstruction process and water-modeling analyses.

During 1999, ATSDR began an epidemiological study to evaluate whether in utero and infant (up to 1 year of age) exposure to VOC-contaminated drinking water was associated with specific birth defects and childhood cancers. The study includes births during 1968–1985 to women who resided at the base anytime during their pregnancy. The first year of the study, 1968, was chosen because North Carolina computerized its birth certificates starting that year. The last year of the study, 1985, was chosen because the most contaminated Tarawa Terrace water-supply wells (TT-23 and TT-26, Figure A1) were removed from regular service that year (February 1985). The study is evaluating the central nervous system defects known as neural tube defects (for example, spina bifida and anencephaly), cleft lip and cleft palate, and childhood leukemia and non-Hodgkin's lymphoma. The study consists of a multistep process that includes:

- a scientific literature review to identify particular childhood cancers and birth defects associated with exposure to VOC-contaminated drinking water,
- a telephone survey to identify potential cases,
- a medical records search to confirm the diagnoses of the reported cases, and
- a case-control study to interview parents (collect information on a mother's residential history and water use as well as potential risk factors such as a mother's occupation and illnesses during pregnancy) and obtain exposure estimates through water-modeling analyses and the historical reconstruction process.

During 2004, the study protocol received approval from the Centers for Disease Control and Prevention Institutional Review Board and the U.S. Office of Management and Budget.

Water-Distribution Investigation

Given the paucity of measured historical contaminant-specific data and the lack of historical exposure data during most of the period relevant to the epidemiological study (January 1968–December 1985), ATSDR decided to apply the concepts of historical reconstruction to synthesize and estimate the spatial and temporal distributions of contaminant-specific concentrations in the drinking-water supply at Tarawa Terrace. Historical reconstruction typically includes the application of simulation tools, such as models, to recreate (or synthesize) past conditions. For this study, historical reconstruction included the linking of groundwater fate and transport models with materials mass balance (simple mixing) and water-distribution system models (Table A4). The primary focus for the investigation of the Tarawa Terrace historical reconstruction analyses was the fate and transport of, and exposure to, a single constituent—PCE. Additional and enhanced analyses that relate to degradation by-products of PCE—TCE, 1,2-tDCE, and VC—also are presented (Figure A2). Based on groundwater and water-quality data collection and analyses by Shiver (1985), PCE originating from the site of ABC One-Hour Cleaners is considered the primary VOC compound responsible for contaminating the Tarawa Terrace water-supply wells.

Models Used for Water-Distribution Investigation

Applying simulation tools or models to reconstruct historical contamination and exposure events at Tarawa Terrace and vicinity required the development of databases from diverse sources of information such as well and geohydrologic analyses, computations of PCE mass at the ABC One-Hour Cleaners site and within the Tarawa Terrace and Upper Castle Hayne aquifers, and analyses and assessment of

[11] Birth defects are only poorly ascertained using birth certificates; childhood cancers are not included on birth certificates.

[12] Current information from the Camp Lejeune Public Works Department Utilities Section indicates that the Holcomb Boulevard WTP began supplying finished water to areas serviced by the Holcomb Boulevard WTP (Plate 1) during June 1972 (S.A. Brewer, U.S. Marine Corps Base Camp Lejeune, written communication, September 29, 2005).

Table A4. Analyses and simulation tools (models) used to reconstruct historical contamination events at Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[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)

historical and present-day (2002) operations of the water-distribution system serving Tarawa Terrace.[13] A complete list of analysis and simulation tools used to reconstruct historical contamination and exposure events at Tarawa Terrace and vicinity is provided in Table A4. Information and data 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.[14] 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 specie 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.

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 was developed by the Multimedia Simulations Laboratory (MESL) at the Georgia Institute of Technology (Jang and Aral 2005, 2007, In press 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, In press 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 the 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, 2007). Based on expert peer review of this approach (Maslia 2005) and exhaustive reviews of historical data—including water-supply well and WTP operational data when available—study staff concluded that the Tarawa Terrace WTP and water-distribution system was not interconnected with other water-distribution systems at Camp Lejeune for any substantial time periods (greater than 2 weeks).[15] Thus, all water

[13] A comprehensive list of references used to gather, analyze, and assemble information and data for the Tarawa Terrace water-distribution investigation is provided on the electronic media (DVD) accompanying this report and in the Chapter K report (Maslia et al. In press 2007a).

[14] Predevelopment or steady-state refers to groundwater conditions prior to or after the cessation of all water-supply well pumping activity.

[15] The term "interconnection" is defined in this study as the continuous flow of water in a pipeline from one water-distribution system to another for periods exceeding two weeks. Pipelines did connect two or more water-distribution systems, but unless continuous flow was documented, the water-distribution systems were assumed not to be interconnected.

arriving at the WTP was assumed to originate solely from Tarawa Terrace water-supply wells (Faye and Valenzuela In press 2007; Faye In press 2007b) and to be completely and uniformly mixed prior to delivery to residents of Tarawa Terrace through the network of distribution system pipelines and storage tanks. Based on these information and data, study staff concluded that a simple mixing model approach, based on the principles of continuity and conservation of mass, would provide a sufficient level of detail and accuracy to estimate monthly PCE exposure concentrations at Tarawa Terrace.[16] Thus, results of the monthly flow-weighted average PCE-concentration computations were provided to agency health scientists and epidemiologists to assess population exposure to PCE.

Data Needs and Availability

The historical reconstruction process required information and data describing the functional and physical characteristics of the groundwater-flow system, the chemical specific contaminant (PCE) and its degradation by-products, and the water-distribution system. Required for the successful completion of the historical reconstruction process, specific data can be categorized into four generalized information types that relate to: (1) aquifer geometry and hydraulic characteristics (for example, horizontal hydraulic conductivity, effective porosity, and dispersivity); (2) well-construction, capacity, and pumpage data (for example, drilling dates, well depth, operational dates, and quantities of pumped groundwater by month); (3) chemical properties and transport parameters (for example, partition coefficients, sorption rate, solubility, and biodegradation rate); and (4) water-distribution system design and operation data (for example, monthly delivery of finished water from the Tarawa Terrace WTP, network geometry and materials of pipelines, and size and location of storage tanks). Availability of specific data, methods of obtaining data, assessment of the reliability of the data, and implications with respect to model assumptions and simulations are discussed in detail in chapter reports B–J (Table A2 and Appendix A1).

[16] This assumption is tested and verified in the Chapter J report (Sautner et al. In press 2007) of this study.

Ideally, data collection in support of the historical reconstruction process is through direct measurement and observation. In reality, however, data collected are not routinely available by direct measurement and must be recreated or synthesized using generally accepted engineering analyses and methods (for example, modeling analyses). Additionally, the reliability of data obtained by direct measurement or observation must be assessed in accordance with methods used to obtain the data. Issues of data sources and the methods used to obtain data that cannot be directly measured, or are based on methods of less accuracy, ultimately reflect on the credibility of simulation results. The methods for obtaining the necessary data for the historical reconstruction analysis were grouped into three categories (ATSDR 2001):

- *Direct measurement or observation*—Data included in this category were obtained by direct measurement or observation of historical data and are verifiable by independent means. Data obtained by direct measurement or observation still must be assessed as to the methods used in measuring the data. For example, in the Chapter C report, Faye and Valenzuela (In press 2007) discuss that water-level data obtained from properly constructed monitor wells using electric- or steel-tape measurements are more reliable than water-level data obtained from water-supply wells using airline measurements. Of the three data categories discussed, data obtained by direct measurement were the most preferred in terms of reliability and least affected by issues of uncertainty. Examples of such data included aquifer water levels, PCE concentrations in water-supply wells and in finished water at the WTP, and PCE concentration at the location of the contaminant source (ABC One-Hour Cleaners).
- *Quantitative estimates*—Data included in this category were estimated or quantified using generally accepted computational methods and analyses, for example, monthly infiltration or recharge rates to the Castle Hayne aquifer system and estimates of contaminant mass in the vicinity of ABC One-Hour Cleaners and the Tarawa Terrace and Upper Castle Hayne aquifers.
- *Qualitative description*—Data included in this category were based on inference or were synthesized using surrogate information, for example, water-supply well operational information, retardation factors, and aquifer dispersivity. Of the three data categories described, data derived by qualitative description were the least preferred in terms of reliability and the most affected by issues of uncertainty.

Chronology of Events

To reconstruct historical exposures, a reliable chronology related to operations of the identified source of the PCE contamination, ABC One-Hour Cleaners, and of water-supply facilities (wells and the WTP) is of utmost importance. This information has a direct impact on the reliability and accuracy of estimates derived for the levels and duration of exposure to contaminated drinking water. Using a variety of information sources and references, events related to water supply and contamination of groundwater and drinking water at Tarawa Terrace and vicinity are shown graphically and explained in Figure A3. Examples of information sources and references used to develop the chronology of events shown in Figure A3 include: (1) capacity and operational histories of Tarawa Terrace water-supply wells and the WTP (Faye and Valenzuela In press 2007), (2) depositions from the owners of ABC One-Hour Cleaners (Melts 2001), (3) identification and characterization of the source of PCE contamination (Shiver 1985), and (4) laboratory analyses of samples from water-supply wells (Granger Laboratories 1982) and the WTP (CLW 3298-3305).

One of the purposes of Figure A3 is to present, in a graphical manner, the relation among water supply, contamination events, exposure to contaminated drinking water in family housing areas, selected simulation results, and the time frame of the epidemiological case-control study. For the first time, all of these different types of information and data sources are summarized in one document that is believed to be an accurate reconciliation of chronological events that relate to Tarawa Terrace and vicinity. Three events are noteworthy: (1) the year shown for the start of operations of ABC One-Hour Cleaners (1953) is used as the starting time for PCE contamination of groundwater in the fate and transport modeling of PCE, (2) sampling events and PCE concentration values of tap water are shown for 1982, and (3) the closure of the Tarawa Terrace WTP is shown as occurring during March 1987. Care has been taken to assure that chronological event information and data required for modeling analyses and the historical reconstruction process (1) honor original data and information sources, (2) are consistent and in agreement with all Tarawa Terrace chapter reports, and (3) reflect the most up-to-date information.

Occurrence of Contaminants in Groundwater[17]

Detailed analyses of concentrations of PCE at groundwater sampling locations and at Tarawa Terrace water-supply wells during the period 1991–1993 were sufficient to estimate the mass, or amount, of PCE remaining in the Tarawa Terrace 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 during field investigations of 1987–1993. These analyses are presented in Faye and Green (In press 2007) and are summarized in Table A5. This information and data were necessary to develop accurate and reliable databases to conduct model simulations of the fate and transport of PCE from its source—ABC One-Hour Cleaners—to Tarawa Terrace water-supply wells and WTP. The total mass of PCE computed in groundwater and within the unsaturated zone during the period 1953–1985 equals about 6,000 pounds and equates to a volume of about 430 gallons (gal).[18] This volume represents an average minimum loss rate of PCE to the

Table A5. Computed volume and mass of tetrachloroethylene in the unsaturated and saturated zones, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.[1]

[PCE, tetrachloroethylene]

Zone	Dates of computation	Volume, in gallons[2]	Average annual contribution of PCE, 1953–1985	
			In gallons	In grams
Unsaturated[3]	1987–1993	190	6	36,340
Saturated[4]	1991–1993	240	7	42,397
Total		**430**	**13**	**78,737**

[1]Refer to Chapter E report (Faye and Green In press 2007) for specific computational details

[2]Density of PCE is 1.6 grams per cubic centimeter, or about 101 pounds per cubic foot

[3]Zone above water table in vicinity of ABC One-Hour Cleaners

[4]Tarawa Terrace and Upper Castle Hayne aquifers

[17] For detailed analyses and discussions of occurrence of contaminants in groundwater at Tarawa Terrace and vicinity, refer to the Chapter E report (Faye and Green In press 2007).

[18] Typically, such volumes also are expressed in terms of 55-gal drums. The aforementioned volume of 430 gal of PCE is equivalent to 7.8 drums of PCE.

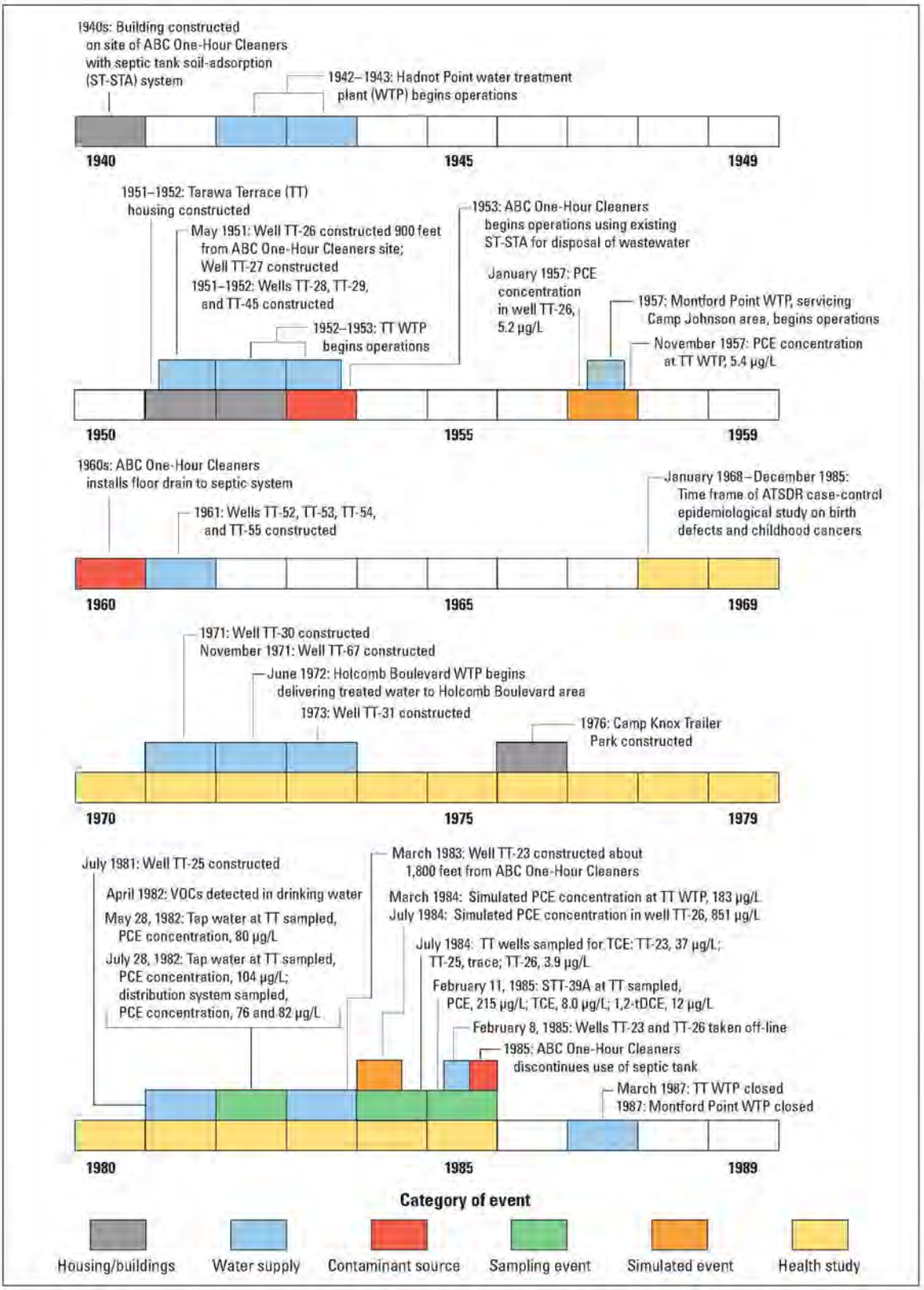


Figure A3. Chronology of events related to supply and contamination of drinking water, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. (STT-39A is the pump house associated with storage tank STT-39.) [ft, foot; µg/L, microgram per liter; VOC, volatile organic compound; PCE, tetrachloroethylene; TCE, trichloroethylene; 1,2-tDCE, *trans*-1,2-dichloroethylene; current maximum contaminant levels: PCE 5 µg/L, TCE 5 µg/L, 1,2-tDCE 100 µg/L]

subsurface at ABC One-Hour Cleaners of about 13 gallons per year during the period 1953–1985. This PCE loss rate should be considered a minimum because (1) the quantity of PCE removed from the aquifers at Tarawa Terrace water-supply wells during 1953–1985 is unknown, (2) biodegradation of PCE to daughter products of TCE, 1,2-tDCE, and VC was probably occurring in the aquifers during and prior to 1991, and (3) PCE mass adsorbed to the sands and clays of the aquifer porous media and was not accounted for during the PCE mass computations. Pankow and Cherry (1996) indicate that computations of contaminant mass similar to those summarized here and described in detail in Faye and Green (In press 2007) represent only a small fraction of the total contaminant mass in the subsurface. Comparing the estimated volume of 430 gal of PCE (7.8 55-gal drums) computed by Faye and Green (In press 2007) with documented contaminant plumes in sand-gravel aquifers indicates that the contaminant mass in the subsurface at Tarawa Terrace would have been ranked as the third greatest volume of contaminant mass among seven contamination sites in the United States listed in a table provided in Mackay and Cherry (Table 1, 1989).

Relation of Contamination to Water Supply, Production, and Distribution

Historically, groundwater was used as the sole source of water supply for Camp Lejeune, and in particular, Tarawa Terrace. Of critical need in terms of historical reconstruction analysis, was information and data on the monthly raw water production of supply wells (to enable computations of flow-weighted drinking-water concentrations), and the distribution of finished water to family housing areas. The supply of drinking water to Tarawa Terrace was composed of two components: (1) the supply of water from groundwater wells to the Tarawa Terrace WTP and (2) the delivery of finished water from the WTP through the network of pipelines and storage tanks of the water-distribution system. The placement of water-supply wells into service and their permanent removal from service are critical to the analysis and simulation of contamination events. For example, water-supply well TT-26 was constructed during May 1951, probably placed into service during 1952, and was permanently taken off-line (service terminated) February 8, 1985. The Tarawa Terrace WTP began operations during 1952–1953 and was closed during March 1987 (Figure A3). All groundwater wells in the Tarawa Terrace area supplied untreated (or raw) water to a central treatment facility—the Tarawa Terrace WTP (Figure A4). Information pertaining to well-capacity histories, including construction, termination of service, and abandonment dates and spatial coordinate data are described in detail in Chapter C (Faye and Valenzuela In press 2007).

After treatment at the Tarawa Terrace WTP, finished water was distributed through pipelines to storage tanks, residential housing, military facility buildings, and shopping centers.[19] Information and data related to the water-distribution system (Plate 1; Figure A4) were gathered as part of data discovery and field investigation activities in support of the ATSDR epidemiological case-control study. The network of pipelines and storage tanks shown on Plate 1 and in Figure A4 represents present-day (2004) conditions, described in detail in Chapter J (Sautner et al. In press 2007). Based on a review of historical operating and housing information, the historical water-distribution system serving Tarawa Terrace was considered very similar and nearly identical to the present-day (2004) water-distribution system—the exception being two pipelines that were put into service during 1987 after the closing of the Tarawa Terrace and Camp Johnson WTPs. One pipeline, constructed during 1984, follows SR 24 northwest from the Holcomb Boulevard WTP and presently is used to supply ground storage tank STT-39 with finished water (Plate 1, Figure A4). The other pipeline, constructed during 1986, trends east-west from the Tarawa Terrace II area to storage tank SM-623 and presently is used to supply finished water from Tarawa Terrace to elevated storage tank SM-623. Historically (1952–1987), the Tarawa Terrace water-distribution system was operated independently of, and was not interconnected with, the Montford Point or Holcomb Boulevard water-distribution systems.[20]

Based on epidemiological considerations, historical reconstruction results were provided at monthly intervals. Ideally, these analyses require monthly groundwater pumpage data for the historical period. However, pumpage data were limited and were available on a monthly basis solely for 1978 and intermittently during the period of 1981–1985. Faye and Valenzuela (In press 2007)

[19] Based on an analysis of building type and usage in Tarawa Terrace, greater than 90% of the buildings were used for residential housing.

[20] Although the two pipelines discussed were constructed during 1984 and 1986, historical records such as water plant operator notes indicate that the pipelines did not convey finished water on a continuous basis prior to 1987.

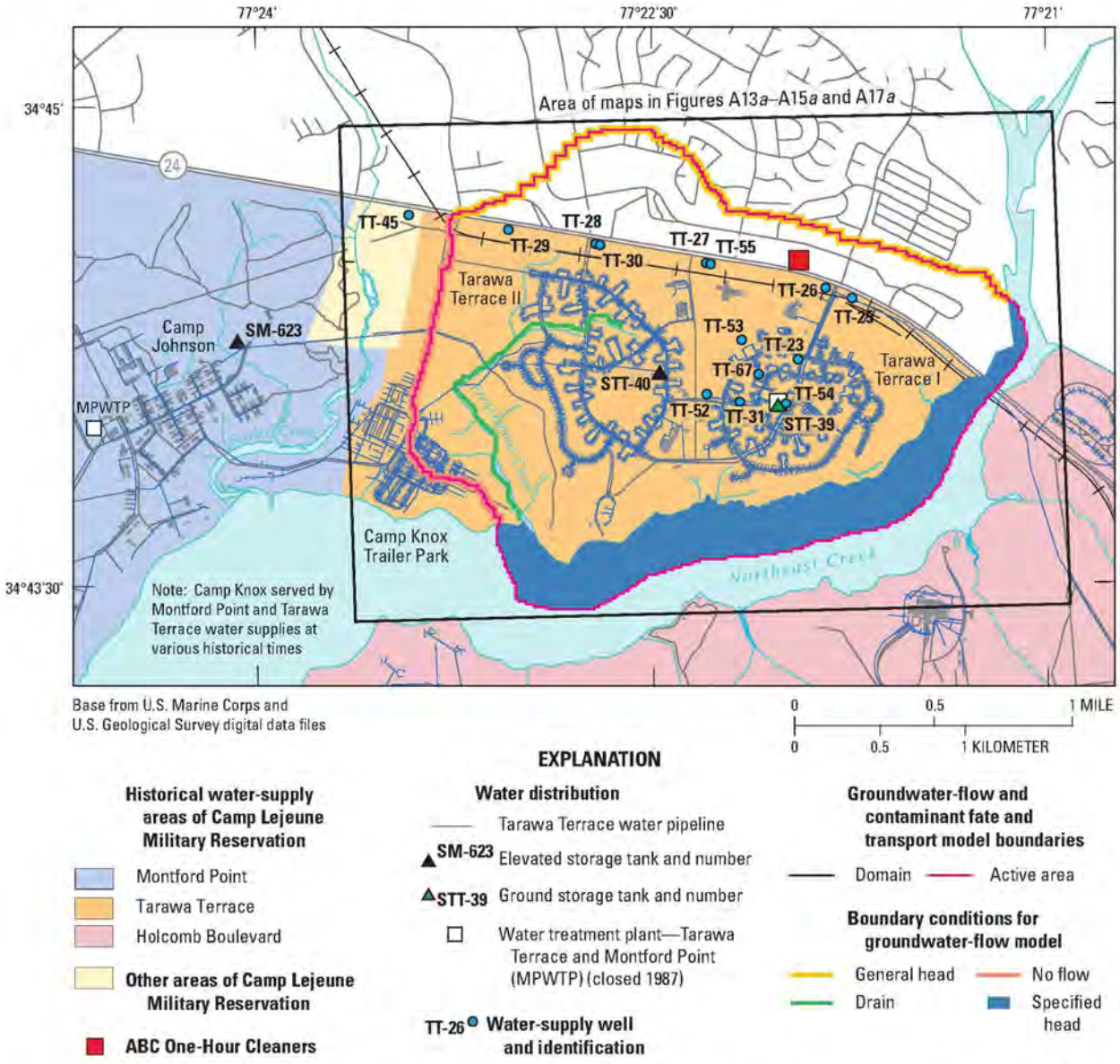


Figure A4. Location of groundwater-flow and contaminant fate and transport modeling areas and water-supply facilities used for historical reconstruction analyses, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

provide details regarding groundwater pumpage including sources and capacity history. Where pumpage data were missing or incomplete, aquifer water-level and water-supply data, in conjunction with model simulation, were used to synthesize and reconstruct monthly water-supply well operations. Tarawa Terrace water-supply well operations—in terms of online dates and off-line dates for water supply—are presented graphically in Figure A5. Once a well was put in service, it was assumed to operate continuously for modeling purposes until it was permanently taken off-line—the exception being temporary shut downs for long-term maintenance. Breaks in continuous operations, such as those for wells TT-26 and TT-53, also are shown in Figure A5 and are based on documented information detailing periods of maintenance for specific wells. For example, water-supply well TT-26 was shut down for maintenance during July–August 1980 and January–February 1983 (Faye and Valenzuela In press 2007). Table A6 lists the specific month and year for the start of service for all Tarawa Terrace water-supply wells and the specific month and year for the end of service. Because raw water from all groundwater wells was

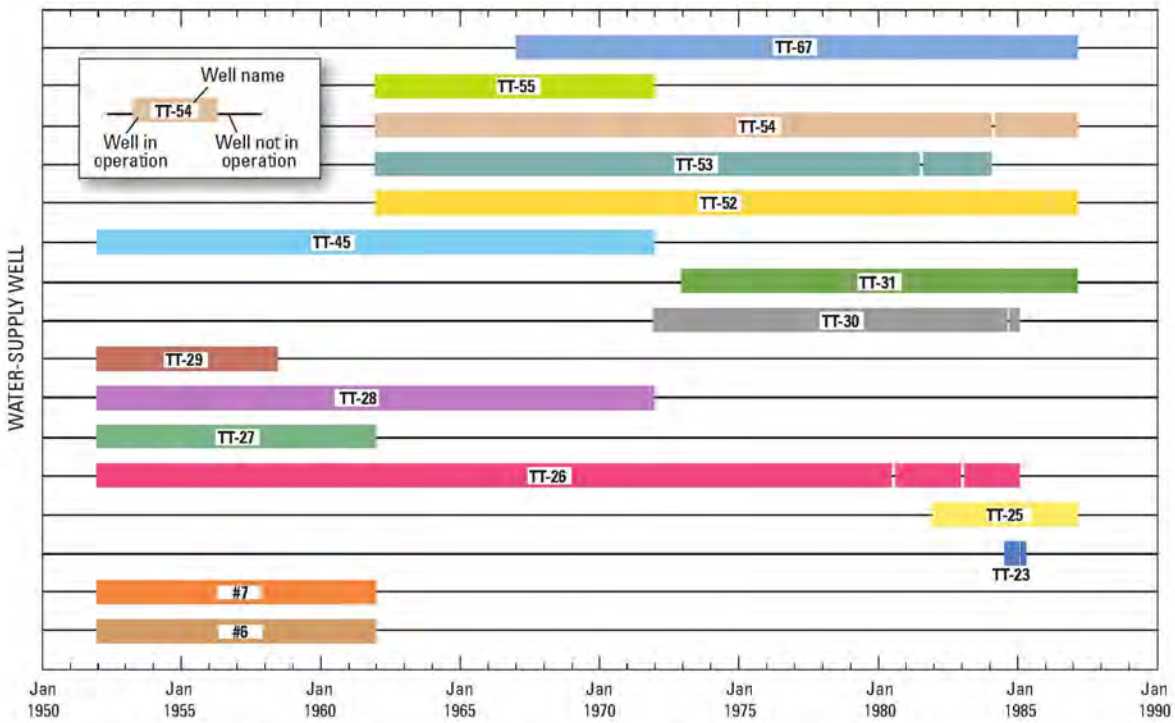


Figure A5. Historical operations of water-supply wells, 1952–87, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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

mixed at the Tarawa Terrace WTP prior to treatment and distribution to Tarawa Terrace housing areas, the start-up and shut-down dates of specific water-supply wells, such as TT-26 and TT-23, were critical to accurately determining the concentration of contaminants in finished water delivered from the Tarawa Terrace WTP.

Total annual groundwater pumpage by well for all Tarawa Terrace water-supply wells is shown graphically in Figure A6. Refer to the Chapter C report (Faye and Valenzuela In Press 2007) for data sources used to derive Figure A6. This illustration also shows the contribution to pumpage by individual wells on an annual basis. For example, during 1978 total annual groundwater pumpage was 327 million gallons (MG) contributed by wells TT-26 (64.7 MG), TT-30 (25.9 MG), TT-31 (46.2 MG), TT-52 (48.1 MG), TT-53 (27.7 MG), TT-54 (62.8 MG), and TT-67 (51.7 MG) (Faye and Valenzuela In press 2007). Thus, well TT-26 and TT-54 contributed about 20 percent (%) each to the total annual pumpage for 1978, and well TT-30 contributed about 8%. This total annual groundwater pumpage is in agreement with the average rate of water delivered to the Tarawa Terrace WTP in 1978 of 0.90 million gallons per day, reported by Henry Von Oesen and Associates Inc. (1979).

The historical Tarawa Terrace water-distribution system was probably nearly identical to the present-day (2004) water-distribution system. Operational characteristics of the present-day water-distribution system were used for historical reconstruction analyses and were based on data gathered during field investigations (Sautner et al. 2005, Maslia et al. 2005). Delivery rates of finished water on a monthly basis during 2000–2004 are listed in Table A7 and shown graphically in Figure A7. For the 5-year period 2000–2004, the mean monthly delivery of finished water to the Tarawa Terrace water-distribution system was estimated to be 18.5 MG.[21] Monthly variations were most probably due to troop deployments. Monthly delivery data indicate that relatively high rates of finished water were delivered during the months of April, May, June, and July of 2000 and 2001. In addition, May and June of 2000 were the months of greatest delivery of finished water to the Tarawa Terrace water-distribution system—an estimated 30.9 MG of finished water during each month (Figure A7, Table A7).

[21] Since March 1987, finished water for the Tarawa Terrace water-distribution system has been provided by the Holcomb Boulevard WTP and delivered to ground storage tank STT-39 (Plate 1). See section on Field Tests and Analyses of the Water-Distribution System or the Chapter J report (Sautner et al. In press 2007).

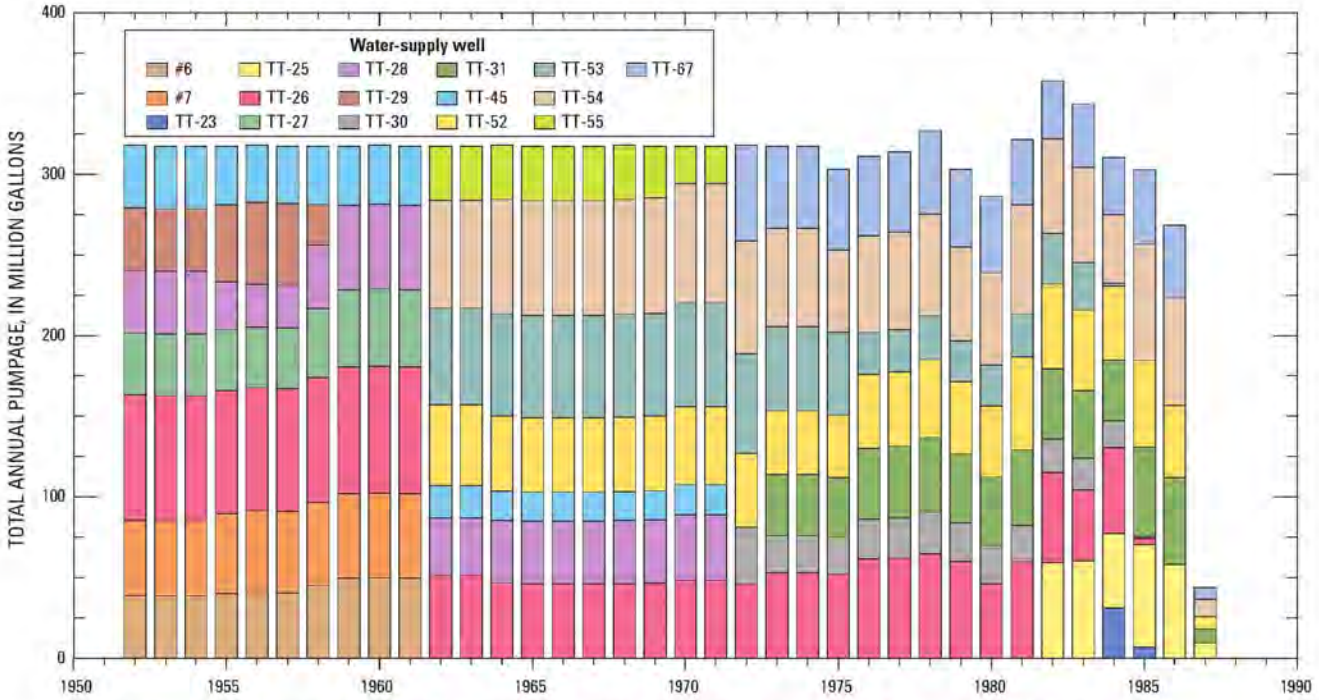


Figure A6. Total annual groundwater pumpage at water-supply wells, 1952–1987, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Table A7. Estimated monthly delivery of finished water to the Tarawa Terrace water-distribution system, 2000–2004, U.S. Marine Corps Base Camp Lejeune, North Carolina.[1,2]

[MG, million gallons; MGD, million gallons per day]

Month	Delivered finished water[3]									
	2000		2001		2002		2003		2004	
	MG	MGD	MG	MGD	MG	MGD	MG	MGD	MG	MGD
January	23.500	0.758	19.028	0.613	21.017	0.678	21.775	0.702	14.238	0.459
February	20.937	0.722	18.557	0.663	17.320	0.619	14.960	0.534	13.715	0.473
March	22.847	0.737	19.338	0.624	18.300	0.590	15.735	0.508	11.721	0.378
April	26.371	0.879	27.060	0.902	18.549	0.618	14.060	0.469	12.805	0.427
May	30.924	0.998	19.468	0.628	16.974	0.548	13.365	0.431	14.088	0.454
June	30.907	1.030	25.156	0.839	17.163	0.570	13.629	0.454	12.763	0.425
July	24.297	0.784	23.984	0.774	16.440	0.530	13.604	0.439	13.945	0.450
August	22.145	0.714	17.931	0.578	18.020	0.581	18.539	0.598	12.106	0.391
September	19.732	0.658	16.469	0.549	16.900	0.563	19.916	0.664	12.135	0.405
October	18.274	0.589	16.619	0.536	15.907	0.513	21.798	0.703	16.435	0.548
November	20.663	0.689	17.240	0.575	16.807	0.560	20.607	0.687	16.982	0.566
December	25.785	0.832	17.101	0.552	17.082	0.551	20.939	0.675	16.861	0.544

[1]Since March 1987, finished water for the Tarawa Terrace water-distribution system has been provided by the Holcomb Boulevard WTP and delivered to ground storage tank STT-39 (Plate 1)

[2]Data from Joel Hartsoe, Camp Lejeune Public Works Department Utilities Section, December 6, 2006

[3]Flow data measured at venturi meter located in building STT-39A (Tarawa Terrace pump house)

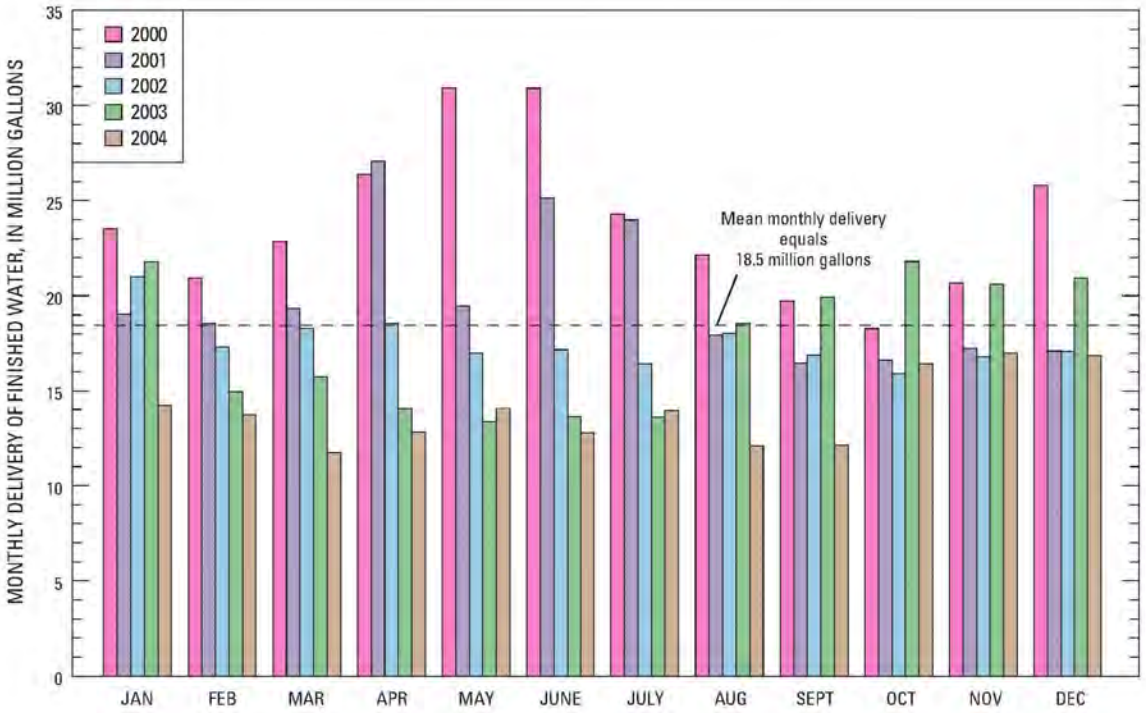


Figure A7. Estimated monthly delivery of finished water to the Tarawa Terrace water-distribution system, 2000–2004, U.S. Marine Corps Base Camp Lejeune, North Carolina. [Data from Joel Hartsoe, Camp Lejeune Public Works Department Utilities Section, December 6, 2006; flow data measured at venturi meter located in building STT-39A (Tarawa Terrace pump house)]

Additional information gathered during a field investigation of the Tarawa Terrace water-distribution system included hourly delivery rates of finished water. These hourly data were used in conjunction with water-distribution system model simulation (see section on Field Tests and Analyses of the Water-Distribution System) to determine a diurnal pattern of water use for Tarawa Terrace (Figure A8). Data from the field test show a gradually increasing demand for water occurring during 0200–0700 hours. Peak demand occurs between 1000–1400 hours, at 1800 hours, and at 2200 hours. Thus, greater amounts of water were delivered (and presumably consumed) during these time periods than during other hours of the day.

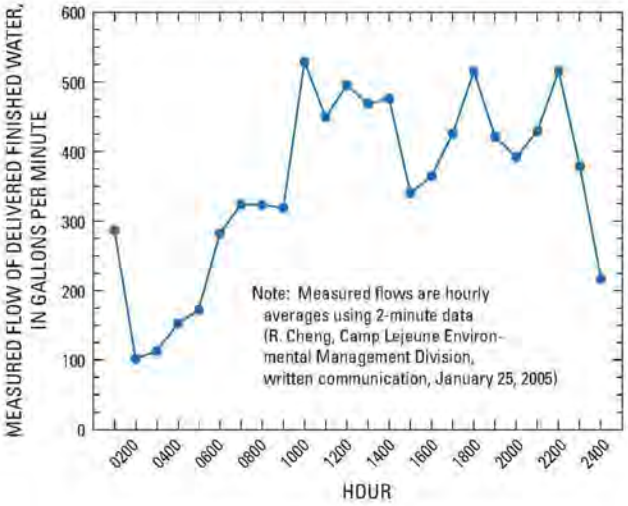


Figure A8. Measured diurnal pattern (24 hours) of delivered finished water during field test, September 22–October 12, 2004, Tarawa Terrace water-distribution system, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Hierarchical Approach for Quantifying Exposure

A simulation or modeling approach was used to reconstruct and estimate (quantify) historical concentrations of PCE in finished water delivered to residents of Tarawa Terrace. In using a simulation approach, a calibration process is used so that the combination of various model parameters—regardless of whether a model is simple or complex—appropriately reproduces the behavior of real-world systems (for example, migration of PCE) as closely as possible. The American Water Works Association Engineering Computer Applications Committee indicates that "true model calibration is achieved by adjusting whatever parameter values need adjusting until a reasonable agreement is achieved between model-predicted behavior and actual field behavior" (AWWA Engineering Computer Applications Committee 1999). A model modified in this manner is called a calibrated model (Hill and Tiedeman 2007). Calibration of models used for the Tarawa Terrace analyses was accomplished in a hierarchical or step-wise approach consisting of four successive stages or levels. Simulation results achieved for each calibration level were refined by adjusting model parameter values and comparing these results with simulation results of previous levels until results at all levels were within ranges of preselected calibration targets or measures. The step-wise order of model-calibration levels consisted of simulating (1) predevelopment (steady or nonpumping) ground-water-flow conditions, (2) transient (time varying or pumping) groundwater-flow conditions, (3) the fate and transport (migration) of PCE from its source at ABC One-Hour Cleaners to water-supply wells, and (4) the concentration of PCE in finished water at the Tarawa Terrace WTP—water from the Tarawa Terrace WTP that was delivered to residents living in family housing.

Conceptual Description of Model Calibration

The hierarchical approach to estimating the concentration of PCE in finished water from the Tarawa Terrace WTP can be conceptually described in terms of Venn or set diagrams (Borowski and Borwein 1991). Such diagrams are useful for showing logical relations between sets or groups of like items and are shown in Figure A9 for each hierarchical calibration level. At level 1 (Figure A9*a*), there may be a large number of combinations of parameters that yield solutions to predevelopment groundwater-flow conditions. However, only a smaller set—the subset of solutions indicated by circle "A" in Figure A9*a*—yields acceptable combinations of parameters for a calibrated predevelopment groundwater-flow model. For transient groundwater-flow conditions, viable solutions are indicated by circle "B" (Figure A9*b*). Only those solutions that successfully simulate both predevelopment and transient groundwater-flow conditions can be accepted and classified as resulting in calibrated transient and predevelopment groundwater-flow models. These

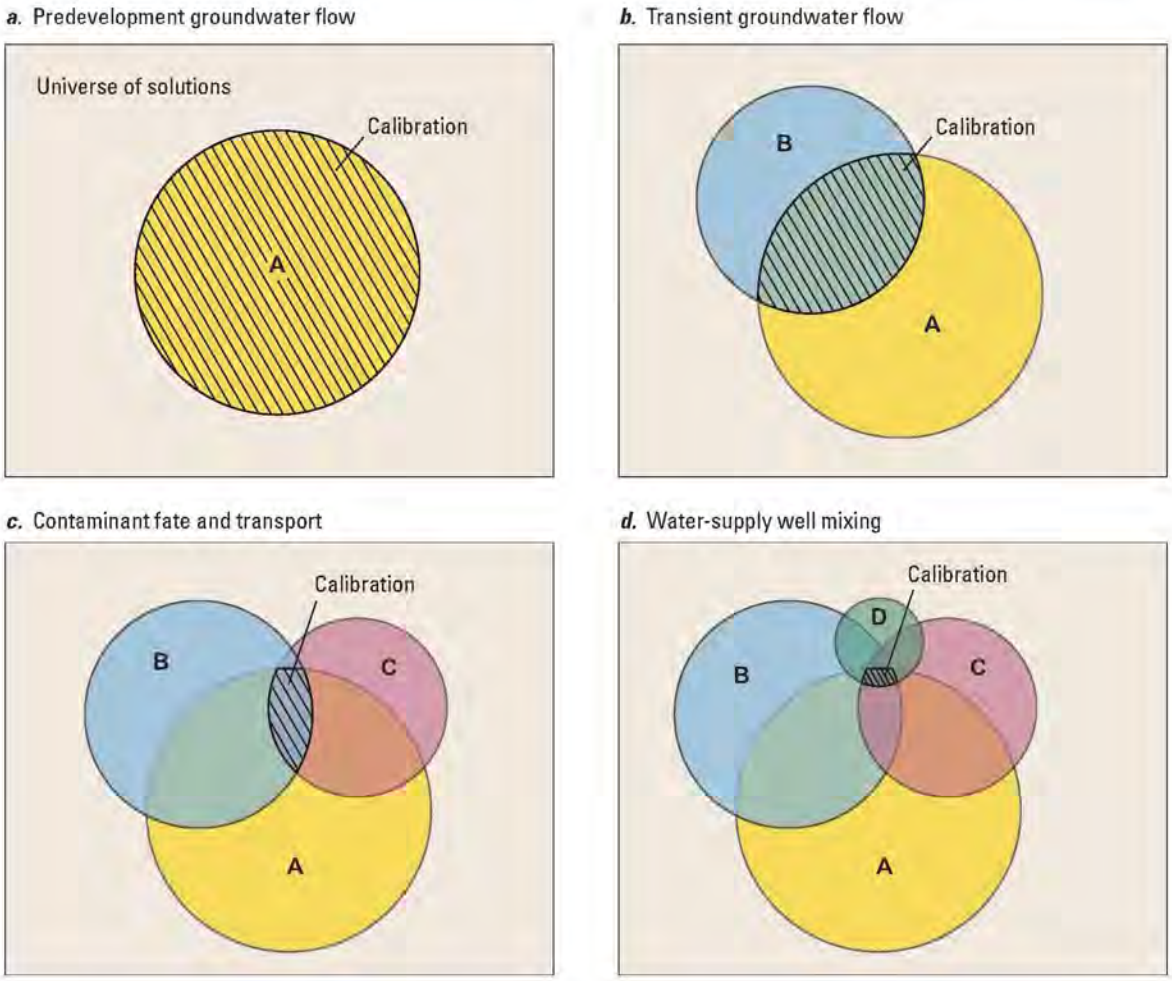


Figure A9. Venn diagrams showing hierarchical approach of model calibration used to estimate concentration of finished water: *(a)* predevelopment groundwater flow, *(b)* transient groundwater flow, *(c)* contaminant fate and transport, and *(d)* water-supply well mixing, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

select and fewer solutions are indicated by the intersection of circles "A" and "B." The transient groundwater-flow simulations provide velocity information (specific discharge) required to conduct a fate and transport simulation. Viable solutions for the fate and transport problem are indicated by circle "C" (Figure A9*c*). Only those solutions that satisfy: (a) predevelopment groundwater-flow, (b) transient groundwater-flow, and (c) contaminant fate and transport calibration criteria are accepted and classified as resulting in a calibrated contaminant fate and transport model. These solutions are even fewer than for predevelopment and transient groundwater flow and are indicated by the intersection of circles "A," "B," and "C." The fourth hierarchical level used to reconstruct PCE concentrations in drinking water was the development of a calibrated mixing model (using the materials mass balance approach and mixing PCE-contaminated and uncontaminated groundwater from supply wells). Viable calibrated solutions depend on calibrated solutions for the previous three hierarchical levels of model calibration, thereby resulting in even fewer calibrated solutions to the mixing problem—circle "D" in Figure A9*d*. Thus, only solutions that satisfy all four levels of model calibration, indicated by the intersection of circles "A," "B," "C," and "D," provide reasonable estimates for the concentration of PCE in finished water at the Tarawa Terrace WTP. The final calibrated models were the end product of this hierarchical process.

Quantitative Assessment of Model Calibration

Specific details of the calibration process for each hierarchical level are described in the Chapter C report for levels 1 and 2 (Faye and Valenzuela In press 2007) and the Chapter F report for levels 3 and 4 (Faye In press 2007b). To summarize, 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 A8. Graphs of observed and simulated water levels using paired data points[22] are shown in Figure A10 for predevelopment and transient groundwater-flow calibrations (hierarchical levels 1 and 2). Of special note are calibration targets and resulting calibration statistics for hierarchal level 2—transient groundwater flow (Figure A10*b* and Table A8). The calibration targets were divided into those reflective of monitor well data and those reflective of water-supply well data. As listed in Table A8, calibration targets for water-level data derived from monitor well data were assigned a smaller head difference (±3 ft) when compared with calibration targets derived from water-supply well data (±12 ft). This difference in the calibration targets—and resulting calibration statistics—reflects the more accurate measurement method used to determine monitor well water levels (steel-tape measurements) when compared with the method used to determine water-supply well water levels (airline measurements). The resulting calibration statistics and paired data point graphs also demonstrate a better agreement between monitor well data and model simulation (average magnitude of head difference of 1.4 ft) than between water-supply well data and model simulation results (average magnitude of head difference of 7.1 ft).[23] Detailed discussion and analyses of calibration procedures and results are provided in the Chapter C report (Faye and Valenzuela In press 2007).

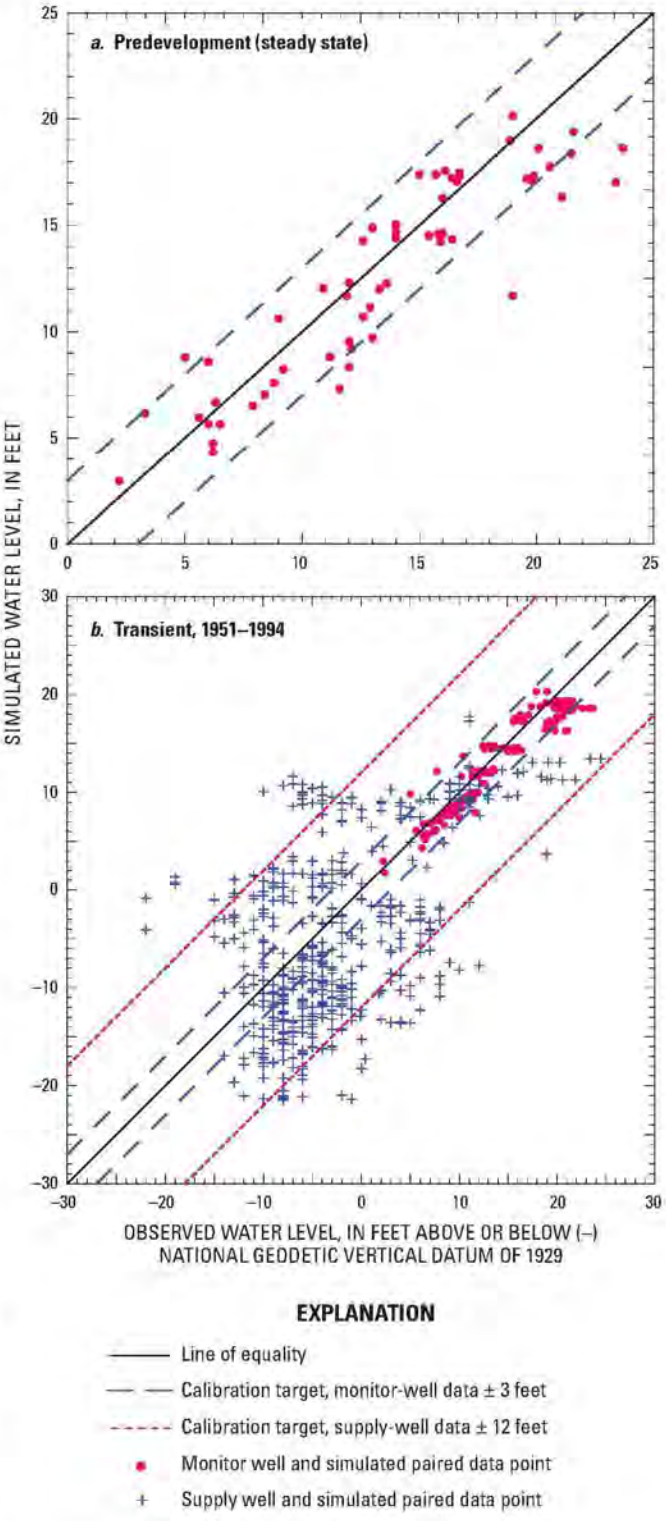


Figure A10. Observed and simulated water levels, model layer 1, and calibration targets for *(a)* predevelopment (steady-state) conditions and *(b)* transient conditions, 1951–1994, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[22] A location with observed data (for example, water level or concentration) that is associated with a model location for the purpose of comparing observed data with model results.

[23] Definitions of head difference, average magnitude of head difference, and other calibration targets and statistics are provided in Table A8.

To assess the calibration of the fate and transport simulation of PCE and the mixing model computations for finished water at the Tarawa Terrace WTP (hierarchical levels 3 and 4), a statistic referred to as the model bias was computed (B_m, Table A8). Model bias allows one to test the accuracy of a model by expressing the bias in terms of a simulated-to-observed (or measured) ratio (Maslia et al. 2000, Rogers et al. 1999). Model bias, defined as the ratio of simulated PCE concentration to observed PCE concentration (C_{sim}/C_{obs}), is characterized by the following properties:

when $C_{sim}/C_{obs} < 1$, there is underprediction by the model,
when $C_{sim}/C_{obs} = 1$, there is exact agreement, and
when $C_{sim}/C_{obs} > 1$, there is overprediction by the model.

Data used to compute model bias are spatially and temporally disparate and are listed in Table A9 for water-supply wells and Table A10 for the Tarawa Terrace WTP. The geometric bias (B_g) is the geometric mean of the individual C_{sim}/C_{obs} ratios and is a measure of model bias ($B_{m,i}$). Geometric bias, (B_g), is computed using the following equation:

$$B_g = \exp\left[\frac{\sum_{i=1}^{N} \ln\left(B_{m,i}\right)}{N}\right], \qquad (1)$$

where

$B_{m,i}$ is the model bias defined as the ratio of simulated PCE concentration to observed PCE concentration (C_{sim}/C_{obs}),
N is the number of observation points,
ln ( ) is the Naperian or natural logarithm, and
B_g is the geometric bias.

The geometric bias is used because the distribution of C_{sim}/C_{obs} ratios is skewed like a lognormal distribution. That is, the values are restricted for underprediction (0–1), but are unrestricted for overprediction (anything greater than 1).

Water-supply well data included 17 of 36 samples recorded as nondetect (Table A9), and these samples were not used in the computation of the geometric bias (B_g). In addition, the computation of geometric bias was accomplished twice: an inclusive bias computation that included all water-supply well data and a selected bias computation that omitted data for water-supply well TT-23. The inclusive geometric bias, using data for water-supply well TT-23, was 5.9. The selected geometric bias, omitting data for supply well TT-23, was 3.9 (Table A8). Both results, however, indicate overprediction by the model. The rationale for computing the selected geometric bias is based on data, observations, and discussions provided in Chapter E of this report series (Faye and Green In press 2007). Briefly, enhanced biodegradation possibly occurred in the vicinity of water-supply well TT-23 during 1984 and 1985. A biodegradation rate for PCE of 0.5/d was computed using analytical results and sample collection dates reported for water-supply well TT-23. This rate probably was not representative of biodegradation occurring in contaminated aquifer media at other wells and was significantly greater than the calibrated reaction rate of 5.0 x 10^{-4}/d (Table A11). Such greatly enhanced biodegradation would result in much lower PCE concentrations in water samples obtained from supply well TT-23. A second reason for computing a selected geometric bias—omitting data from water-supply well TT-23—is bias introduced into analytical results caused by incomplete or inadequate sampling methodology. As noted in Table A9, four sequential sampling events took place during March 11–12, 1985, at water-supply well TT-23. Each sampling event resulted in increased PCE concentrations compared to the preceding sample. Thus, sampling methodology at water-supply well TT-23 may not have included a sufficient volume of water discharged from the well bore prior to sampling, and samples obtained did not represent PCE concentration within the entire volume of aquifer material contributing to the well.

For the Tarawa Terrace WTP, 15 of 25 samples were recorded as nondetect (Table A10). The nondetect samples were not used in the computation of the geometric bias (B_g). The resulting geometric bias computed for measured data at the Tarawa Terrace WTP is 1.5, which indicates a slight overprediction by the model.

All data, measured and nondetect, and simulated values are displayed in Figures A11 and A12 for water-supply wells and the WTP, respectively. The sample numbers shown on the horizontal (x-) axis of each graph correspond to the sample numbers listed in Table A9 for water-supply wells and Table A10 for the WTP. The data in Figures A11 and A12 are compared with the corresponding PCE concentration calibration targets for water-supply wells and the WTP listed in Table A8.

Table A8. Summary of calibration targets and resulting calibration statistics for simulation models used to reconstruct historical contamination events at Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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

For the nondetect sample data, the upper calibration target was selected as the detection limit for the sample (Tables A9 and A10), and the lower calibration target was selected as 1 µg/L. The statistical analyses summarized in Table A8 and comparisons of observed data, simulated values, and calibration targets shown in Figures A10*a*, A10*b*, A11, and A12 for the four hierarchical levels of model analyses provide evidence that the models of groundwater flow (predevelopment and transient—Figure A10), contaminant fate and transport (Figure A11), and water-supply well mixing at the Tarawa Terrace WTP (Figure A12) presented herein: (1) are reasonably calibrated and (2) provide an acceptable representation of the groundwater-flow system, the fate and transport of PCE, and the distribution of PCE-contaminated finished water to residences of Tarawa Terrace. A listing of calibrated model parameter values for the predevelopment (hierarchical level 1), transient (hierarchical level 2), and fate and transport (hierarchical level 3) models is presented in Table A11.

Table A9. Summary of model-derived values and observed data of tetrachloroethylene at water-supply wells, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.[1]

[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

[1]Model-derived values for water-supply wells based on simulation results obtained from the fate and transport model MT3DMS (Zheng and Wang 1999); see the Chapter F report (Faye In press 2007b) for details

[2]Calibration targets are ±½-order of magnitude for observed data; when observed data are indicated as ND, upper calibration target is detection limit and lower calibration target is 1 µg/L

[3]See Figure A11

Table A10. Summary of model-derived values and observed data of tetrachloroethylene at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.[1]

[PCE, tetrachloroethylene; µg/L, microgram per liter; 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

[1]Model-derived values for water treatment plant based on simulation results obtained from the fate and transport model MT3DMS (Zheng and Wang 1999) and application of a materials mass balance (mixing) model; see the Chapter F report (Faye In press 2007b) for details

[2]Calibration targets are ±½-order of magnitude for observed data; when observed data are indicated as ND, upper calibration target is detection limit and lower calibration target is 1 µg/L

[3]See Figure A12

Table A11. Calibrated model parameter values used for simulating groundwater flow and contaminant fate and transport, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[ft/d, foot per day; ft³/d, cubic foot per day; ft³/g, cubic foot per gram; g/ft³, gram per cubic foot; d⁻¹, 1/day; g/d, gram per day; ft, foot; ft²/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 (ft³/d)	See footnote[4]	—	See footnote[4]	—	0	—	0
Fate and transport of tetrachloroethylene (PCE) model, January 1951–December 1994							
Distribution coefficient, K_d (ft³/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/ft³)	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], $q_S C_S$ (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* (ft²/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 In press 2007a) and Chapter C (Faye and Valenzuela In press 2007) reports for geohydrologic framework corresponding to appropriate model layers; aquifers are model layers 1, 3, 5, and 7; semiconfining 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 2007a) for specific pumpage data

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

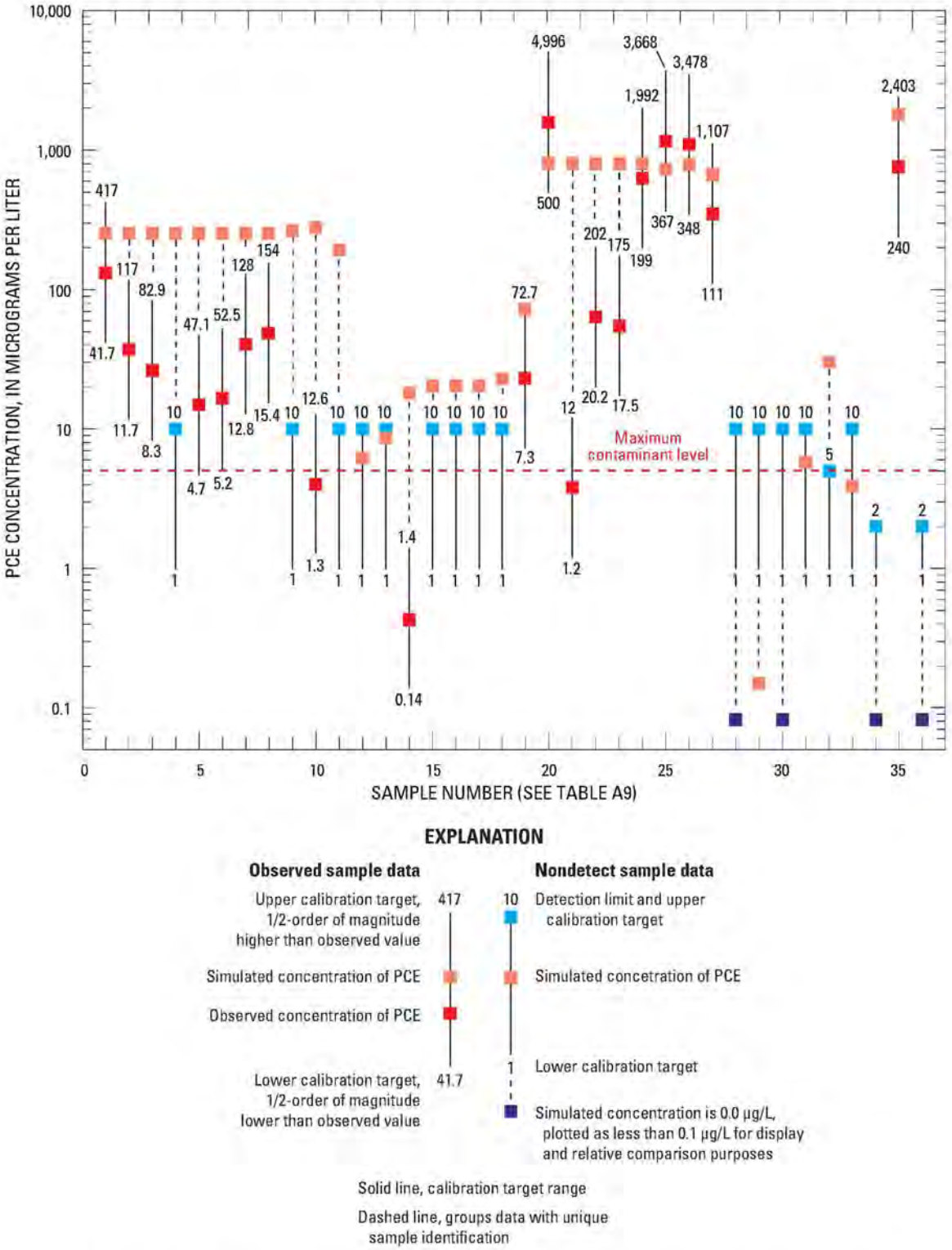


Figure A11. Comparison of observed and nondetect tetrachloroethylene sample data with calibration targets and simulated concentrations at water-supply wells, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [PCE, tetrachloroethylene; µg/L, microgram per liter]

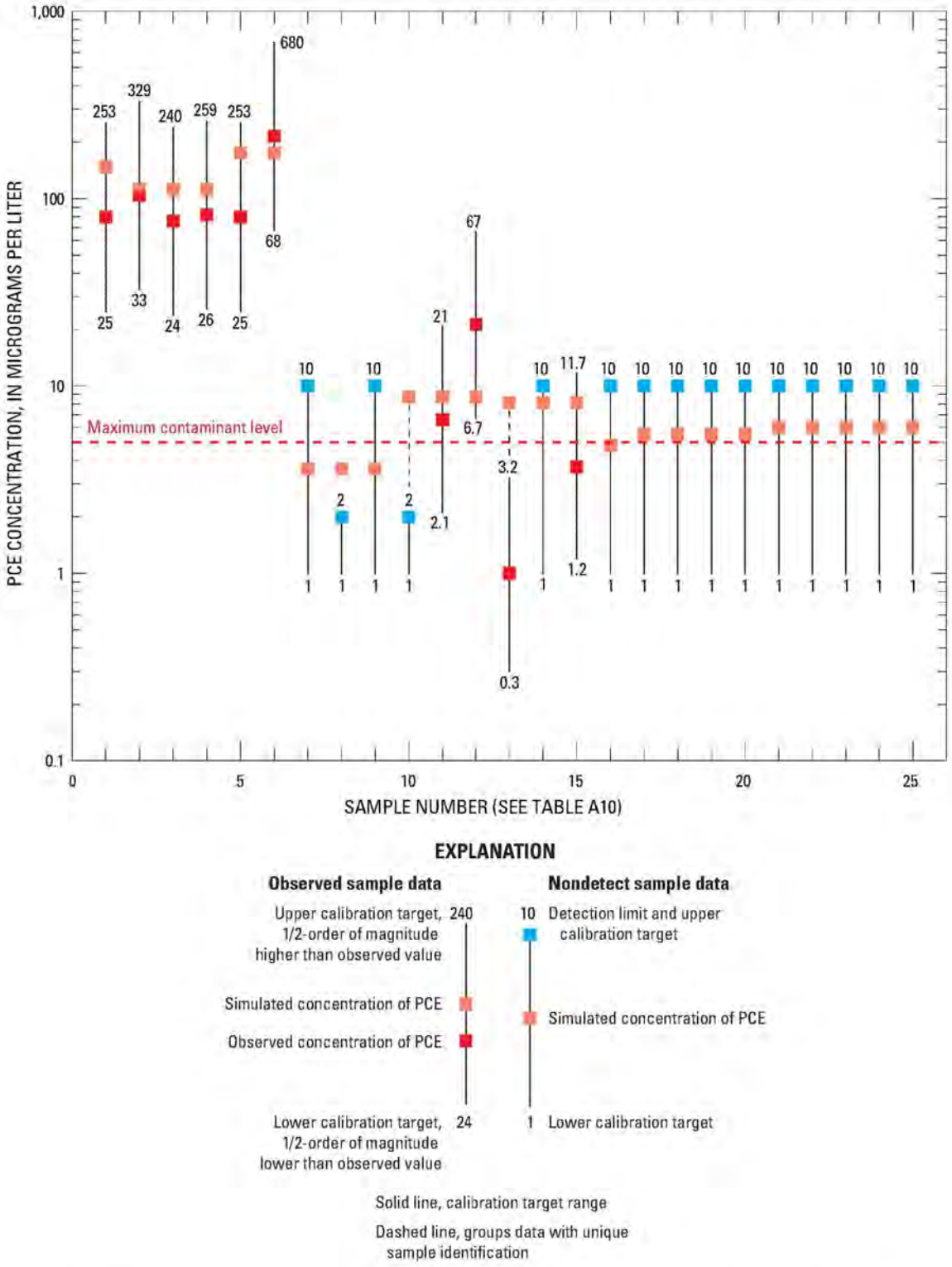


Figure A12. Comparison of observed and nondetect tetrachloroethylene sample data with calibration targets and simulated concentrations at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [PCE, tetrachloroethylene]

Selected Simulation Results

Examples of simulation results showing the distribution of PCE in groundwater and the concentration of PCE in finished water at the Tarawa Terrace WTP are presented in the form of maps and graphs. Maps show simulated water levels, directions of groundwater flow, and the areal distribution of PCE. The concentrations of PCE at specific water-supply wells and in finished water at the WTP are shown as graphs in the form of time versus concentration.

Distribution of Tetrachloroethylene (PCE) in Groundwater

Simulation results of groundwater flow and the fate and transport of PCE are shown as a series of maps for January 1958 (Figure A13), January 1968 (Figure A14), December 1984 (Figure A15), and December 1994 (Figure A17).[24] Each illustration is composed of two maps. The upper map shows simulated potentiometric levels (or water levels) and directions of groundwater flow for model layer 1 throughout the entire active model domain (for example, Figure A13*a*). Groundwater flow is from highest to lowest potentiometric level. The lower map (for example, Figure A13*b*) shows an enlarged area of the Tarawa Terrace housing area and the site of ABC One-Hour Cleaners. This map shows simulated potentiometric levels and the areal distribution of PCE-contaminated groundwater. The lower maps show simulated PCE values ranging from 5 µg/L to greater than 1,500 µg/L. The values of PCE shown on the maps—assigned a specific color to represent a concentration range—are values of PCE that were simulated at the center of a finite-difference cell that was part of the numerical model's finite-difference grid.[25] The simulated PCE values shown in Figures A13–A17 were derived by applying the inverse-distance weighting method to simulated PCE-concentration values at the center of finite-difference cells.

January 1958

With the onset of simulated pumping at water-supply well TT-26 during January 1952, local cones of depression are shown around all active supply wells. In general, however, flow is toward Northeast Creek and Frenchmans Creek (A13*a*). 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 A13*b*). The simulated PCE concentration at water-supply well TT-26 during January 1958 was about 29 µg/L.[26]

January 1968

During January 1968, the designated start date of the epidemiological case-control study (Figure A3), groundwater flow in the northern half of the model domain was little changed from January 1958 conditions (Figure A14*a*). 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. 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 A14*b*) 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 in the vicinity of the Tarawa Terrace I housing area and probably accelerated the migration of PCE toward the vicinity of well TT-54 (Figure A15*a*). 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 A15*b*). The areal extent of simulated

[24] For synoptic maps of model layer 1 (1951–1994), refer to the Chapter K report (Maslia et al. In press 2007a).

[25] Refer to report Chapter C (Faye and Valenzuela In press 2007) and Chapter F (Faye In press 2007b) reports for details specific to the computational grid and model boundaries used to simulate groundwater flow and contaminant fate and transport.

[26] Refer to the Chapter K report (Maslia et al. In press 2007a) for a monthly listing of simulated PCE concentrations at water-supply wells during January 1952–February 1987.

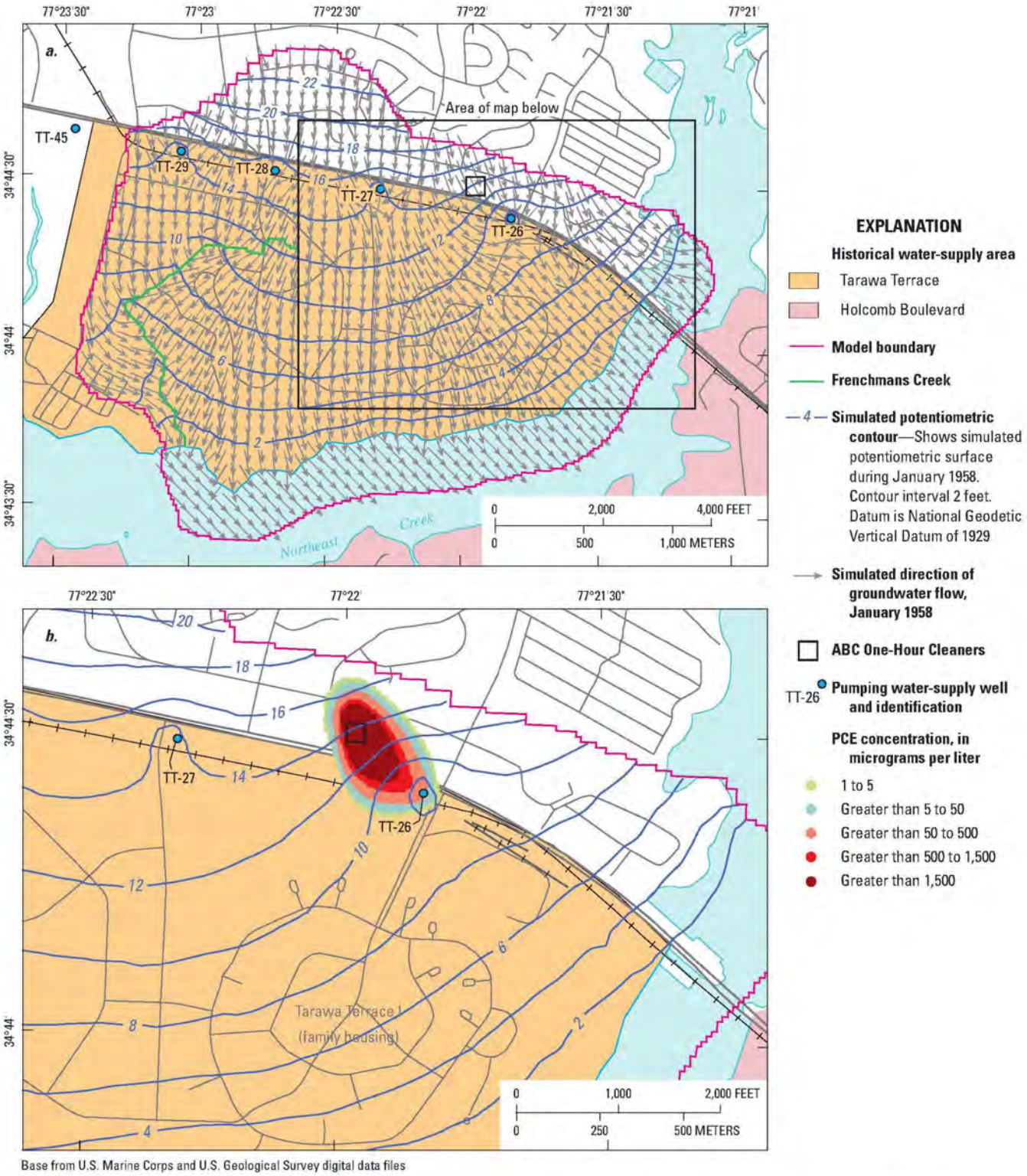
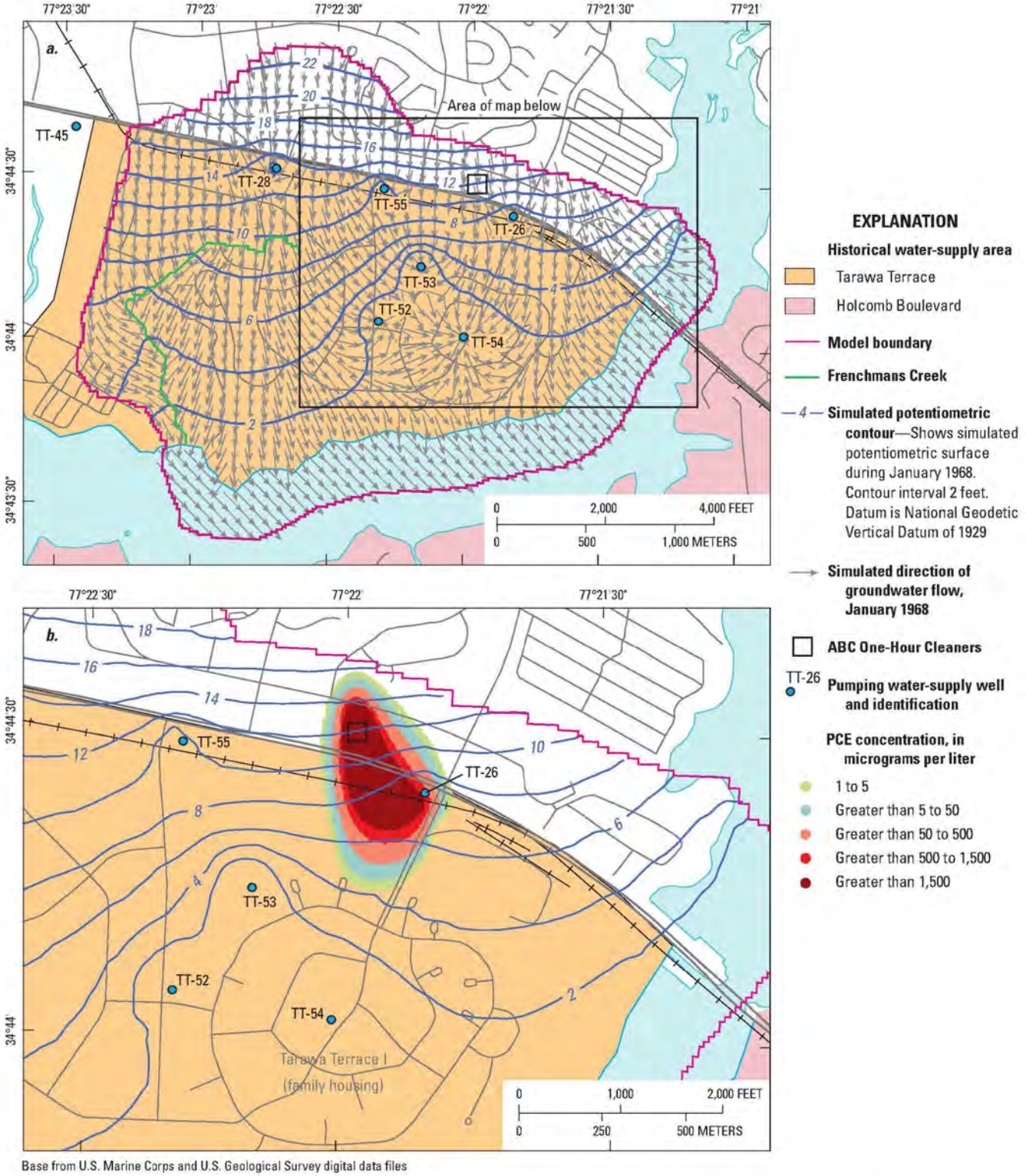


Figure A13. Simulated *(a)* water level and direction of groundwater flow and *(b)* distribution of tetrachloroethylene, model layer 1, January 1958, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [PCE, tetrachloroethylene]



Base from U.S. Marine Corps and U.S. Geological Survey digital data files

Figure A14. Simulated *(a)* water level and direction of groundwater flow and *(b)* distribution of tetrachloroethylene, model layer 1, January 1968, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [PCE, tetrachloroethylene]

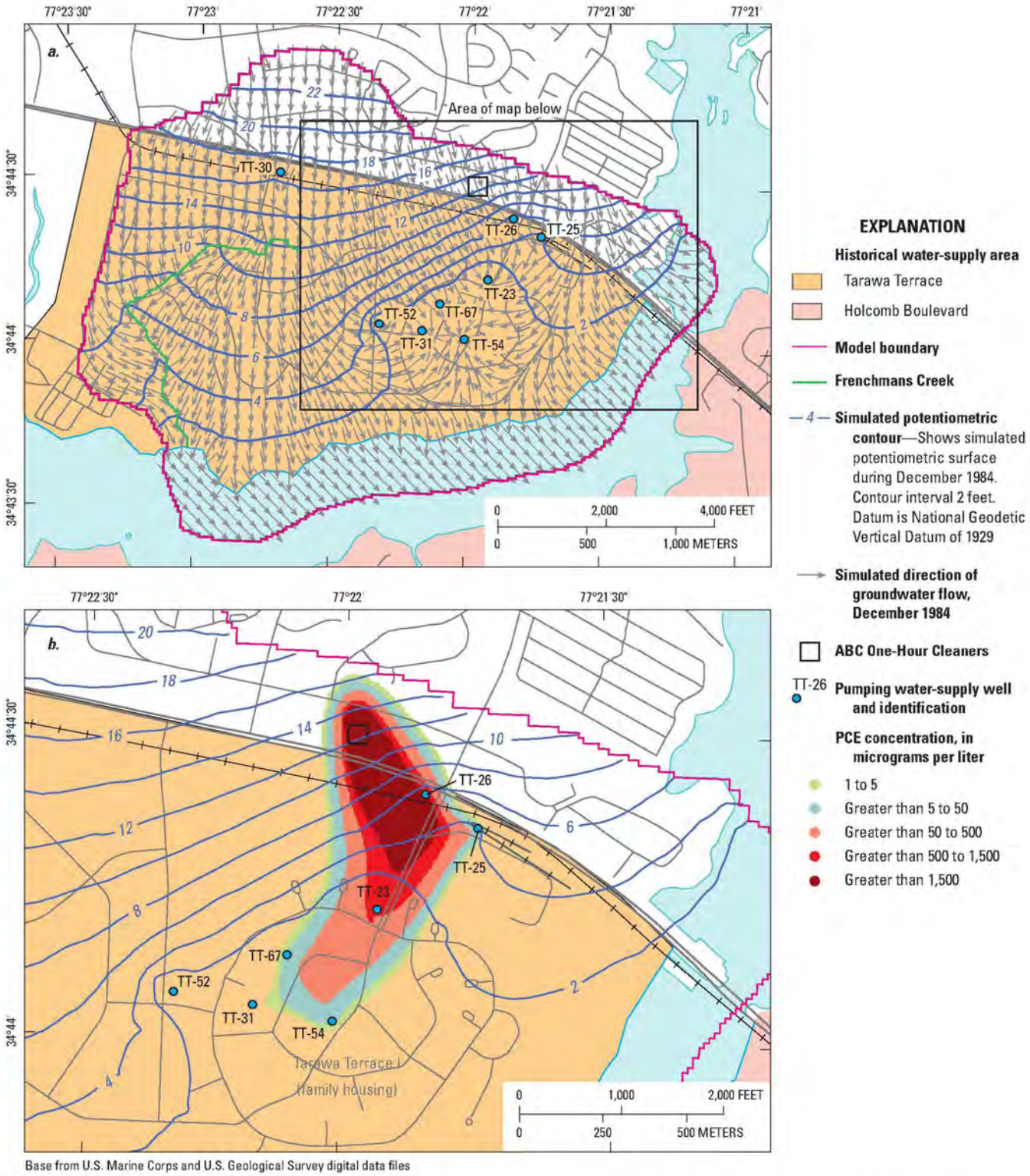


Figure A15. Simulated *(a)* water level and direction of groundwater flow and *(b)* distribution of tetrachloroethylene, model layer 1, December 1984, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [PCE, tetrachloroethylene]

PCE contamination has increased significantly from the areal extent of January 1958 and January 1968 (Figures A13*b* and A14*b*, 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. These and other water-supply wells were pumping from model layer 3. Therefore, simulated concentrations for these water-supply wells are lower than the simulated PCE concentrations shown in Figure A15*b*. For maps showing simulated PCE concentration in model layer 3, refer to the Chapter F report (Faye In Press 2007b). For information on model layers that water-supply wells pumping from, refer to the Chapter K report (Maslia et al. In Press 2007a).

Some water-supply wells were constructed to obtain water from multiple water-bearing zones. Therefore, in the model representation of these wells, groundwater can be withdrawn from more than one model layer. For example, water-supply wells TT-31, TT-52, and TT-54 withdraw groundwater from model layers 1 and 3, whereas water-supply wells TT-23, TT-25, TT-26, TT-27, and TT-67 withdraw groundwater solely from model layer 3 (Faye and Valenzuela In press 2007; Maslia et al. In press 2007a). Consequently, the distribution of PCE will differ by model layer and by time, depending on groundwater-flow velocities, the number of water-supply wells withdrawing groundwater from a particular model layer, and the volume of groundwater being withdrawn. An example of the multilayer distribution of PCE by model layer for December 1984 is shown as a perspective diagram in Figure A16. In this diagram, water-supply wells are shown penetrating the model layer or layers from which they withdraw groundwater. Because no water-supply wells withdraw groundwater directly from model layer 5, the distribution of PCE in layer 5 covers a smaller area and is of lower concentration compared to model layers 1 and 3.

December 1994

Owing to documented PCE contamination in water samples obtained from the Tarawa Terrace water-supply wells and the WTP (Tables A9 and A10), wells TT-23 and TT-26 were taken off-line during February 1985. The Tarawa Terrace WTP was closed and pumping at all Tarawa Terrace water-supply wells was discontinued during March 1987 (Figures A3 and A5, Table A6). As a result, potentiometric levels began to recover. By December 1994, the simulated potentiometric levels (Figure A17*a*), were nearly identical to predevelopment conditions of 1951 (Faye and Valenzuela In press 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 (Figure A17*a*). Water-supply wells shown in Figure A17 were not operating during December 1994, but are shown on this illustration for reference purposes.

A graph showing simulated concentrations of PCE at Tarawa Terrace water-supply wells from the beginning of operations at ABC One-Hour Cleaners through the closure of the wells and the WTP is shown in Figure A18. Simulated PCE concentrations in water-supply well TT-26 exceeded the current MCL of 5 µg/L 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. This represents a duration of 333 months (27.7 years). These results are summarized in Table A12 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), by far, the highest concentration of PCE and the longest duration of contamination occurred in water-supply well TT-26 (Figure A18).

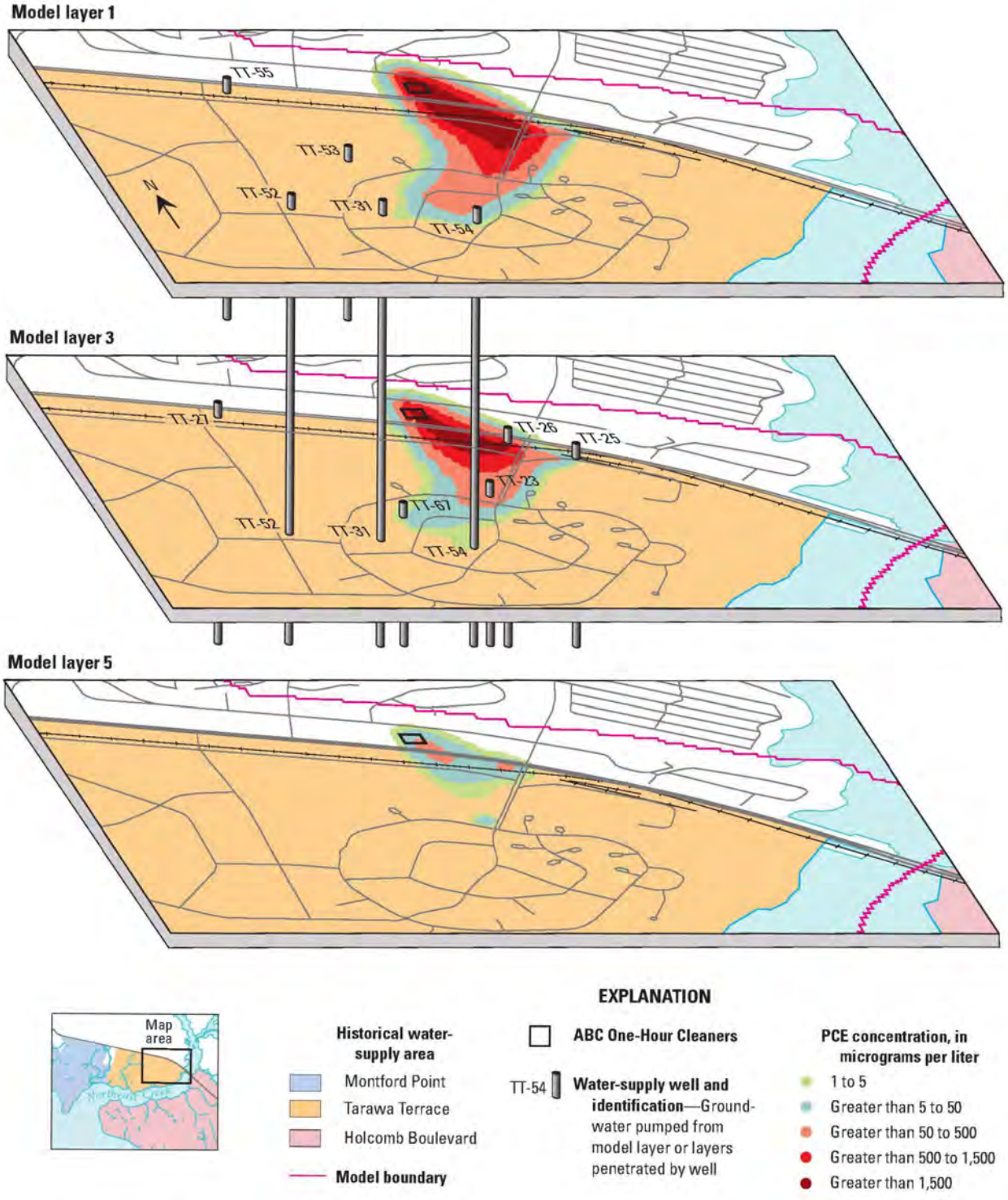


Figure A16. Diagram showing perspective views of the simulated distribution of tetrachloroethylene, model layers 1, 3, and 5, December 1984, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [PCE, tetrachloroethylene; thickness and vertical separation of layers not to scale]

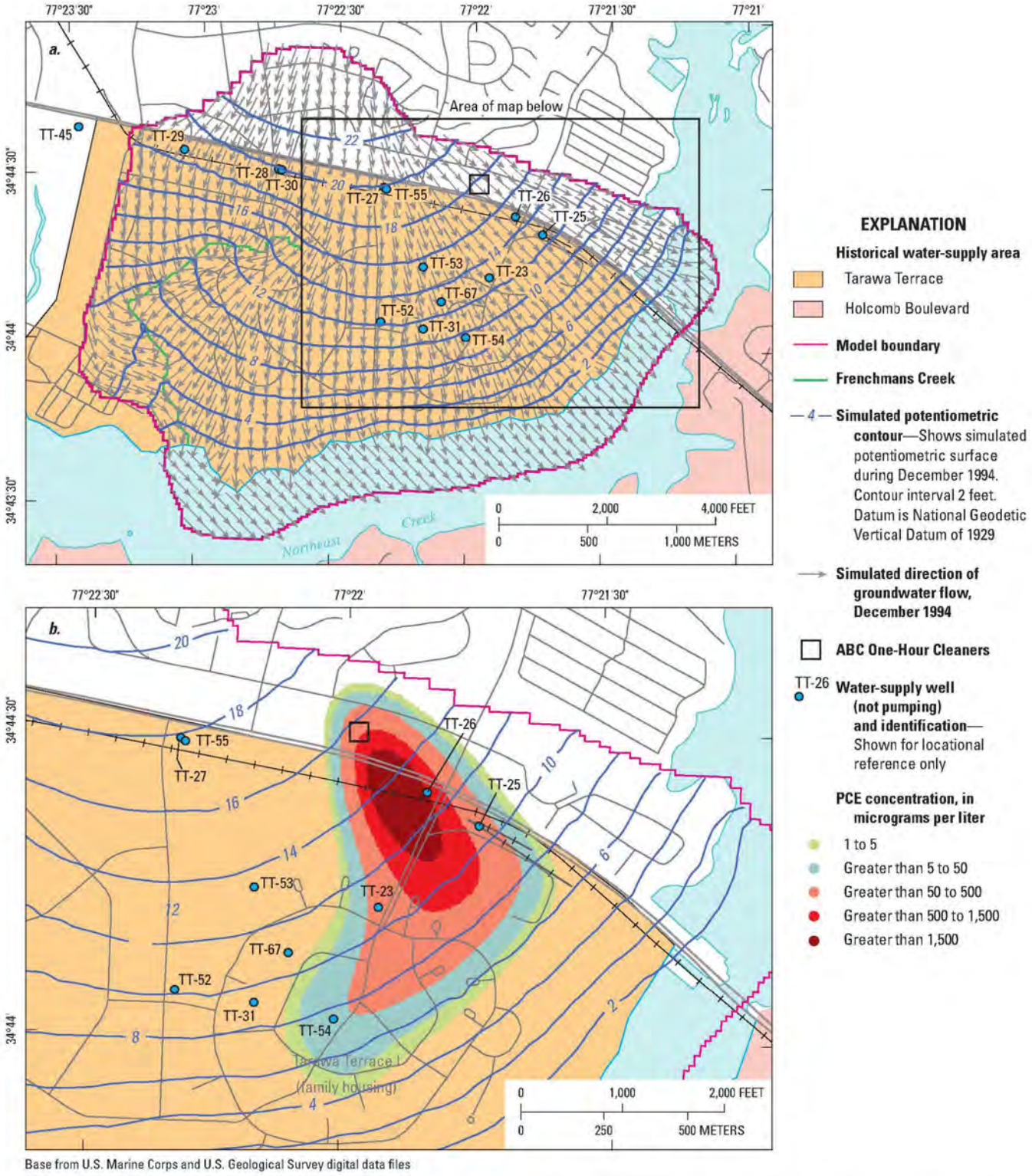


Figure A17. Simulated *(a)* water level and direction of groundwater flow and *(b)* distribution of tetrachloroethylene, model layer 1, December 1994, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [PCE, tetrachloroethylene]

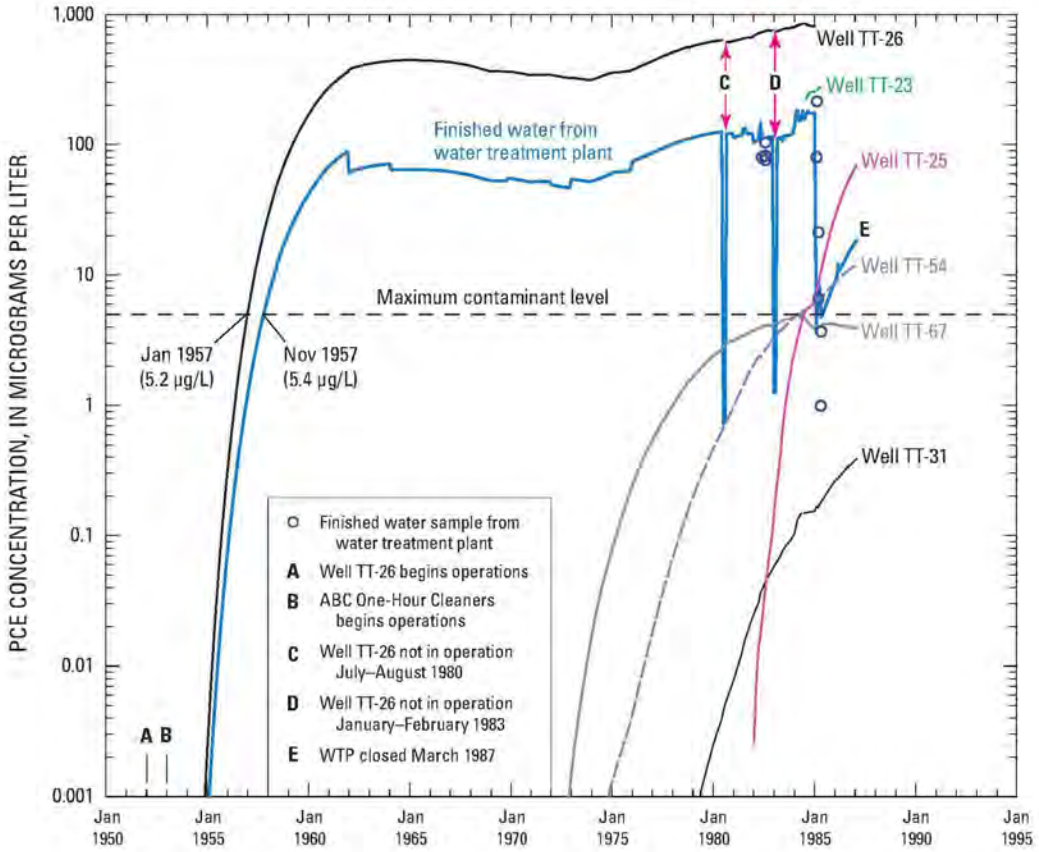


Figure A18. Concentration of tetrachloroethylene: simulated at selected water-supply wells and in finished water at the water treatment plant, and measured in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [PCE, tetrachloroethylene; µg/L, microgram per liter]

Table A12. Summary statistics for simulated tetrachloroethylene contamination of selected water-supply wells and the water treatment plant based on calibrated model simulation, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[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

Concentration of Tetrachloroethylene (PCE) in Finished Water

Figure A18 shows simulated PCE concentrations in finished water delivered by the Tarawa Terrace WTP. A monthly listing of simulated PCE concentrations also is provided in Appendix A2. PCE concentrations for the water-supply wells depicted in Figure A18 are based on simulated monthly results for the period of well operations (Figure A5, Table A6). PCE contamination of water-supply well TT-26 was the primary contributor to contamination in the finished water of the WTP. When water-supply well TT-26 was temporarily shut down during July–August 1980 and January–February 1983, the PCE concentration in finished water at the WTP was significantly lower (Figure A18). For example, during June 1980, the simulated PCE concentration in finished water at the Tarawa Terrace WTP was 126 µg/L, but during July–August 1980, the simulated PCE concentration in finished water at the Tarawa Terrace WTP did not exceed 0.8 µg/L. Furthermore, during December 1982, the simulated PCE concentration in finished water at the Tarawa Terrace WTP was 115 µg/L, but during January–February 1983, the simulated PCE concentration in finished water at the Tarawa Terrace WTP was 1.3 µg/L. The PCE concentration of finished water at the Tarawa Terrace WTP is less than the PCE concentration of water-supply well TT-26 because the mixing model uses water supplied to the WTP from all wells—contaminated and uncontaminated.

For any given month during the historical reconstruction period, the PCE concentration of finished water at the Tarawa Terrace WTP was computed using the following equations:

$$Q_T = \sum_{i=1}^{NWP} Q_i \tag{2}$$

and

$$C_{WTP} = \frac{\sum_{i=1}^{NWP} C_i Q_i}{Q_T}, \tag{3}$$

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 Tarawa Terrace WTP for the month of interest.

Equation 2 is known as the continuity equation, and Equation 3 describes the conservation of mass.

The simulated concentration of PCE in finished water delivered by the Tarawa Terrace WTP first exceeded the current MCL of 5 µg/L during November 1957—10 months after the PCE concentration in water-supply well TT-26 exceeded the MCL (Figure A18). Using simulated water-supply well concentrations and mixing model computations (Equations 2 and 3), exposure to PCE-contaminated drinking water that exceeded the current MCL of 5 µg/L occurred for a duration of 346 months (28.8 years)—November 1957–February 1987. A summary of dates and durations of PCE concentrations at selected water-supply wells and in finished water at the Tarawa Terrace WTP is provided in Table A12. Simulated values of PCE concentration in finished water of the WTP compare well with available measured data shown in Figures A12 and A18 and listed in Table A10.

Analysis of Degradation By-Products

Although exposure to contaminated drinking water was eliminated after February 1987 due to the closure of the Tarawa Terrace WTP during March 1987 (Figures A3 and A18; Table A12), measurable quantities of PCE remained in the subsurface—at the source (ABC One-Hour Dry Cleaners) and distributed within the aquifer (Figure A17*b*). For example, during July 1991, the PCE concentrations in water samples obtained from off-line water-supply wells TT-25 and TT-26 were 23 µg/L and 350 µg/L, respectively (Table A9). This mass of PCE in the subsurface continued to migrate and undergo transformation through physical and biochemical processes such as volatilization and biodegradation. As such, the potential for exposure to PCE and its degradation by-products TCE,[27] 1,2-tDCE, and VC from a route other than ingestion and inhalation of drinking water—such as inhalation of soil vapors—continued beyond cessation of exposure to drinking water after the closure of the Tarawa Terrace WTP in March 1987 (Figure A3). To quantify historical concentrations of PCE degradation by-products in groundwater and in soil (vapor phase) requires a model capable of simulating multiphase flow and multispecies mass transport. For PCE, this complex analysis is summarized herein.[28]

The degradation of VOCs in groundwater is a transformation process from a parent compound (for example, PCE) to degradation by-products such as TCE, 1,2-tDCE, and VC (Lawrence 2006, In press 2007). Evidence of the transformation of PCE to degradation by-products of TCE and 1,2-tDCE can be found in water samples obtained January 16, 1985, from Tarawa Terrace water-supply wells TT-23 and TT-26. Laboratory analyses of the water samples indicated concentrations of PCE, TCE, and 1,2-tDCE of 132, 5.8, and 11.0 µg/L, respectively, for water-supply well TT-23 and concentrations of PCE, TCE, and 1,2-tDCE of 1,580, 57.0, and 92.0 µg/L, respectively, for water-supply well TT-26 (Faye and Green In press 2007). The simulation of the fate and transport of PCE in groundwater, described in the Chapter F report (Faye In press 2007b), accounted for the degradation of PCE by applying a biodegradation rate to PCE during the simulation process. (The biodegradation rate was determined from field data and the calibration process [Faye In press 2007b].) This transformation process typically is expressed in terms of a rate constant or half-life. For example, in the fate and transport simulations of PCE, the calibrated biodegradation (or reaction) rate for PCE was 5.0×10^{-4}/day (Table A11). It is important to note, however, that the basic chemical reaction package that is contained in the MT3DMS model was used to simulate a single-specie and single-phase system (Zheng and Wang 1999). Thus, as described in Faye (In press 2007b), MT3DMS was used to simulate the transport and fate (biodegradation) solely of PCE. To account for sequential biodegradation of VOCs, parent-daughter chain reactions must be taken into account in a multiphase environment (Zheng and Bennett 2002). For example, in a four-species system, the source (ABC One-Hour Cleaners) contains only a single specie—PCE. As PCE migrates from the source, it undergoes decay, and the decay product is TCE. TCE in turn undergoes decay, and the decay product can be 1,2-tDCE. 1,2-tDCE is again biologically transformed into VC (Lawrence 2006, In press 2007).[29] Thus, to account for and to simulate (1) parent-daughter chain reactions, (2) multiphase environments (water and vapor), and (3) fate and transport in the unsaturated (above the water table) and saturated (in groundwater) zones, a multispecies, multiphase modeling approach was required. For this purpose, the TechFlowMP model code was used to simulate the sequential biodegradation and transport of PCE and its associated daughter by-products (TCE, 1,2-tDCE, and VC) at Tarawa Terrace and vicinity.[30]

Using TechFlowMP, three-dimensional multispecies, and multiphase simulations were conducted to quantify the fate and transport of PCE and its degradation by-products from the source of the PCE contamination—ABC One-Hour Cleaners. The same model domain used for the MODFLOW-96 and MT3DMS model simulations (Faye and Valenzuela In press 2007, Faye In press 2007b) was used for the

[27] TCE also is used in some dry-cleaning processes. However, based on the deposition from the owner of ABC One-Hour Cleaners (Melts 2001), only PCE was used at ABC One-Hour Cleaners. Therefore, any TCE detected in Tarawa Terrace water-supply wells or in WTP finished water occurred because of the degradation of PCE.

[28] For a detailed discussion of the analysis and simulation of PCE degradation by-products at Tarawa Terrace and vicinity, refer to the Chapter G report (Jang and Aral In press 2007).

[29] Degradation pathways are very complex processes that depend on availability of microorganisms and environmental conditions. Details are provided in Lawrence (2006 In press 2007).

[30] TechFlowMP is a three-dimensional multispecies, multiphase mass transport model developed by the Multimedia Environmental Simulations Laboratory at the Georgia Institute of Technology, Atlanta, Georgia (Jang and Aral 2005).

TechFlowMP model. Contaminants simulated using this more complex model formulation were PCE and its degradation by-products TCE, 1,2-tDCE, and VC. Parameter values calibrated using the MODFLOW-96 and MT3DMS models (for example, water-supply well pumping rates, infiltration [recharge] rate, porosity, dispersivity, and PCE biodegradation [reaction] rate) were used in the TechFlowMP model simulations (Table A11). However, owing to the more complex set of mathematical equations approximated by this model, and because the contaminant source was applied to both the unsaturated and saturated zones (zones above and below the water table, respectively), additional model parameters were determined and assigned. Examples of these parameters include: moisture content; partitioning coefficients for TCE, 1,2-tDCE, and VC; and aerobic (unsaturated zone) and anaerobic (saturated zone) biodegradation rates for PCE, TCE, 1,2-tDCE, and VC. Details on specific TechFlowMP model parameters and their calibrated values are described in the Chapter G report (Jang and Aral In press 2007).

Results obtained by conducting three-dimensional, multispecies, and multiphase simulations are presented herein in terms of (1) graphs of time versus concentration of PCE and its degradation by-products (Figure A19), (2) a table listing summary statistics for PCE and its degradation by-products (Table A13), (3) maps showing the distribution of vapor-phase PCE (Figure A20), and (4) a table listing monthly PCE and PCE degradation by-products in finished water at the Tarawa Terrace WTP (Appendix A2). Figure A19 shows graphs of simulated concentrations of PCE and its degradation by-products—obtained by using the TechFlowMP model—at water-supply well TT-26 and at the Tarawa Terrace WTP. Also shown on the graphs is the concentration of PCE simulated using the MT3DMS single-specie and single-phase model (compare Figure A18 and Figure A19). Simulated concentrations of PCE at water-supply well TT-26 obtained using the TechFlowMP model are slightly lower in value than PCE concentrations obtained using the MT3DMS model (Figure A19*a*). This is to be expected because the TechFlowMP simulations take into account flow and transport in both the unsaturated zone (zone above the water table) and saturated zone (zone at and below the water table) and loss of PCE into the vapor phase, whereas the MODFLOW-96 and MT3DMS models consider groundwater flow and contaminant fate and transport solely in the saturated zone and in the water phase. Given the same total mass of PCE loaded into each of these models, the PCE concentration at water-supply well TT-26 (and other water-supply wells) will be simulated as a lesser amount in the saturated zone by the TechFlowMP model because a fraction of the mass is allocated to the unsaturated zone, as well as being partitioned into the vapor phase. Because water-supply well TT-26 was the primary contributor of PCE contamination in finished water at the Tarawa Terrace WTP (Figure A18), the resulting PCE concentrations in finished water at the Tarawa Terrace WTP computed using results from the TechFlowMP model also were lower (Figure A19*b* and Appendix A2).

Based on the TechFlowMP model simulations, TCE, 1,2-tDCE, and VC concentrations at water-supply well TT-26 generally ranged from about 10 µg/L to 100 µg/L (Figure A19*a*). Simulated concentrations of TCE, 1,2-tDCE, and VC in finished water at the Tarawa Terrace WTP generally ranged from about 2 µg/L to 15 µg/L (Figure A19*b* and Appendix A2). Comparison of the simulated concentrations of PCE degradation by-products in finished water at the Tarawa Terrace WTP indicate the following (Figure A19*b*):

1. TCE was below the current MCL value of 5 µg/L[31] for nearly the entire historical period except during January 1984–January 1985 when it ranged between 5 and 6 µg/L;

2. 1,2-tDCE was below the current MCL value of 100 µg/L[31] for the entire historical period;

3. VC was at or above the current MCL value of 2 µg/L[31] from May 1958 through February 1985 at which time water-supply well TT-26 was shut down.

Simulated concentration values of TCE in water-supply well TT-26 and in finished water delivered by the Tarawa Terrace WTP are less than simulated concentrations of VC and 1,2-tDCE. This is in agreement with measured data obtained from water samples in well TT-26 which shows a TCE concentration less than that of 1,2-tDCE. Summary statistics of PCE and degradation by-product contamination of selected water-supply wells (TT-23, TT-25, and TT-26) and at the Tarawa Terrace WTP derived from simulations of the TechFlowMP model (based on three-dimensional multispecies and multiphase simulation) are listed in Table A13.

[31] 40 CFR, Section 141.60, Effective Dates, July 1, 2002, ed.

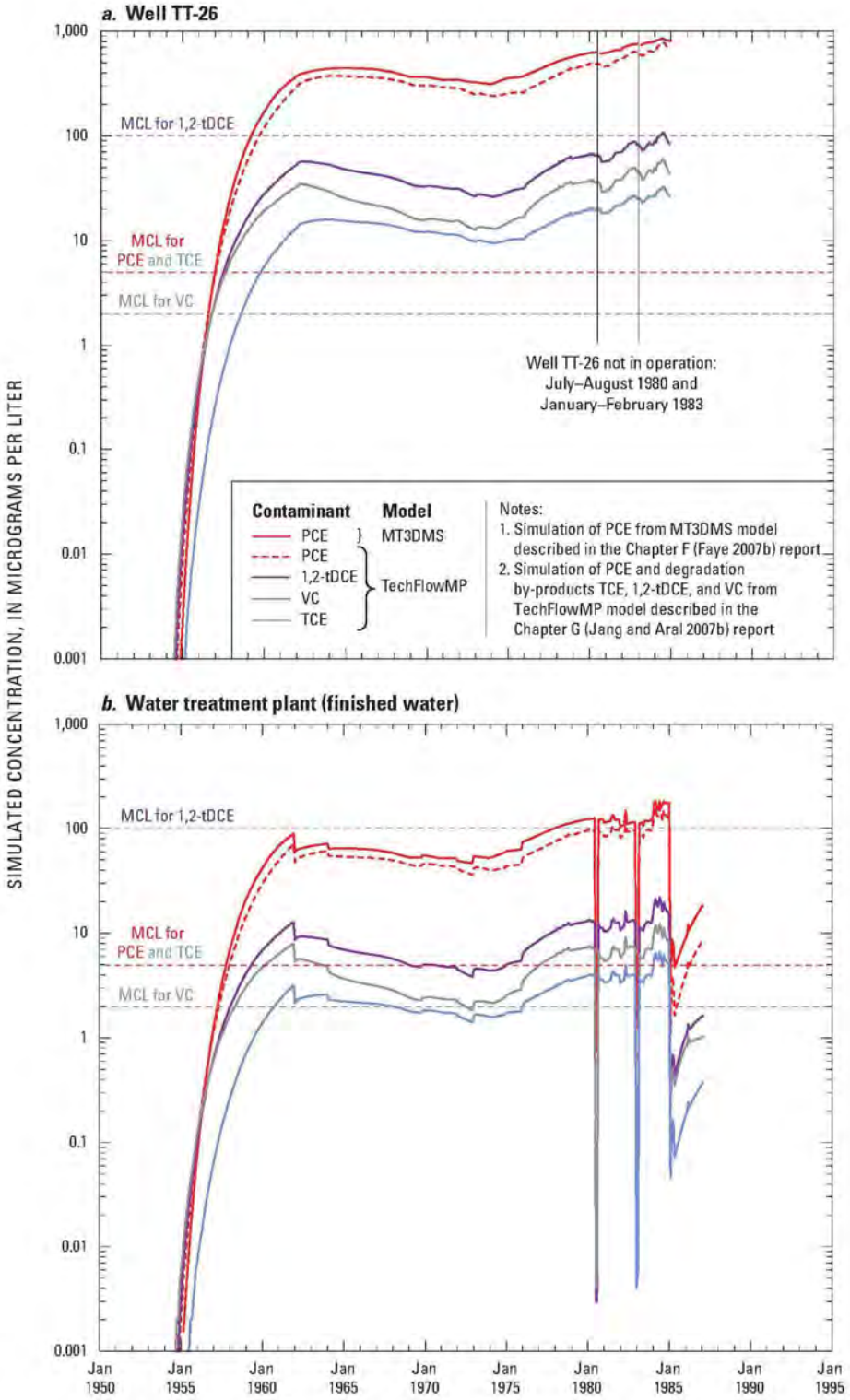


Figure A19. Simulated concentration of tetrachloroethylene (PCE) and degradation by-products trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) *(a)* at water-supply well TT-26 and *(b)* in finished water from water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [MCL, maximum contaminant level]

Table A13. Summary statistics for simulated tetrachloroethylene and degradation by-product contamination of selected water-supply wells and the water treatment plant based on three-dimensional multispecies and multiphase model simulation, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.[1]

[MCL, maximum contaminant level; µg/L, microgram per liter; PCE, tetrachloroethylene; TCE, trichloroethylene; 1,2-tDCE, *trans*-1,2-dichloroethylene; VC, vinyl chloride; Aug, August; Sept, September; Nov, November; Mar, March; Feb, February; Jan, January; WTP, water treatment plant]

Water supply	Month and year exceeding MCL,[2] in µg/L				Maximum concentration, in µg/L				Average concentration,[3] in µg/L				Duration exceeding MCL, in months			
	PCE	TCE	1,2-tDCE	VC	PCE	TCE	1,2-tDCE	VC	PCE	TCE	1,2-tDCE	VC	PCE	TCE	1,2-tDCE	VC
[4]TT-23	Aug 1984	Sept 1984	—[6]	Aug 1984	167	7	21	13	143	7	—[6]	10	8	7	—[6]	8
TT-25	Mar 1985	—[6]	—[6]	July 1985	40	2	7	5	21	—[6]	—[6]	4	24	—[6]	—[6]	20
[5]TT-26	Feb 1957	Nov 1959	June 1984	Nov 1956	775	33	107	60	332	15	105	24	332	299	3	335
WTP	Jan 1958	Feb 1984	—[6]	May 1958	158	7	22	12	57	6	—[6]	5	332	11	—[6]	311

[1]All simulations conducted using the TechFlowMP model. See text and the Chapter G report (Jang and Aral In press 2007) for details

[2]Current MCLs are: PCE and TCE, 5 µg/L; 1,2-tDCE, 100 µg/L; and 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.)

[3]For periods exceeding MCL when water-supply well operating

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

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

[6]MCL never exceeded during simulation

Maps of the areal distributions of vapor-phase PCE for December 1984 and December 1994 are shown in Figure A20. The maps depict simulated vapor-phase PCE concentrations in soil to a depth of about 10 ft. Concentration units for the vapor-phase PCE distributions shown in Figure A20 are in micrograms per liter of air.[32] Comparing these maps with similar maps for dissolved-phase PCE in groundwater for model layer 1 (Figures A15*b* and A17*b*, respectively) indicates that vapor-phase concentrations are lower than dissolved-phase PCE concentrations by about a factor of 10–15 for December 1984 and December 1994. The following examples are noteworthy.

1. During December 1984:
   a. the maximum simulated PCE concentration in groundwater at family housing (model layer 1) was 638 µg/L (Figure A15*b*), whereas the maximum simulated vapor-phase PCE (in the top 10 ft of soil) was 20 µg/L (Figure A20*a*); and
   b. the maximum simulated PCE concentration in groundwater (model layer 1) at the Tarawa Terrace elementary school was 1,418 µg/L (Figure A15*b*), whereas the maximum simulated vapor-phase PCE (in the top 10 ft of soil) was 137 µg/L (Figure A20*a*);

[32] To obtain air concentration units of micrograms per cubic meter (mg/m^3) that are typically used for indoor air studies, multiply micrograms per liter by 1000 (refer to Conversion Factors in Contents section of this report.

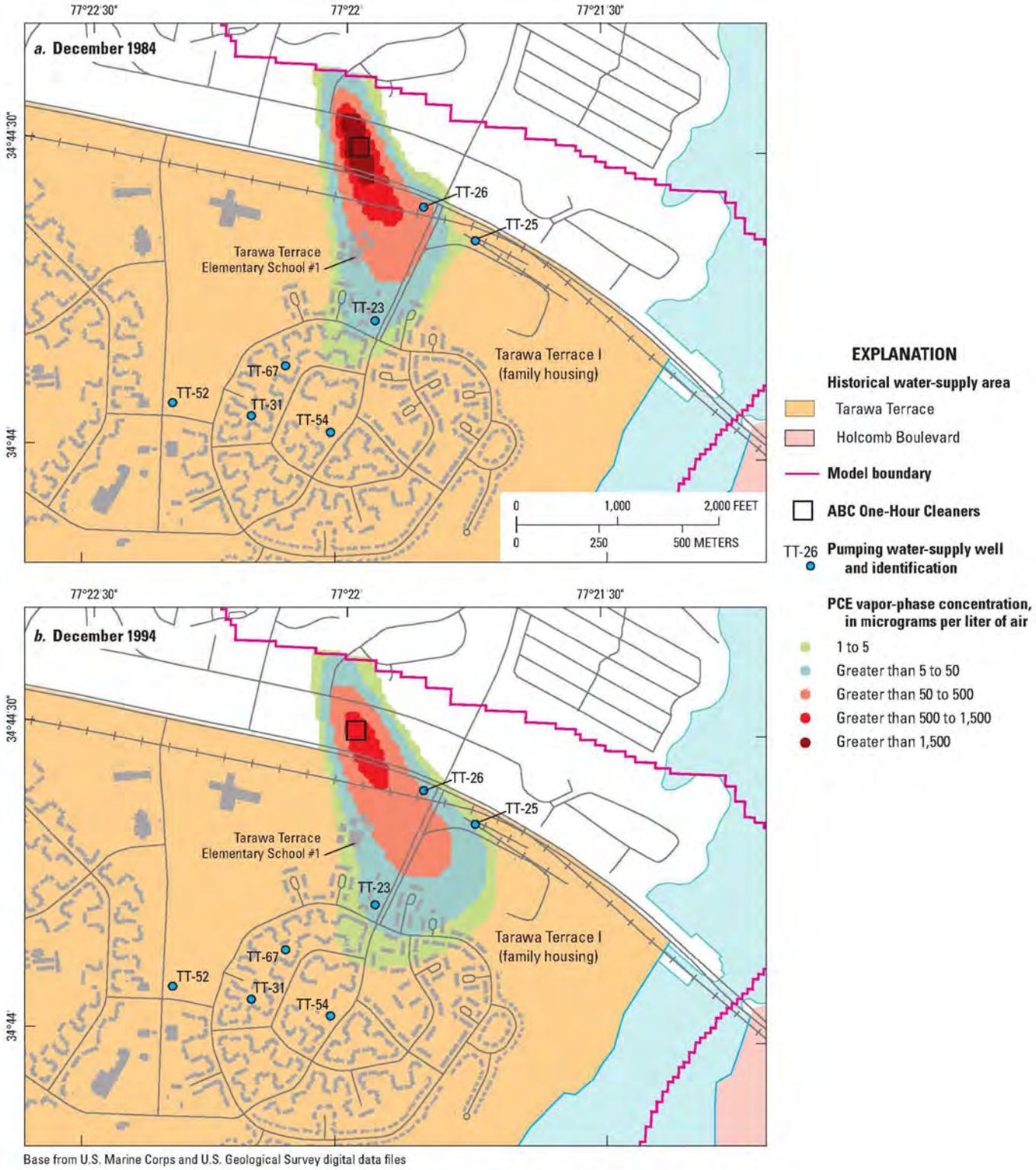


Figure A20. Simulated distribution of vapor-phase tetrachloroethylene to a depth of 10 feet below land surface, *(a)* December 1984 and *(b)* December 1994, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [PCE, tetrachloroethylene]

2. During December 1994:

   a. the maximum simulated PCE concentration in groundwater at family housing (model layer 1) was 688 µg/L (Figure A17*b*), whereas the maximum simulated vapor-phase PCE (in the top 10 ft of soil) was 44 µg/L (Figure A20*b*); and

   b. the maximum simulated PCE concentration in groundwater (model layer 1) at the Tarawa Terrace elementary school was 688 µg/L (Figure A17*b*), whereas the maximum simulated vapor-phase PCE (in the top 10 ft of soil) was 56 µg/L (Figure A20*b*).

Due to sandy soils found at Camp Lejeune (including Tarawa Terrace), there is potential for vapors from these plumes (for example, Figure A20) to enter buildings, thereby providing a potential exposure pathway from inhalation of PCE and PCE degradation by-product vapors. At Tarawa Terrace, these buildings would include some family housing and the elementary school.

It is important to note that historical measurements of soil vapor (soil gas) were not available. Therefore, the TechFlowMP model parameters related to the simulation of vapor-phase PCE and PCE degradation by-products could not be calibrated against field conditions. For example, an assumption was made that homogeneous vapor exit conditions exist at land surface throughout the entire Tarawa Terrace area. Realistically, housing built on concrete slabs, streets and parking lots paved with asphalt, bare playground areas, and lawns will each have different vapor exit conditions requiring adjustment of model parameters to those specific conditions. This may seem like a limitation of the reliability of vapor-phase modeling results (for example, Figure A20). However, the focus of the current investigation is on drinking-water contamination and the historical reconstruction of PCE and PCE degradation by-product contamination of groundwater (water phase) and drinking water at Tarawa Terrace. The concentration of PCE and PCE degradation by-products in groundwater significantly impacts the vapor-phase simulation results. Because simulated groundwater concentrations are based on calibrated groundwater-flow and contaminant fate and transport models, the results presented for vapor-phase simulations should be viewed as reliable historical estimates of generalized vapor-phase conditions in soil during December 1984 and December 1994 at a depth of about 10 ft (Figure A20). For present-day soil-gas conditions or to obtain a more refined historical vapor-phase calibration for Tarawa Terrace, field studies, including the collection of unsaturated zone, soil gas, and indoor air concentration data would have to be undertaken as a separate detailed study. Details regarding the development of the TechFlowMP model are provided in Jang and Aral (2005). Assumptions, parameter values specific to three-dimensional multiphase flow and multi-species mass transport, and resulting simulations of PCE and PCE degradation by-products in groundwater and vapor-phase specific to Tarawa Terrace and vicinity are provided in Jang and Aral (2007) and in the Chapter G report (Jang and Aral In Press 2007).

Confidence in Simulation Results

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 Tarawa Terrace, the availability of data to thoroughly characterize and describe model parameters and operations of water-supply wells was considerably limited, as described in the section on Water-Distribution Investigation. Such limitations give 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 A18)?

To answer these questions and address the overarching 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 (In press 2007) and Faye (In press 2007b), respectively. These analyses were: (1) an assessment of pumping schedule variation at Tarawa Terrace water-supply wells with respect to contaminant arrival times and concentrations,[33] (2) sensitivity analysis,[34] and (3) probabilistic analysis.[34] All of the additional analyses were conducted using PCE dissolved in groundwater as a single specie. MODFLOW-96 and MT3DMS calibrated models are described in the Chapter C (Faye and Valenzuela In press 2007) and Chapter F (Faye In press 2007b) reports.

[33] A detailed description and discussion of the effect of water-supply well schedule variation on the arrival of PCE at water-supply wells and the Tarawa Terrace WTP is presented in the Chapter H report (Wang and Aral In press 2007).

[34] A detailed description and discussion of sensitivity and uncertainty analysis, including the use of Monte Carlo simulation is presented in the Chapter I report (Maslia et al. In press 2007b).

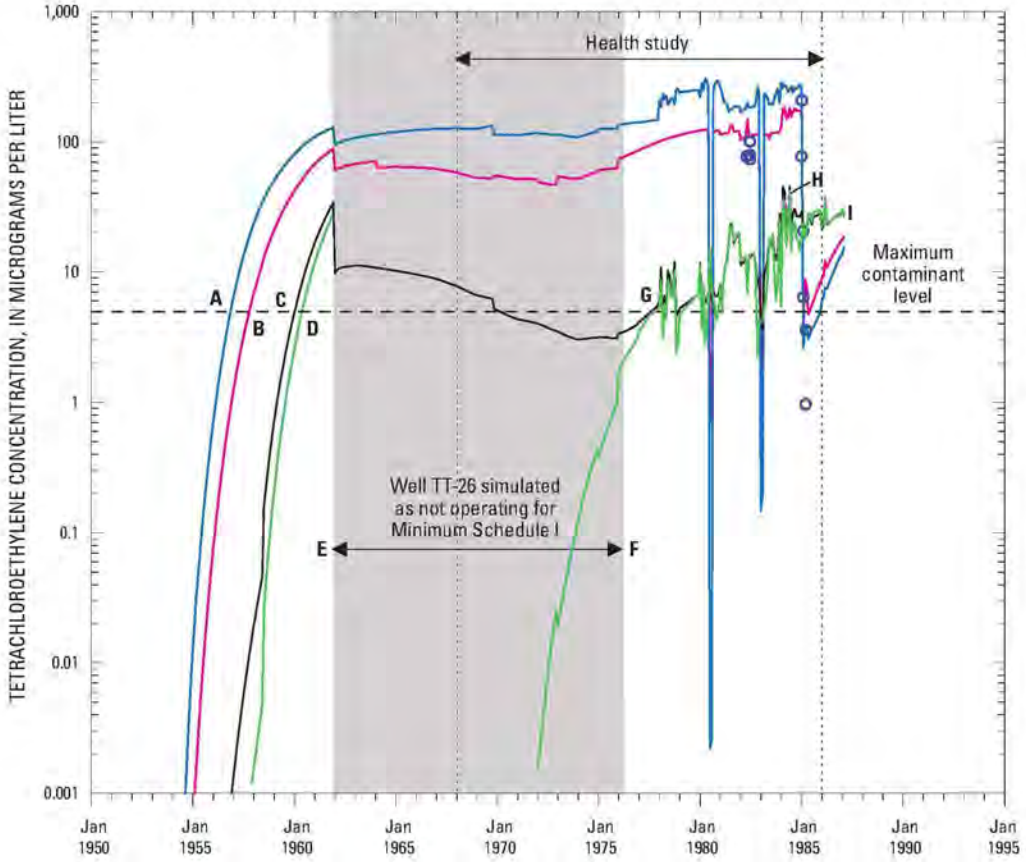
Water-Supply Well Scheduling Analysis

The scheduling and operation histories of Tarawa Terrace 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 concentration at water-supply wells and in finished water at the Tarawa Terrace WTP. 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. This procedure is described in detail in the Chapter H report (Wang and Aral In press 2007). The simulation tool developed for this analysis—PSOpS (Table A4)—combines the MODFLOW-96 and MT3DMS groundwater simulators with a rank-and-assign optimization method developed specifically for the Tarawa Terrace 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. It is important to note that in this analysis, with the exception of pumping rates, groundwater-flow and contaminant transport model parameters were not varied from their calibrated values (Table A11; Faye and Valenzuela [In press 2007]; Faye [In press 2007b]).

Results of analyses using the PSOpS simulation tool to assess the effects of water-supply well pumping variation are presented graphically as a series of curves of simulated PCE concentration in finished water at the Tarawa Terrace WTP versus time (Figure A21).[35] The calibration curve in Figure A21 represents the same data presented in Figure A18 and represents the simulated concentration of finished drinking water delivered from the Tarawa Terrace WTP—derived from analyses described in the Chapter F report (Faye In press 2007b). Calibrated model results indicate that PCE exceeding the

[35] In the following discussion, reference is made to locations shown in Figure A21. These locations are labeled points A–I. Thus, in the ensuing discussion for the section on "Water-Supply Well Scheduling Analysis," a reference to a specific location on the graph, for example, point A, refers solely to Figure A21.

current MCL of 5 µg/L in finished water was delivered from the WTP during November 1957 (point B). By determining an optimal combination of water-supply well pumping in terms of on-off operations and the volumetric pumping rate, it would have been possible for PCE at the 5 µg/L concentration to arrive at the WTP at a date earlier than that reported for the calibrated MT3DMS model. These optimized arrival times are shown as "Earliest arrival" in Figure A21 and are defined as the "Maximum Schedule" in the Chapter H report (Wang and Aral In press 2007). The results show an arrival date 11 months earlier—December 1956 (point A)—than the



EXPLANATION

Calibration—As described in Chapter F (Faye 2007b)

Arrival—As described in Chapter H (Wang and Aral In press 2007),

Late—Defined as *Minimum Schedule I*, well TT-26 not operated January 1962–February 1976

Earliest—Defined as *Maximum Schedule*

Late—Defined as *Minimum Schedule II*, well TT-26 operated at least at 25 percent of capacity

Measured at water treatment plant

Simulation time

Location on graph	Month and year
A	December 1956
B	November 1957
C	February 1960
D	June 1960
E	January 1962
F	February 1976
G	November 1977
H	June 1984
I	February 1987

Figure A21. Sensitivity of tetrachloroethylene concentration in finished water at the water treatment plant to variation in water-supply well operations, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [PCE, tetrachloroethylene; see text for discussion of points A–I]

calibrated arrival date of November 1957. Also notable is the simulated concentration for January–February 1985 of 262 µg/L. This value (262 µg/L) exceeds the observed value of 215 µg/L by 47 µg/L compared with the calibrated value of 176 µg/L (Table A10) that underestimates the observed value by 39 µg/L. Overall, the "Earliest arrival" simulation shows a higher concentration of PCE in finished water delivered from the Tarawa Terrace WTP with a maximum value of 305 µg/L and an average (for concentrations exceeding 5 µg/L) of 132 µg/L. The period during which the current MCL of 5 µg/L for PCE was exceeded under the "Early arrival" scenario was 348 months (29 years).

The PSOpS simulation tool also was used to investigate a variety of other pumping scenarios by specifying limiting values for such well properties as the maximum or minimum pumping rate for a specific water-supply well or group of wells. Two additional results are presented in Figure A21 for simulations that specify minimum operating rates for water-supply well TT-26—25% and 0% of total capacity.[36] The results of these simulations show that when water-supply well TT-26 operated at least at 25% of its capacity—identified as "Minimum Schedule II" in Figure A21 and in the Chapter H report—the arrival of groundwater contaminated with PCE exceeding the current MCL (5 µg/L) was delayed by 27 months—February 1960 (point C)—when compared with the calibrated arrival time of November 1957 (point B). A notable result occurs, however, when water-supply well TT-26 is simulated as being shut down for a period of time—identified as "Minimum Schedule I" in Figure A21 and in the Chapter H report. Based on simulation results, water-supply well TT-26 could have been taken out of service in January 1962 (point E) and kept out of service until February 1976 (point F) with the remaining water-supply wells still capable of meeting all of the water demand during this period for Tarawa Terrace and vicinity. During this time, water-supply well TT-26 was modeled as being off-line, and the resulting simulated concentration of PCE in finished water from the Tarawa Terrace WTP ranged from 0 to less than 2 µg/L. After February 1976 (point F), water-supply well TT-26 had to be simulated as operating to meet increasing demand. Thus, using the PSOpS simulation tool, it was possible to simulate the operation of water-supply well TT-26 in such a manner that the PCE concentration of finished water delivered from the Tarawa Terrace WTP was below 5 µg/L from January 1962 (point E) through February 1976 (point F). Under this simulation scenario—"Minimum Schedule I"—the current MCL was exceeded during the period June 1960 (point D)–December 1961 and for most months during the period November 1977–February 1987 (points G and I, respectively).[37] Under the "Minimum Schedule I" scenario, the maximum PCE concentration in finished water at the Tarawa Terrace WTP was simulated as 41 µg/L during June 1984 (point H).

In summary, analyses of the variation in water-supply well scheduling demonstrate that the current MCL for PCE (5 µg/L) could have been exceeded in finished drinking water delivered from the Tarawa Terrace WTP as early as December 1956 (point A) and no later than June 1960 (point D). Because Tarawa Terrace WTP records indicate that water-supply well TT-26 was most likely operated routinely, the analysis also demonstrates that the earliest time that finished water at the Tarawa Terrace WTP exceeded the current MCL for PCE of 5 µg/L most likely occurred between December 1956 ("Earliest arrival" scenario, point A) and November 1957 (calibrated arrival time, point B). The most likely maximum concentration of PCE in finished water ranged between the "Earliest arrival" scenario maximum of 305 µg/L and the calibrated maximum of 183 µg/L. The mean concentration of PCE in finished water exceeding the current MCL of 5 µg/L most likely ranged between the "Earliest arrival" scenario mean of 131 µg/L and the calibrated mean of 70 µg/L. The analyses conducted using the PSOpS simulation tool provide further evidence that drinking water contaminated with PCE exceeding the current MCL of 5 µg/L was delivered to residents of Tarawa Terrace for a period ranging between the "Earliest arrival" duration of 348 months and the calibrated model duration of 346 months. This analysis further indicates that the concentration of PCE in finished water delivered to residents of Tarawa Terrace, determined from the contaminant fate and transport and mixing model analyses (Faye In press 2007b), are reasonable estimates of historical concentrations.

[36] Using the PSOpS simulation tool, the operation of water-supply well TT-26 was simulated as being shut down for a period of time—0% capacity—and it was allowed to operate as low as 25% of its rated capacity at times. A complete listing of water-supply well capacity data is provided in the Chapter C report (Faye and Valenzuela In press 2007).

[37] There were 103 months during the period November 1977–February 1987. For 14 different months during this period, the PCE concentration in finished water at the Tarawa Terrace WTP was below the current MCL of 5 µg/L, ranging in value from 2.3 to 4.9 µg/L.

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. Numerous methods are described in the literature for conducting sensitivity analysis (Saltelli et al. 2000). For the Tarawa Terrace models, selected model parameters were varied one at a time from their respective calibrated values (Table A11), and the corresponding effect of this variation on the change in the PCE concentration of finished drinking water at the Tarawa Terrace WTP was assessed.[38] In conducting the sensitivity analysis, all calibrated model parameters—with the exception of pumpage—were increased and decreased by factors ranging from 50% to 400% of their calibrated values (Table A14).[39] For example, horizontal hydraulic conductivity for model layer 1 was varied by 90%, 110%, 150%, and 250% of its calibrated value; dispersivity was varied by 50%, 200%, and 400% of its calibrated value. Groundwater-flow model parameters that were subjected to the sensitivity analysis were:

- horizontal hydraulic conductivity of the aquifers (model layers 1, 3, 5, and 7),
- vertical hydraulic conductivity of the semi-confining units (model layers 2, 4, and 6),
- infiltration (recharge) rate, and
- storage coefficients (includes specific yield for model layer 1).

Contaminant fate and transport model parameters that were subjected to the sensitivity analysis were:

- distribution coefficient,
- bulk density,
- effective porosity,
- reaction rate,
- mass-loading rate,
- longitudinal dispersivity, and
- molecular diffusion.

Measures of the effect of varying the groundwater-flow and contaminant fate and transport model parameters were quantified in terms of five computations: (1) the date (month and year) when finished drinking water at the Tarawa Terrace WTP first exceeded the current MCL for PCE (5 µg/L), (2) the duration (in months) that finished drinking water at the WTP exceeded the current MCL, (3) the relative change in these durations (percent) caused by varying the calibrated parameter values, (4) the maximum PCE concentration in finished water at the Tarawa Terrace WTP, and (5) the relative change (percent) in the maximum concentration. Results for selected sensitivity analyses are listed in Table A14. Recall that for calibrated model parameters, the date that the PCE in finished water at the WTP first exceeded the current MCL was simulated as November 1957, and the duration that finished water exceeded the MCL for PCE was 346 months (Figure A18, Table A12). Results of the sensitivity analysis show that some parameters are insensitive to change, even when varied by factors of 10 and 20. For example, large changes in specific yield, storage coefficient, and molecular diffusion resulted in very little change in simulated results (Table A14). Changes in other parameters—for example, horizontal hydraulic conductivity for model layer 1 and infiltration, using values that were less than calibrated values—resulted in wells going dry during the simulation process. Generally, increasing or decreasing a calibrated parameter value by 10% (ratio of varied to calibrated parameter value of 0.9–1.1) resulted in changes of 6 months or less to the date that finished water first exceeded the MCL for PCE (5 µg/L). Complete details pertaining to the use of the sensitivity analysis in relation to calibrated model parameter values and results obtained from the sensitivity analysis are discussed in the Chapter I report (Maslia et al. In press 2007b).

[38] This particular approach to sensitivity analysis is referred to as one-at-a-time (OAT) designs or experiments; details can be found in Saltelli et al. (2000).

[39] Table A14 is a list of selected parameters varied during the sensitivity analysis. For a complete list and discussion of all parameters varied, see the Chapter I report (Maslia et al. In press 2007b).

Table A14. Summary of selected sensitivity analyses conducted on calibrated groundwater-flow and contaminant fate and transport model parameters, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.[1]

[PCE, tetrachloroethylene; MCL, maximum contaminant level; µg/L, microgram per liter; ft/d, foot per day; ft³/g, cubic foot per gram; g/ft³, grams per cubic foot; d⁻¹, 1/day; g/d, grams per day; ft²/d, square foot per day; —, not applicable; WTP, water treatment plant]

Model parameter[2]	Calibrated value	Ratio of varied to calibrated parameter value	Simulated PCE in finished water at the water treatment plant[3]				
			Date first exceeding MCL[4]	Duration exceeding MCL, in months	Relative change in duration, percent[5]	Maximum concentration, in µg/L	Relative change in maximum concentration, percent[6]
Groundwater-flow model parameters							
Horizontal hydraulic conductivity, layer 1, K_H (ft/d)	12.2–53.4	0.9	—[7]	—[7]	—[7]	—[7]	—[7]
		1.1	Aug. 1957	351	1.4	196	7.0
		1.5	Oct. 1956	365	5.5	223	22.0
		2.5	Oct. 1955	377	9.0	209	14.1
Horizontal hydraulic conductivity, layer 3, K_H (ft/d)	4.3–20.0	0.9	Oct. 1957	348	0.6	184	0.5
		1.1	Nov. 1957	345	–0.3	182	–0.5
		1.5	Feb. 1958	341	–1.4	179	–2.3
		2.5	Jul. 1958	339	–2.0	187	2.1
Horizontal hydraulic conductivity, layer 5, K_H (ft/d)	6.4–9.0	0.9	Oct. 1957	347	0.3	185	1.2
		1.1	Nov. 1957	346	0.0	181	–1.0
Horizontal hydraulic conductivity, layer 7, K_H (ft/d)	5.0	0.9	Nov. 1957	346	0.0	183	–0.1
		1.1	Nov. 1957	346	0.0	183	0.1
Infiltration (recharge), I_R (inches per year)	6.6–19.3	0.75	—[7]	—[7]	—[7]	—[7]	—[7]
		1.25	Dec. 1957	343	–0.9	210	14.8
Specific yield, S_y	0.05	10.0	Nov. 1957	342	–1.2	182	–0.6
		20.0	Nov. 1957	338	–2.3	178	–2.6
Storage coefficient, S	4.0×10^{-4}	10.0	Nov. 1957	346	0.0	183	–0.2
		20.0	Nov. 1957	346	0.0	182	–0.3
Fate and transport model parameters							
Distribution coefficient, K_d (ft³/g)	5.0×10^{-6}	0.5	Apr. 1956	371	7.2	214	16.7
		0.9	Jul. 1957	352	1.7	191	4.2
		1.5	Jun. 1959	310	–10.4	165	–10.0
		2.0	Dec. 1960	286	–17.3	143	–21.7
Bulk density, ρ_b (g/ft³)	77.112	0.9	Jul. 1957	352	1.7	191	4.2
		1.1	Mar. 1958	338	–2.3	180	–1.8
Effective porosity, n_E	0.2	0.5	Dec. 1956	363	4.9	349	90.9
		2.0	Sep. 1959	301	–13.0	86	–53.0
Reaction rate, r (d^{-1})	5.0×10^{-4}	0.5	Oct. 1957	349	0.9	294	60.4
		2.0	Jan. 1958	326	–5.8	94	–48.7
Mass-loading rate[5], $q_S C_S$ (g/d)	1,200	0.5	May 1958	329	–4.9	92	–50.0
		1.5	Aug. 1957	351	1.4	275	50.0
Longitudinal dispersivity, α_L (foot)	25	0.5	Apr. 1958	337	–2.6	184	0.3
		2.0	Mar. 1957	356	2.9	181	–1.0
		4.0	Jun. 1956	367	6.1	176	–3.7
Molecular diffusion coefficient, D* (ft²/d)	8.5×10^{-4}	5.0	Nov. 1957	346	0.0	183	–0.1
		10.0	Nov. 1957	346	0.0	183	–0.1
		20.0	Nov. 1957	346	0.0	182	–0.3

[1] See the Chapter I report (Maslia et al. In press 2007b) for a complete listing of parameters that were subjected to variation in the sensitivity analysis

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

[3] For calibrated model, date finished water at WTP exceeded MCL for PCE is November 1957, duration of exceeding MCL is 346 months, and maximum PCE concentration is 183 µg/L—see Table A12

[4] Current MCL for PCE is 5 µg/L (USEPA, 2003); effective date for MCL is July 6, 1992 (40 CFR, Section 141.60, Effective Dates, July 1, 2002, ed.)

[5] Relative change in duration (R_{D_i}) of finished water at the WTP exceeding the MCL for PCE is defined as: $R_{D_i} = \frac{D_i - D_0}{D_0} \times 100\%$, where D_0 is the calibrated duration in months (346) and D_i is the duration in months for the sensitivity analysis using a varied parameter

[6] Relative change in concentration (R_{C_i}) of finished water at Tarawa Terrace WTP exceeding MCL for PCE is defined as: $R_{C_i} = \frac{C_i - C_0}{C_0} \times 100\%$, where C_0 is the calibrated concentration in µg/L (183) and C_i is the PCE concentration for the sensitivity analysis using a varied parameter

[7] Dry wells simulated for this sensitivity analysis

Probabilistic Analysis[40]

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 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). A number of 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 Tarawa Terrace models used numerical methods—Monte Carlo simulation (MCS) and sequential Gaussian simulation (SGS)—to assess model uncertainty and parameter variability. Readers interested in specific details about these methods and about probabilistic analysis in general should refer to the following references: Cullen and Frey (1999), Deutsch and Journel (1998), Doherty (2005), USEPA (1997), and Tung and Yen (2005).

It is important to understand the conceptual difference between the deterministic modeling analysis approach used to calibrate model parameter values by Faye and Valenzuela (In press 2007) and Faye (In press 2007b) 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 A22*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 A22*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).

For the groundwater-flow and contaminant fate and transport models (Faye and Valenzuela In press 2007, Faye In press 2007b), eight parameters were assumed to be uncertain and variable: (1) horizontal hydraulic conductivity, (2) recharge rate, (3) effective porosity, (4) bulk density, (5) distribution coefficient, (6) dispersivity, (7) reaction rate, and (8) the PCE mass loading rate. With the exception of dispersivity, these parameters were selected for the probabilistic analysis because the sensitivity analysis indicated that variation from the calibrated value of the seven parameters resulted in the greatest percentage change in the simulated concentration of PCE in finished water at the Tarawa Terrace WTP (Table A14). Dispersivity was selected for the probabilistic analysis because it is a characteristic aquifer property and represents the effect of aquifer heterogeneity on the spreading of a dissolved contaminant mass (Schwartz and Zhang 2003). Each of the aforementioned model parameters can be represented by a PDF such as a normal, lognormal, triangular, or uniform distribution (Cullen and Frey 1999). In the current analysis, a normal distribution was chosen to represent each uncertain parameter (or variant) with the exception of dispersivity. This variant was represented by a lognormal distribution. Statistics associated with the normal and lognormal distributions for the variants, such as the mean, standard deviation, minimum, and maximum, are listed in Table A15. The calibrated value associated with each variant—derived from model calibrations described in Chapter C (Faye and Valenzuela In press 2007) and Chapter F reports (Faye In press 2007b)—was assigned as the

[40] A probabilistic analysis is defined as an analysis in which frequency (or probability) distributions are assigned to represent variability (or uncertainty) in quantities. The output of a probabilistic analysis is a distribution (Cullen and Frey 1999).

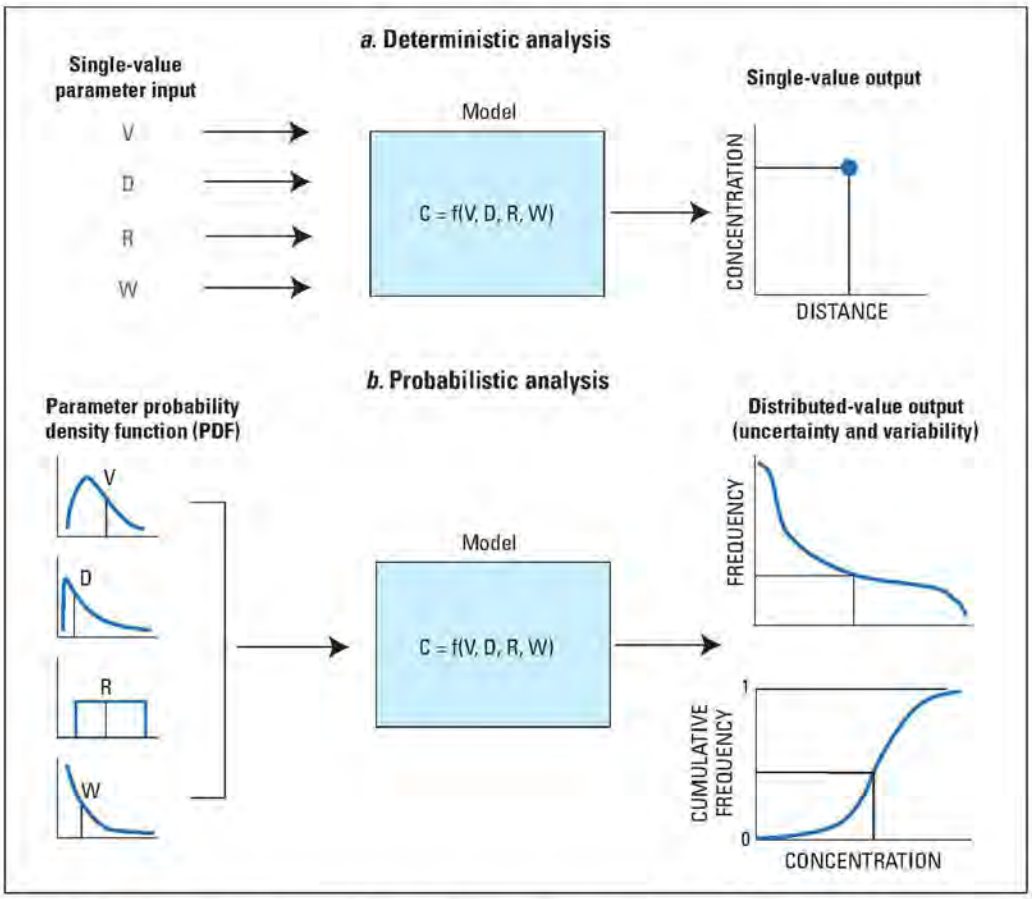


Figure A22. Conceptual framework for *(a)* a deterministic analysis and *(b)* a probabilistic analysis (from Maslia and Aral 2004).

mean value of the distribution associated with each variant. Examples of PDFs generated for recharge, mass loading rate, and dispersivity compared with the appropriate theoretical distribution are shown in Figure A23*a*, A23*b*, and A23*c*, respectively. Two points are noteworthy: (1) for a normal distribution (Figure A23*a* and A23*b*), values for the mean, mode, and median are equal, whereas for a lognormal distribution (Figure A23*c*), the values for the mean, mode, and median are not equal; and (2) because the mean value of recharge varies yearly, the generated values of recharge associated with the PDF also will vary yearly, but the type of PDF will always be the same—in this case, a normal distribution (Figure A23*a*). These types of PDFs were generated for seven of the aforementioned variants[41] with the exception of horizontal hydraulic conductivity.

Horizontal hydraulic conductivity is a parameter for which field values were spatially distributed. For example, in model layers 1, 3, and 5, there were 18, 22, and 5, respectively, spatially distributed values of horizontal hydraulic conductivity (Faye and Valenzuela In press 2007). Using these field values, spatially distributed values of horizontal hydraulic conductivity were generated using Shepard's inverse distance method to approximate values throughout the entire model domain (Chiang and Kinzelbach 2001). This approach resulted in cell by cell and layer by layer spatial variations of horizontal hydraulic conductivity. In this situation, an alternative method, SGS, was used to estimate the distribution of horizontal hydraulic conductivity. The specific code using the SGS methodology, FIELDGEN (Doherty 2005), is advantageous in this situation because it allows the statistical samples or realizations to be representative of field observations. Examples of spatial

[41] See the Chapter I report (Maslia et al. In press 2007b) for additional discussion on PDFs for all varied parameters.

Table A15. Model parameters subjected to probabilistic analysis, Tarawa Terrace and vicinity, U.S. Marine Corp Base Camp Lejeune, North Carolina.[1]

[ft/d, foot per day; ft^3/g, cubic foot per gram; g/ft^3, gram per cubic foot; d^{-1}, 1/day; g/d, grams per day; ft, foot; SGS, sequential Gaussian simulation; MCS, Monte Carlo simulation; PDF, probability density function; —, not applicable]

Model parameter or variant[2]	Calibrated value	Statistical descriptions of input parameter probabilistic distributions[3]				
		Mean	Minimum	Maximum	Standard deviation	Comment
Groundwater-flow model parameters						
Horizontal hydraulic conductivity, layer 1, K_H (ft/d)	12.2–53.4	12.2–53.4	—	—	—	SGS used to generate hydraulic conductivity under a normal distribution[4]
Horizontal hydraulic conductivity, layer 3, K_H (ft/d)	4.3–20.0	4.3–20.0	—	—	—	SGS used to generate hydraulic conductivity under a normal distribution
Horizontal hydraulic conductivity, layer 5, K_H (ft/d)	6.4–9.0	6.4–9.0	—	—	—	SGS used to generate hydraulic conductivity under a normal distribution
Infiltration (recharge), I_R (inches per year)	6.6–19.3	6.6–19.3	4.4	21.9	2.2	MCS used to generate the PDF using a normal distribution; PDF generated for each stress period
Fate and transport model parameters						
Distribution coefficient, K_d (ft^3/g)	5.0×10^{-6}	5.0×10^{-6}	3.53×10^{-6}	2.68×10^{-6}	1.77×10^{-6}	MCS used to generate the PDF using a normal distribution
Bulk density, ρ_b (g/ft^3)	77,112	77,112	69,943	79,004	1,100	MCS used to generate the PDF using a normal distribution
Effective porosity, n_E	0.2	0.2	0.1	0.3	0.05	MCS used to generate the PDF using a normal distribution
Reaction rate, r (d^{-1})	5.0×10^{-4}	5.0×10^{-4}	2.30×10^{-4}	7.70×10^{-4}	1.35×10^{-4}	MCS used to generate the PDF using a normal distribution
Mass-loading rate[5], $q_S C_S$ (g/d)	1,200	1,200	200	2,200	100	MCS used to generate the PDF using a normal distribution
Longitudinal dispersivity, α_L (ft)	25	3.2189	5	125	0.8047	MCS used to generate the PDF using a log-normal distribution[5]

[1]See the Chapter I report (Maslia et al. In press 2007b) for a complete listing of parameters that were subjected to variation in the uncertainty analysis

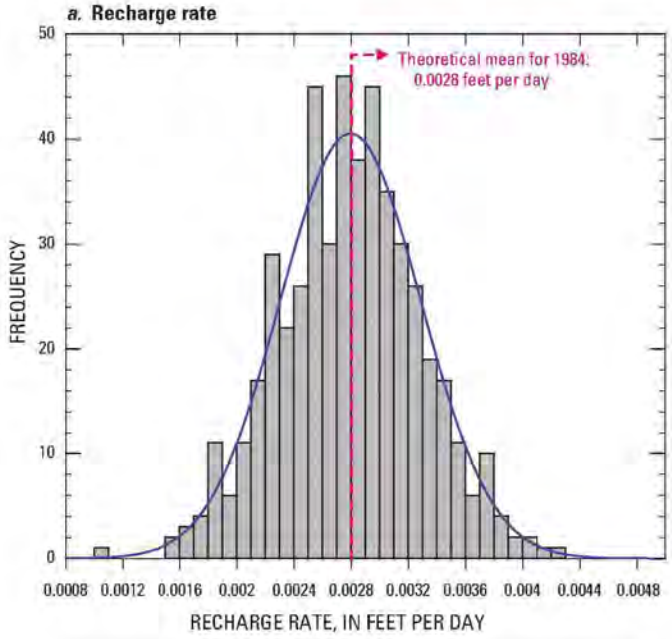
[2]Symbolic notation used to describe model parameters obtained from Chiang and Kinzelbach (2001)

[3]Input values used to seed the pseudo-random number generator

[4]The FIELDGEN model code described in Doherty (2005) was used to generate the random, spatially varying fields of hydraulic conductivity

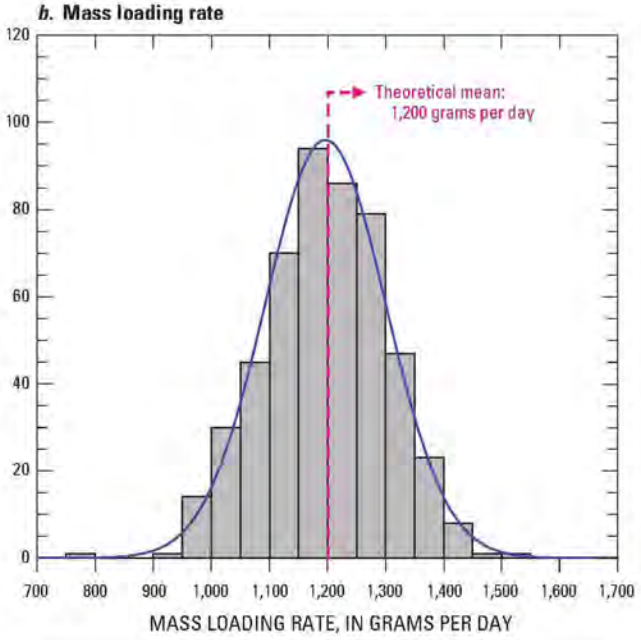
[5]The mean value derived from ln (25); standard deviation derived from ln (5)/2, where ln ( ) is the Naperian logarithm

a. Recharge rate



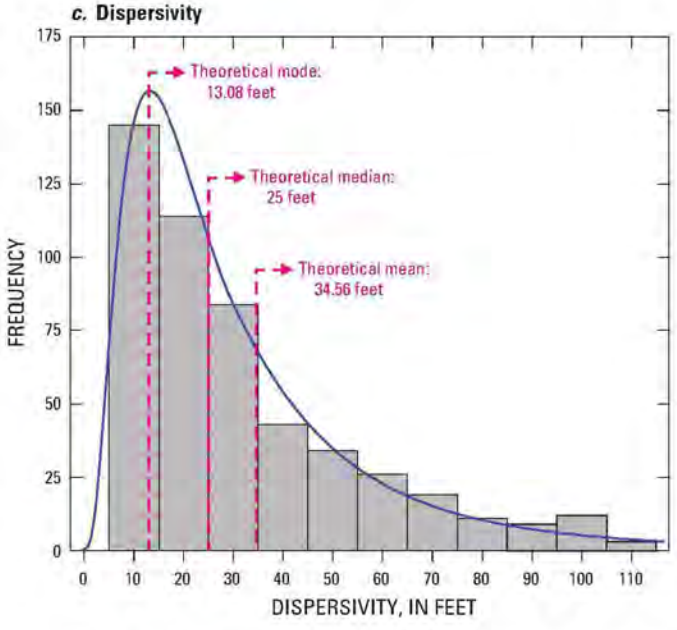
STATISTICS		
	Theoretical	Monte Carlo simulation
Distribution	Normal	Normal
Number of realizations	Not applicable	500
Minimum	– Infinity	0.001
Maximum	+ Infinity	0.005
Mean	0.00280	0.00280
Mode	0.00280	0.00260
Median	0.00280	0.00279
Standard deviation	0.00050	0.00049

b. Mass loading rate



STATISTICS		
	Theoretical	Monte Carlo simulation
Distribution	Normal	Normal
Number of realizations	Not applicable	500
Minimum	– Infinity	200
Maximum	+ Infinity	2,200
Mean	1,200	1,196.1993
Mode	1,200	1,256.5000
Median	1,200	1,198.0200
Standard deviation	100	104.0659

c. Dispersivity



STATISTICS		
	Theoretical	Monte Carlo simulation
Distribution	Lognormal	Lognormal
Number of realizations	Not applicable	500
Minimum	0	5
Maximum	Infinity	125
Mean	34.56	31.32
Mode	13.08	Not available
Median	25	23.85
Standard deviation	32.98	23.59

Figure A23. Probability density functions for *(a)* recharge rate, *(b)* mass loading rate (source concentration), and *(c)* dispersivity used to conduct probabilistic analyses. [–, minus; +, plus]

distributions of horizontal hydraulic conductivity derived by using the SGS process are discussed in greater detail in the Chapter I report (Maslia et al. In press 2007b).

Once the variant PDFs and the multiple spatial distributions of horizontal hydraulic conductivity were generated as previously described, they were used by the MODFLOW-2K (Harbaugh et al. 2000)[42] and MT3DMS groundwater-flow and contaminant fate and transport models, respectively, instead of single-valued input data used in the deterministic approach (Figure A22*a*). This process is shown conceptually in Figure A22*b*. Approximately 500 realizations or Monte Carlo simulations were conducted using a procedure developed specifically for the Tarawa Terrace analyses.[43] This procedure included using MODFLOW-2K, MT3DMS, and mixing models previously described. Each realization randomly selected values from PDFs of the variants derived from MCS and from the random distributions of horizontal hydraulic conductivity derived from the SGS. Specific details about the procedures developed to conduct the probabilistic analysis using the MODFLOW-2K, MT3DMS, and mixing models are described in the Chapter I report (Maslia et al. In press 2007b).

Probabilistic analysis results of finished water for the Tarawa Terrace WTP are shown as a series of histograms for selected times: January 1958 (Figure A24*a*), January 1968 (A24*b*), January 1979 (A24*c*), and January 1985 (A24*d*). These histograms show the probability of a range of PCE-concentration values occurring during a specific month and year. For example, the probability of a PCE concentration of about 100 µg/L occurring in finished water at the Tarawa Terrace WTP during January 1979 can be identified according to the following procedure:

1. Locate the nearest concentration range that includes the 100 µg/L PCE concentration value along the x-axis of the graph in Figure A24*c*, (in this example, the different shaded histogram bar between 96 and 105 µg/L)
2. Move vertically upward until intersecting the top of the histogram bar derived from the Monte Carlo simulation results, and
3. Move horizontally to the left until intersecting the y-axis—for Figure A24*c*, about 15%.

In this example, therefore, the value on the y-axis of Figure A24*c* at the point of intersection—about 15%—is the probability that finished water at the Tarawa Terrace WTP was contaminated with a PCE concentration of about 100 µg/L during January 1979. As a comparison, the same procedure described above is used to determine the probability that finished water was contaminated with the same concentration of PCE (100 µg/L) during January 1985 (Figure A24*d*). For this situation, the probability that finished water at the Tarawa Terrace WTP was contaminated with a PCE concentration of about 100 µg/L during January 1985 is determined to be less than 2%. In other words, for conditions occurring during January 1985, a PCE concentration in the range of 100 µg/L is on the lower end (or "tail") of the normal distribution curve (Figure A24*d*).

[42] MODFLOW-2K is an updated version of the MODFLOW-96 model code developed by the U.S. Geological Survey. Because of programming requirements associated with conducting the MCS, it was programmatically more efficient to use the MODFLOW-2K model code. Model parameter values for MODFLOW-2K were identical and equivalent to the calibrated model parameter values derived using MODFLOW-96 (Table A11; Faye and Valenzuela In press 2007), thereby resulting in equivalent groundwater-flow simulation results for both MODFLOW-96 and MODFLOW-2K.

[43] Initially, 840 MCS realizations were conducted. However, every simulation did not necessarily result in a set of parameter values that yielded a physically viable groundwater-flow or fate and transport solution. For example, some combinations of parameter values resulted in wells drying. Therefore, out of an initial 840 MCS realizations, 510 yielded physically viable solutions.

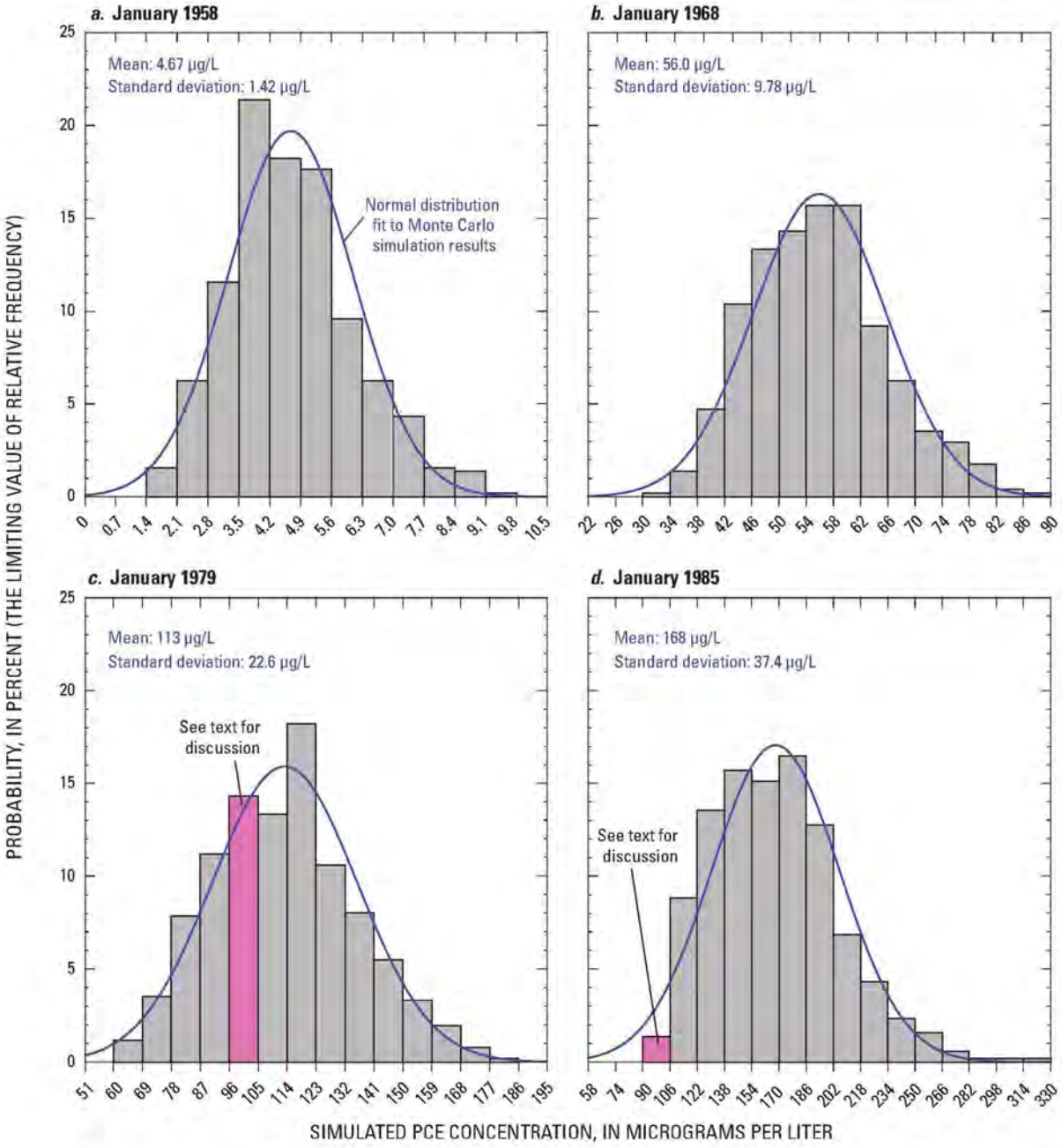


Figure A24. Probability of occurrence of tetrachloroethylene contamination in finished water at the water treatment plant derived from probabilistic analysis using Monte Carlo simulation for *(a)* January 1958, *(b)* January 1968, *(c)* January 1979, and *(d)* January 1985, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [PCE, tetrachloroethylene; µg/L, micrograms per liter]

For purposes of a health study or exposure assessment, epidemiologists and health scientists are interested in obtaining information on the probability that a person or population was exposed to a contaminant exceeding a given health guideline or criteria. For example, the probability that residents of Tarawa Terrace were exposed to drinking water contaminated with PCE exceeding an MCL of 5 µg/L. To address this issue, the MCS results described above can be presented in the form of the complementary cumulative probability function and plotted as a series of probability "type curves" (Figure A25). The complementary cumulative probability function describes the probability of exceeding a certain value or answers the question: how often is a random variable (for example, the concentration of PCE in finished water) above a certain value? Using results shown in figure A25, the probability that the PCE concentration in finished water at the Tarawa Terrace WTP exceeded a value of 5 µg/L during January 1958 is determined in the following manner:

1. Locate the probabilistic type curve for January 1958 in Figure A25*a*,
2. Locate the 5 µg/L PCE concentration along the x-axis of the graph in Figure A25*a*,
3. Follow the vertical line until it intersects with the January 1958 complementary cumulative probability function type curve (point A, Figure A25*a*), and
4. Follow the horizontal line until it intersects the y-axis—for this example, 39%.

In this case, there is a probability of 39% that the PCE concentration in finished water at the Tarawa Terrace WTP exceeded the current MCL of 5 µg/L during January 1958. Because the MCL does not intersect with any other type curves on the graph (Figure A25*a*), this can be interpreted that for other years shown in Figure A25*a* and until water-supply well TT-26 was removed from regular service during February 1985, the probability of exceeding the MCL for PCE is at least 99.8%, or a near certainty.[44]

As discussed previously, because of contaminated groundwater, water-supply well TT-26 was removed from regular service during February 1985 (Figure A5, Table A6). This caused an immediate reduction in the PCE concentration in finished water at the Tarawa Terrace WTP because of the dilution of contaminated WTP water with water from other water-supply wells that were not contaminated or were contaminated with much lower concentrations of PCE than water-supply well TT-26 (Figure A18; Appendix A2). As a result, PCE concentrations in finished water at the Tarawa Terrace WTP during February 1985–February 1987 (when the WTP was permanently closed) were significantly reduced compared with January 1985 concentrations (Figure A18; Appendix A2). Probabilistic type curves representing the complementary cumulative probability function for selected months during January 1985–February 1987 shown in Figure A25*b* also confirm this observation. For example, using the procedure described previously—for February 1985—the probability of exceeding the current MCL for PCE of 5 µg/L is 10% (point F in Figure A25*b*), compared to a probability of 39% during January 1958 and a probability of greater than 99.8% during January 1985.

The probability type curves shown in Figure A25 also can be used to ascertain uncertainty and variability associated with simulated PCE concentrations in finished water at the Tarawa Terrace WTP. For example, referring to points B and C in Figure A25*a*, during January 1958, there is a 97.5% probability that the concentration of PCE in finished water at the Tarawa Terrace WTP exceeded 2 µg/L (point B), and correspondingly, a 2.5% probability that the concentration exceeded 8 µg/L (point C). Thus, during January 1958, 95% of MCS results[45] indicate that the concentration of PCE in finished water at the Tarawa Terrace WTP was in the range of 2–8 µg/L. Stated in terms of uncertainty and variability, during January 1958, the uncertainty is 5% (100% minus 95% of all MCS results), and the corresponding variability in PCE concentration in finished water at the Tarawa Terrace WTP is 2–8 µg/L. As a comparison, this same analysis is conducted for January 1968 (points D and E). For the conditions during January 1968 (the start of the epidemiological case-control study), 95% of MCS results indicate that the concentration of PCE in finished water at the Tarawa Terrace WTP was in the range of 40–80 µg/L. Stated in terms of uncertainty and variability, during January 1968, the uncertainty is 5% (100% minus 95% of all MCS results), and the corresponding variability in PCE concentration in finished water at the Tarawa Terrace WTP is 40–80 µg/L.

[44] Except during July and August 1980 and January and February 1983 when water-supply well TT-26 was out of service—see Figure A18.

[45] In this example, point B (Figure A25*a*) represents 97.5 percentile of Monte Carlo simulations, and point C represents 2.5 percentile of Monte Carlo simulations. Thus, the range of results representing 95 percentile of Monte Carlo simulations is obtained by subtracting the probability-axis value of point C from point B or 97.5%–2.5%.

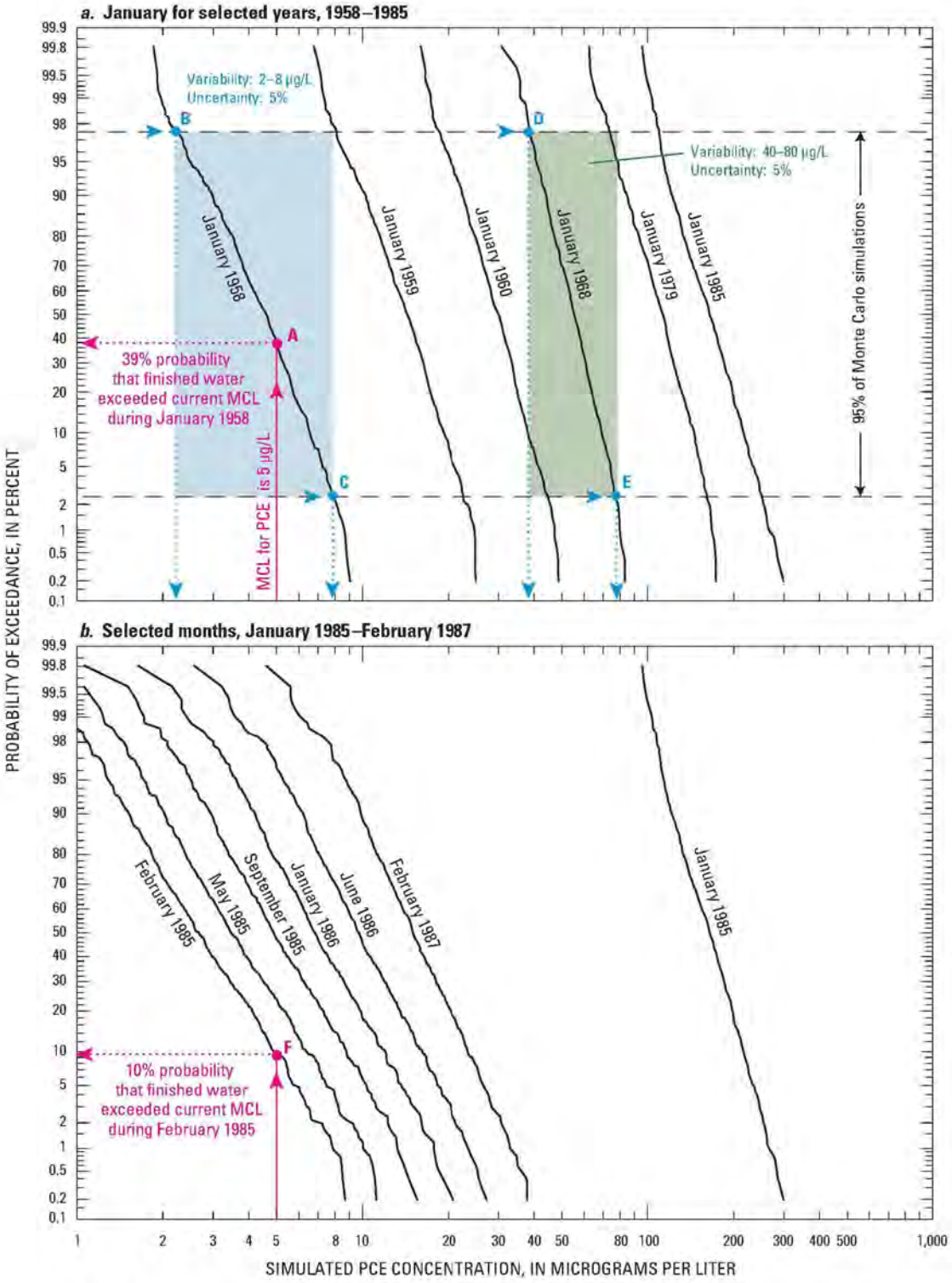


Figure A25. Probabilities of exceeding tetrachloroethylene concentrations in finished water at the water treatment plant derived from probabilistic analysis using Monte Carlo simulation for *(a)* selected years, 1958–1985, and *(b)* selected months, January 1985–February 1987, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina (see text for discussion of points A–F).
[PCE, tetrachloroethylene; MCL, maximum contaminant level; µg/L, micrograms per liter; %, percent]

The probabilistic analysis conducted using MCS was applied to the entire period of operation of the Tarawa Terrace WTP (January 1953–February 1987). The PCE concentration in finished water determined using the deterministic analysis (single-value parameter input and output; Figure A18) also can be expressed and presented in terms of a range of probabilities for the entire duration of WTP operations. Figure A26 shows the concentration of PCE in finished water at the Tarawa Terrace WTP in terms of the MCS results. Several results shown on this graph are worthy of further explanation:

1. The range of PCE concentrations derived from the probabilistic analysis using MCS is shown as a band of solutions in Figure A26 and represents 95% of all possible results.

2. The current MCL for PCE (5 µg/L) was first exceeded in finished water during October 1957–August 1958; these solutions include November 1957, the date determined using the calibrated fate and transport model (Faye In press 2007b)—a deterministic modeling analysis approach.

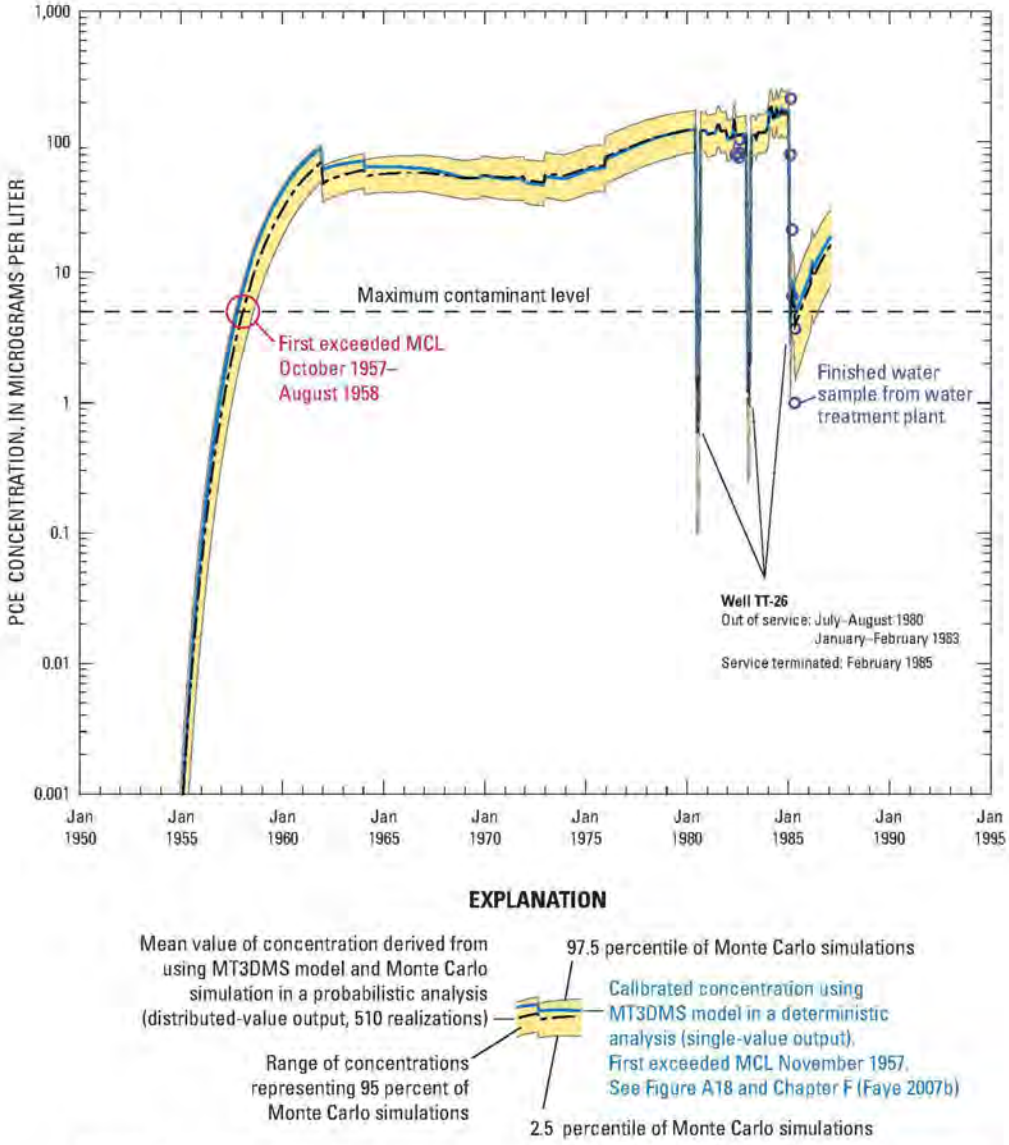


Figure A26. Concentrations of tetrachloroethylene in finished water at the water treatment plant derived from probabilistic analysis using Monte Carlo simulation, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [PCE, tetrachloroethylene; MCL, maximum contaminant level]

3. The PCE concentration in Tarawa Terrace WTP finished water during January 1985, simulated using the probabilistic analysis, ranges from 110–251 µg/L (95 percent of Monte Carlo simulations). This range includes the maximum calibrated value of 183 µg/L (derived without considering uncertainty and variability using MT3DMS [Faye In press 2007b]) and the maximum measured value of 215 µg/L (Table A10).

Therefore, these probabilistic analysis results—obtained by using Monte Carlo simulation—provide a sense of confidence in the historically reconstructed PCE concentrations that were delivered to residents of Tarawa Terrace in finished water from the WTP.

In summary, effects of parameter uncertainty and variability have been 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 (for example, Figure A18), described in the Chapter C (Faye and Valenzuela In press 2007) and Chapter F (In press Faye 2007b) reports. The probabilistic analysis, conducted using the combination of MODFLOW-2K, MT3DMS, MCS, and SGS, provides a tool (probability type curves, Figure A25) to address issues of parameter uncertainty and variability with respect to the concentration of PCE in finished water delivered from the Tarawa Terrace WTP to residents of family housing at Tarawa Terrace and vicinity.

Field Tests and Analyses of the Water-Distribution System

As discussed previously in the section on Water-Distribution Investigation, the initial approach for quantifying the concentration of PCE delivered to residences of Tarawa Terrace was to develop and calibrate a model representation of the water-distribution system using the public domain model EPANET 2 (Rossman 2000). With this approach, street-by-street concentrations of PCE could be simulated and reconstructed. Although using this rigorous approach was replaced with a simpler mixing model approach, field studies were conducted early in the project to gather information needed to develop and calibrate a model of the Tarawa Terrace water-distribution system. A summary of this information and comparison of PCE concentration results using the street-by-street water-distribution system model with the mixing model results are presented herein. A detailed description and discussion of the use and application of water-distribution system modeling with respect to the Tarawa Terrace water-distribution system is provided in the Chapter J report (Sautner et al. In press 2007).

Based on reviews of historical WTP operations as well as housing information, the authors concluded that the historical water-distribution system serving Tarawa Terrace was nearly identical to the present-day (2004) water-distribution system. Thus, information and data collected to characterize the present-day water-distribution system also would be useful in characterizing the historical water-distribution system. The network of pipelines and storage tanks, shown in Figure A27 represents the present-day water-distribution systems serving the Tarawa Terrace and Holcomb Boulevard areas, are nearly identical to historical water-distribution systems serving these areas with the following exceptions:

1. The Holcomb Boulevard WTP came online during June 1972 (Figure A3); prior to that date, the Holcomb Boulevard area received finished water from the Hadnot Point WTP (Plate 1);

2. The Tarawa Terrace and Montford Point WTPs were closed during 1987 (Figure A3) and presently, the Holcomb Boulevard WTP provides finished water to these areas;

3. A pipeline, constructed during 1984, follows SR 24 northwest from the Holcomb Boulevard WTP to ground storage tank STT-39 and presently is used to supply STT-39 in the Tarawa Terrace water-distribution system with finished water (Figure A27); and

4. A pipeline, constructed during 1986, trends east-west from the Tarawa Terrace II area to storage tank SM-623 and presently is used to supply the storage tank with finished water.

Two types of field tests were conducted to determine the hydraulic and water-quality parameter values needed to develop and calibrate a water-distribution system model for Tarawa Terrace: (1) fire-flow tests, conducted during August 2004, in the Tarawa Terrace and Camp Johnson areas; and (2) a fluoride tracer test, conducted during September and October 2004, in the Tarawa Terrace and Holcomb Boulevard areas. Detailed descriptions of the test procedures and results of the field tests are described in the Chapter J report (Sautner et al. In press 2007) and in a number of related papers.

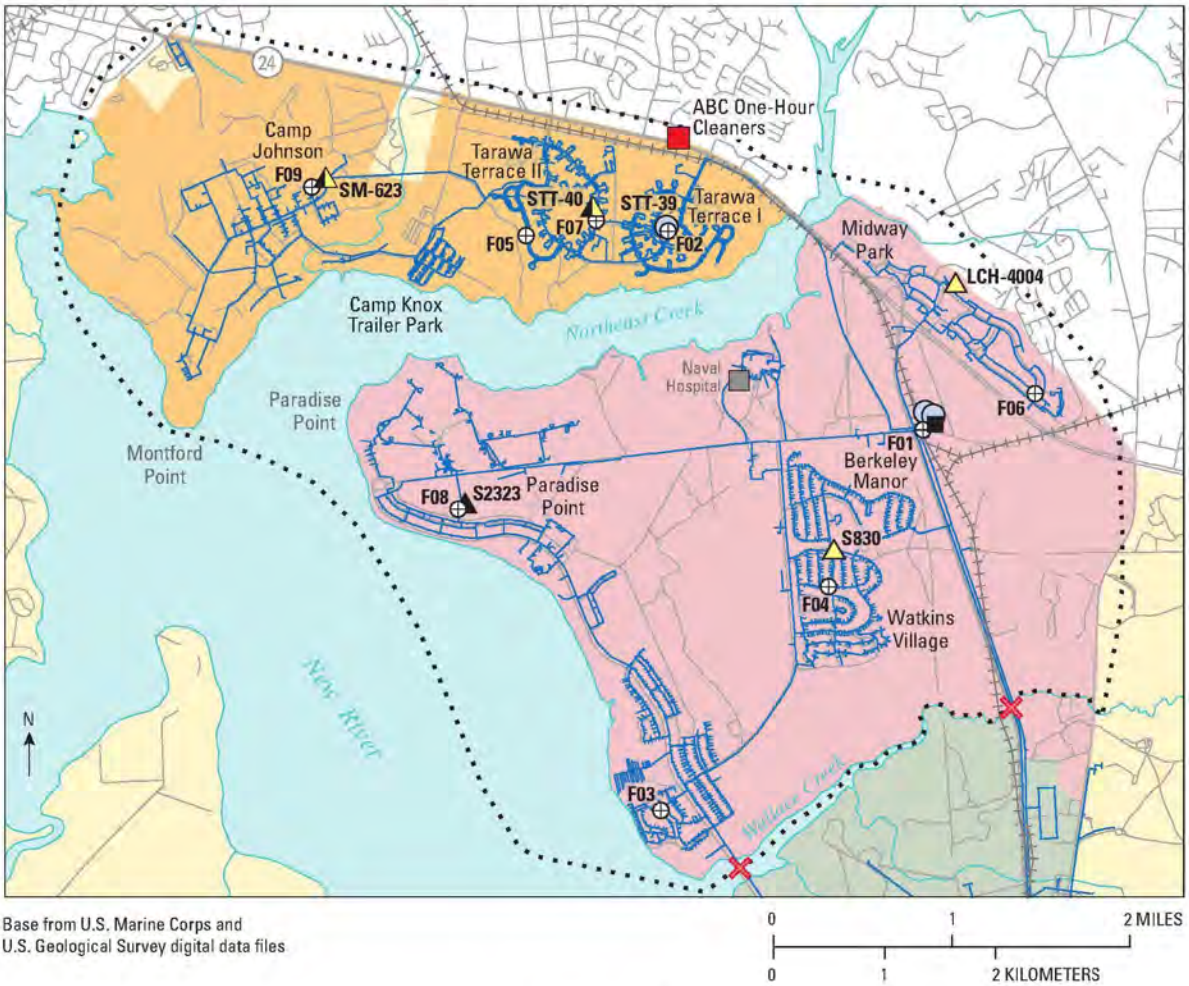


Figure A27. Locations of continuous recording water-quality monitoring equipment (CRWQME; F01–F09) and present-day (2004) Tarawa Terrace and Holcomb Boulevard water-distribution systems used for conducting a fluoride tracer test, September 22–October 12, 2004, U.S. Marine Corps Base Camp Lejeune, North Carolina.

For example, fire-flow tests are described in Sautner et al. (2005) and Grayman et al. (2006). A fluoride tracer test is described in Maslia et al. (2005) and Sautner et al. (2005, 2007).

The use of a fluoride tracer test to characterize a water-distribution system is of particular importance because results obtained from the test—the impact of storage tank operation, travel times, and dilution rates of constituents in the water-distribution system—assist with determining parameter values needed to calibrate a water-distribution system model using extended period simulation (EPS). Additionally, the movement and distribution of fluoride through the Tarawa Terrace water-distribution system would be similar to the movement and distribution of a contaminant, such as PCE through the water-distribution system. Since March 1987, the Holcomb Boulevard WTP has supplied finished water to two water-distribution systems at Camp Lejeune (Figure A27): (1) Holcomb Boulevard[46] and (2) Tarawa Terrace.[47] Therefore, the fluoride tracer test included the collection of data at selected locations within the Tarawa Terrace and Holcomb Boulevard water-distribution systems.

The fluoride tracer test was conducted September 22–October 12, 2004. The test consisted of monitoring fluoride dilution and re-injection (shutoff and startup of the sodium fluoride feed at the Holcomb Boulevard WTP). Nine locations in the Tarawa Terrace and Holcomb Boulevard water-distribution systems were equipped with continuous recording water-quality monitoring equipment (CRWQME). Monitor locations are shown in Figure A27 and are designated as F01–F09. A list of the monitoring locations and the water-distribution system location being monitored is provided in Table A16. Monitoring locations included the main transmission line from the Holcomb Boulevard WTP to the water-distribution system (F01), the Tarawa Terrace finished water reservoir (F02), two controlling elevated storage tanks (Paradise Point [S2323] and

[46] The Holcomb Boulevard WTP provides finished water to the following areas within the Holcomb Boulevard water-distribution system: Berkeley Manor, Watkins Village, Paradise Point, and Midway Park (Figure A27).

[47] Based on present-day operations (2004), the Tarawa Terrace water-distribution system includes the following areas: Tarawa Terrace housing areas I and II, Camp Knox Trailer Park, Camp Johnson, and Montford Point (Figure A27).

Table A16. Description of locations equipped with continuous recording water-quality monitoring equipment used to conduct a fluoride tracer test of the Tarawa Terrace and Holcomb Boulevard water-distribution systems, September 22–October 12, 2004, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Monitoring station identification[1]	Location of continuous recording water-quality monitoring equipment[2]		Water-distribution system location or area	Description of hydraulic device being monitored
	North	East		
F01	356478.25	2498392.43	Holcomb Boulevard	Water treatment plant, main transmission line, fluoride source
F02	362057.78	2490580.75	Tarawa Terrace	Ground storage tank, source for Tarawa Terrace water-distribution system
F03	344823.33	2491037.83	Holcomb Boulevard	Distribution system hydrant
F04	351648.84	2495750.35	Holcomb Boulevard, Berkeley Manor	Distribution system hydrant and elevated storage tank
F05	362270.35	2488417.94	Tarawa Terrace, housing area II	Distribution system hydrant
F06	357638.42	2501665.36	Holcomb Boulevard, Midway Park	Distribution system hydrant
F07	361760.20	2486365.30	Tarawa Terrace, housing area II	Distribution system hydrant and elevated storage tank
F08	353489.91	2484738.57	Holcomb Boulevard, Paradise Point	Controlling elevated storage tank
F09	362945.52	2479935.36	Tarawa Terrace, Camp Johnson	Controlling elevated storage tank

[1] See Figure A27 for station locations

[2] Coordinates are in North Carolina State Plane coordinate system, North American Datum 1983, National Geodetic Vertical Datum of 1929

Camp Johnson [SM623]—F08 and F09, respectively), and five hydrants located throughout housing areas (F03, F04, F05, F06, and F07). The fluoride at the Holcomb Boulevard WTP was shut off at 1600 hours on September 22. A background concentration of about 0.2 milligram per liter (mg/L) in the water-distribution system was reached by September 28. At 1200 hours on September 29, the fluoride was turned back on at the Holcomb Boulevard WTP, and the test continued until loggers were removed and data downloaded on October 12. In addition to CRWQME, grab samples were collected and analyzed for quality-assurance and quality-control purposes. Nine rounds of water samples were collected at each monitoring location during the test. For each round, the Holcomb Boulevard WTP water-quality lab analyzed 25 milliliters (mL) of the sampled water, and the Federal Occupational Health (FOH) laboratory, located in Chicago, Illinois, analyzed the remaining 225 mL of water.

Storage tanks in the Tarawa Terrace and Holcomb Boulevard water-distribution systems are categorized as either controlling or noncontrolling. Controlling elevated storage tanks are operated in the following manner. Finished water is supplied to the respective water-distribution system from the elevated controlling storage tank in response to system demand. When the water level in the controlling tank falls below a pre-set water-level mark, pumps turn on and fill the tank with finished water from a ground storage tank. When the water level in the controlling tank reaches a pre-set high water-level mark, the pumps are turned off. The water level in the tank then begins to drop based on demand until, once again, the water level reaches the pre-set low water level. The fill and drain process is then repeated. An example of water-level data collected by the Camp Lejeune supervisory control and data acquisition (SCADA) system for controlling storage tank STT-40 (Tarawa Terrace elevated, Figure A27) is shown in Figure A28. Two other elevated storage tanks are noncontrolling tanks. These elevated storage tanks show little water-level fluctuation because they are not exercised very often—they are primarily used for fire protection. The elevated storage tanks are S830 (Berkeley Manor) and LCH-4004 (Midway Park), both serving the Holcomb Boulevard water-distribution system (Figure A27).

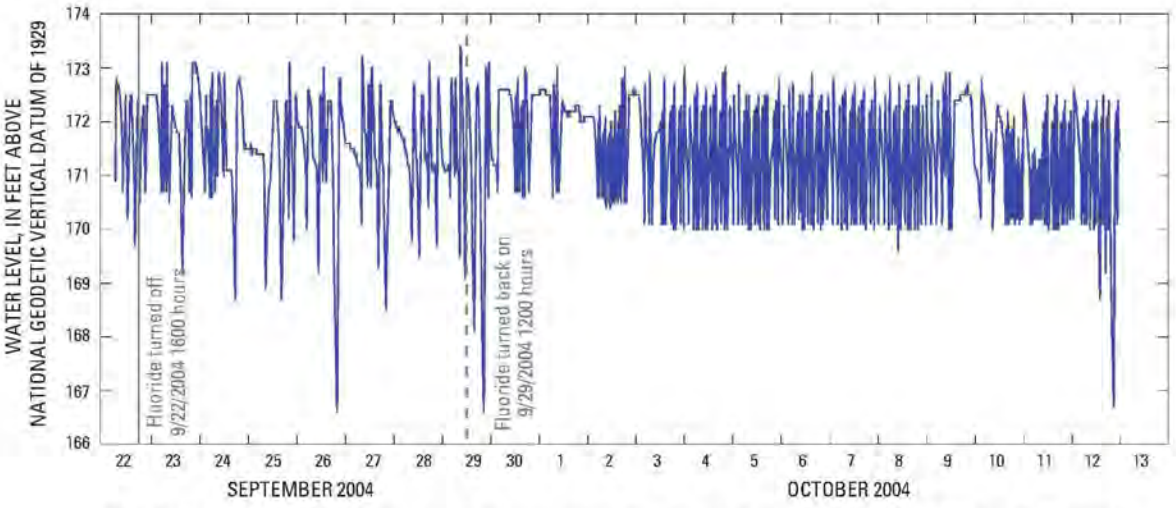


Figure A28. Measured water-level data from the Camp Lejeune SCADA system for controlling elevated storage tank STT-40, September 22–October 12, 2004, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SCADA, supervisory control and data acquisition]

Using results from the fluoride tracer test described previously and the fire-flow test of August 2004, an all-pipes EPS model of the Tarawa Terrace water-distribution system was calibrated. To simplify and reduce the computational requirements, a skeletonized version of an all-pipes representation of the water-distribution system was used for all subsequent EPANET 2 simulations.[48] A 24-hour diurnal pattern based on measured flow data (delivered finished water) and calibrated demand factors is shown in Figure A29.[49] Flow data were measured using a venturi meter located in the Tarawa Terrace pump house (building adjacent to STT-39 in Figure A27).[50] Calibrated demand factors are in reasonable agreement with measured flow data. Details of the calibration procedure and calibration statistics are provided in the Chapter J report (Sautner et al. In press 2007).

[48] Skeletonization is the reduction or aggregation of a water-distribution system network so that only the major hydraulic characteristics need be represented by a model. Skeletonization often is used to reduce the computational requirements of modeling an all-pipes network.

[49] Data for measured delivered flow were previously presented and discussed in the section on Relation of Contamination to Water Supply, Production, and Distribution (Figure A8).

[50] A venturi meter is a device used to measure the flow rate or velocity of a fluid through a pipe. A photograph of the Tarawa Terrace pump house is shown on the front cover of this report.

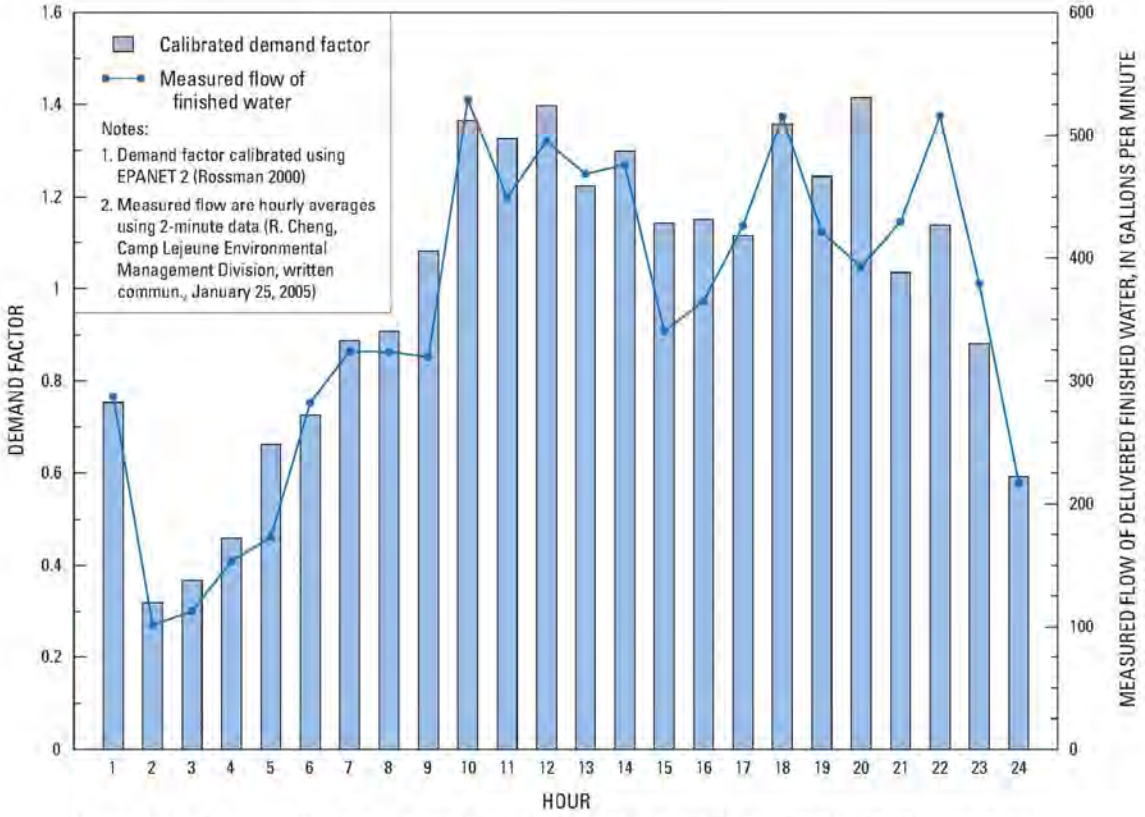


Figure A29. Calibrated and measured diurnal pattern (24 hours) of delivered finished water during field test, September 22–October 12, 2004, Tarawa Terrace water-distribution system, U.S. Marine Corps Base Camp Lejeune, North Carolina. [Flow data measured at venturi meter located in building STT-39A (Tarawa Terrace pump house)]

Simulated fluoride concentrations are compared with measured field data concentrations obtained from the CRWQME and with the grab sample measurements for the Tarawa Terrace water-distribution system at locations F02, F05, F07, and F09 (Figure A27). These comparisons are shown in the graphs of Figure A30. Note that monitoring location F02 is used as the source of fluoride for the Tarawa Terrace water-distribution system. Results shown in Figure A30 along with calibration statistics presented in the Chapter J report (Sautner et al. In press 2007) provide evidence that the EPS model of the Tarawa Terrace water-distribution system is reasonably calibrated and adequately characterizes the present-day (2004) Tarawa Terrace water-distribution system.

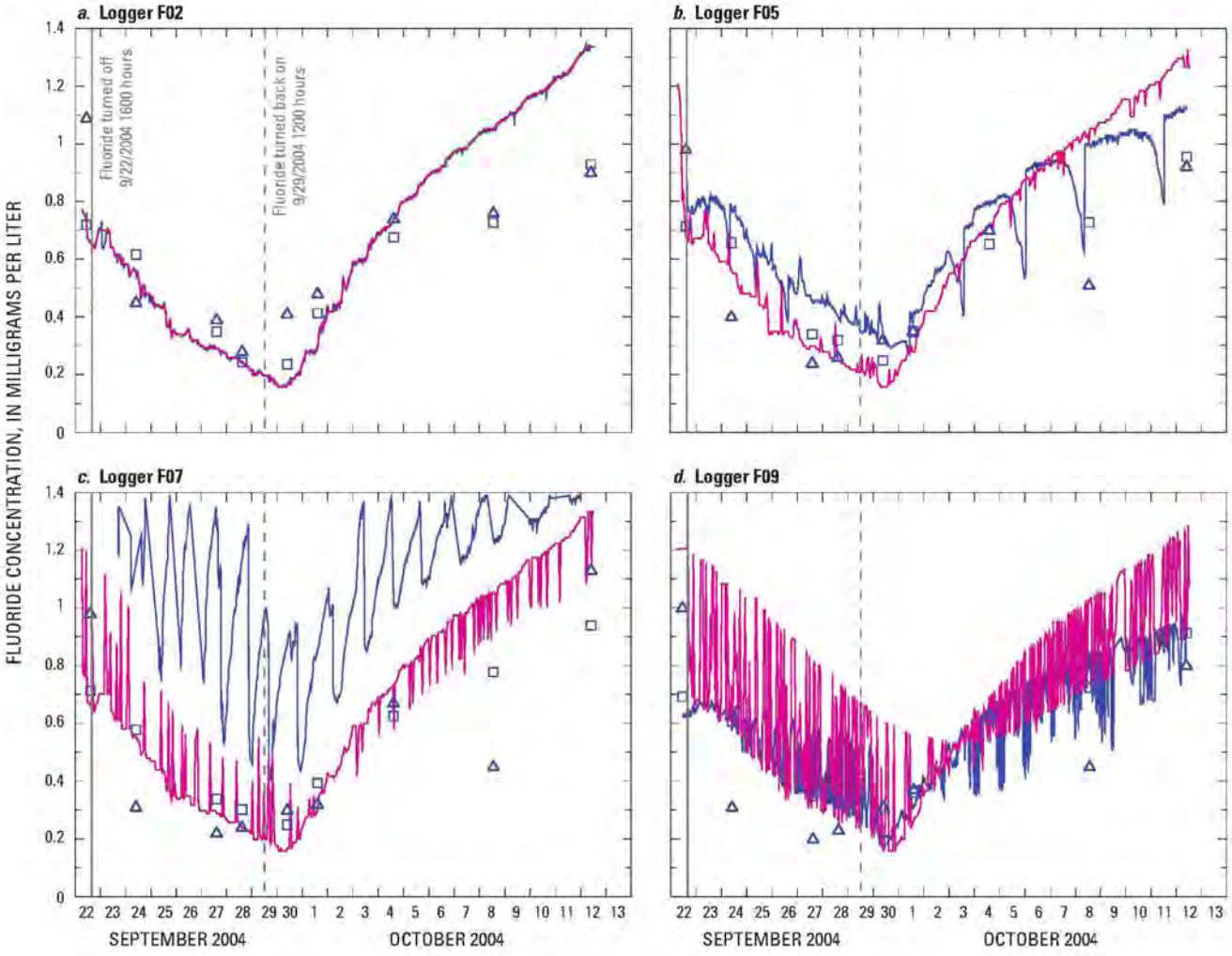


Figure A30. Measured and simulated fluoride concentrations at four monitoring locations *(a)* F02, *(b)* F05, *(c)* F07, and *(d)* F09 in the Tarawa Terrace water-distribution system, September 22–October 12, 2004, U.S. Marine Corps Base Camp Lejeune, North Carolina. (See Figure A27 for monitoring locations and Table A16 for description of hydraulic device being monitored.)

Using the calibrated EPS model of the Tarawa Terrace water-distribution system, conditions representing December 1984 were simulated. This was a period of high water production and usage. The duration of the simulation was 744 hours (31 days). The purpose of the simulation was to test the concept that a mixing model, based on the principles of continuity and conservation of mass (Equations 2 and 3), could be used to estimate the street-by-street concentrations of a contaminant derived using a sophisticated numerical model of the water-distribution system, such as EPANET 2. The mixing model represents a condition of complete mixing and stationary water-quality dynamics in a water-distribution system like Tarawa Terrace where all source water (groundwater) is mixed at the treatment plant. Using the calibrated water-distribution system model, for a simulation period of 744 hours (31 days)—representing December 1984—and an initial source concentration of 173 µg/L at the Tarawa Terrace WTP (Figure A18, Appendix A2), the following results were obtained:

- 100% of the concentration of PCE in finished water at the Tarawa Terrace WTP (173 µg/L) reached locations F05 and F07 (Figure A27), located in the Tarawa Terrace housing area within 2 days,
- 100% of the concentration of PCE in finished water at the Tarawa Terrace WTP (173 µg/L) reached the Camp Johnson elevated storage tank within 3 days, and
- 100% of the simulated concentration of PCE in finished water at the Tarawa Terrace WTP (173 µg/L) reached the Montford Point area (farthest point from the Tarawa Terrace WTP) within 7 days.

These results demonstrate that on a monthly basis, the concentration of PCE at residential housing areas throughout Tarawa Terrace would be nearly the same as the concentration of PCE in finished water at the Tarawa Terrace WTP. Therefore, using a mixing model based on the principles of continuity and conservation of mass is appropriate for determining the concentration of PCE in finished water delivered from the Tarawa Terrace WTP.

Summary and Conclusions

Two of the three drinking-water systems that served family housing at U.S. Marine Corps Base Camp Lejeune were contaminated with VOCs. Groundwater was the sole source of drinking-water supply. One system, the Tarawa Terrace drinking-water system, was mostly contaminated with PCE when water-supply wells were contaminated by off-base dry-cleaning operations at ABC One-Hour Cleaners (Shiver 1985). The other system, the Hadnot Point drinking-water system, was contaminated mostly with TCE from on-base industrial operations. The contaminated wells were continuously used until 1985 and sporadically used until early 1987. ATSDR's health study will try to determine if an association exists between in utero and infant (up to 1 year of age) exposures to drinking-water contaminants and specific birth defects and childhood cancers. The study includes births occurring during 1968–1985 to mothers who lived in base family housing during their pregnancies. Historical exposure data needed for the epidemiological case-control study are limited. To obtain estimates of historical exposure, ATSDR is using water-modeling techniques and the process of historical reconstruction. These methods are used to quantify concentrations of particular contaminants in finished water and to compute the level and duration of human exposure to contaminated drinking water. The analyses and results presented and discussed in this Summary of Findings, and in reports described herein, refer solely to Tarawa Terrace and vicinity. Future analyses and reports will present information and data about contamination of the Hadnot Point water-distribution system.

Based on information, data, and simulation results, the onset of pumping at Tarawa Terrace is estimated to have begun during 1952. Water-supply well TT-26, located about 900 ft southeast of ABC One-Hour Cleaners, probably began operations during 1952 (Figure A1, Table A6). Additionally, the first occurrence of PCE contamination at a Tarawa Terrace water-supply well probably occurred at well TT-26, following the onset of dry-cleaning operations during 1953 (Faye In press 2007b).

Detailed analyses of PCE concentrations in groundwater monitor wells, 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 Terrace 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 (78,737 grams per year) for the period 1953–1985. Pankow and Cherry (1996) indicate that computations of contaminant mass similar to those summarized here represent only a small fraction of the total contaminant mass in the subsurface.

Calibration of the Tarawa Terrace models was accomplished in a hierarchical approach consisting of four successive stages or levels (Figure A9). Simulation results achieved for each calibration level were iteratively adjusted and compared to simulation results of previous levels until results at all levels satisfactorily conformed to pre-selected calibration targets (Table A8). In hierarchical order, calibration levels consisted of the simulation of (1) predevelopment groundwater-flow conditions (Figure A10*a*), (2) transient or pumping groundwater-flow conditions (Figure A10*b*), (3) the fate and transport of PCE from the source at ABC One-Hour Cleaners (Figure A11), and (4) the concentration of PCE in finished water at the Tarawa Terrace WTP (Figure A12).

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 A18). The simulated PCE concentration in water-supply well TT-26 exceeded the current MCL of 5 µg/L during January 1957 (simulated value 5.2 µg/L) and reached a maximum simulated value of 851 µg/L during July 1984 (Table A12). The mean simulated PCE concentration during the period exceeding the current MCL of 5 µg/L—January 1957–January 1985—was 414 µg/L, a duration of 333 months.

The monthly concentrations of PCE assigned to finished water at the Tarawa Terrace WTP were determined using a materials mass balance model (simple mixing). 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. Finished water contaminated with PCE exceeded the current MCL of 5 µg/L during November 1957. Based on mixing model results, finished water exceeded the MCL for 346 months (29 years)—November 1957–February 1987 (Figure A18, Table A12).[51] The maximum simulated PCE concentration in finished water was 183 µg/L occurring during March 1984. The maximum observed PCE concentration was 215 µg/L measured on February 11, 1985 (Table A10). The average simulated PCE concentration for the period exceeding the current MCL of 5 µg/L—November 1957–February 1987—was 70 µg/L.

The calibrated fate and transport model simulated PCE as a single-specie contaminant dissolved in groundwater. However, evidence of the transformation of PCE to degradation by-products of TCE and 1,2-tDCE was found in water samples obtained from Tarawa Terrace water-supply wells TT-23 and TT-26. Thus, the simulation of PCE and its degradation by-products was necessary. For this simulation, a model code identified as TechFlowMP, developed by the Multimedia Environmental Simulations Laboratory (MESL) at the Georgia Institute of Technology, was used. TechFlowMP simulates three-dimensional multiphase, multispecies mass transport of PCE and its associated degradation by-products TCE, 1,2-tDCE, and VC in the unsaturated and saturated zones at Tarawa Terrace and vicinity (that is, the sequential biodegradation and transport of PCE). Simulation results for finished water at the Tarawa Terrace WTP (Figure A19*b*), contaminated with PCE degradation by-products TCE, 1,2-tDCE, and VC, show that: (1) TCE was below the current MCL value of 5 µg/L for nearly the entire historical period except during January 1984–January 1985 when it ranged between 5 and 6 µg/L; (2) 1,2-tDCE was below the current MCL value of 100 µg/L for the entire historical period; and (3) VC was at or above the current MCL value of 2 µg/L from May 1958 through February 1985 when water-supply well TT-26 was shut down. As part of the degradation by-product simulation using the TechFlowMP model, results also were obtained for VOCs in the vapor phase (above the water table in the unsaturated zone). Analyses of the distribution of vapor-phase PCE indicate there is

[51] This period does not include the months of July–August 1980 and January–February 1983, when water-supply well TT-26 was not operating.

potential for vapors from these plumes to enter buildings at Tarawa Terrace I, thereby providing a potential exposure pathway for inhalation of PCE vapor. At Tarawa Terrace I these buildings would include family housing and the elementary school (Figure A20).

To address issues of model uncertainty and parameter variability, three types of analyses were conducted: (1) water-supply well scheduling analysis, (2) sensitivity analysis, and (3) probabilistic analysis. All of the additional analyses were conducted using PCE as a single-specie contaminant dissolved in groundwater—the calibrated models described in Chapter C (Faye and Valenzuela In press 2007) and Chapter F (Faye In press 2007b) reports. The simulation tool, PSOpS, was used to investigate the effects of unknown and uncertain historical well operations and analyses of the variation in water-supply well scheduling. PSOpS simulations demonstrate 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 (points A and D, respectively, in Figure A21).

Sensitivity analyses were conducted using Tarawa Terrace models. Selected model parameters were varied one at a time from their respective calibrated values (Table A11). The effect of this variation on the change in the PCE concentration of finished drinking water at the Tarawa Terrace WTP was assessed. Four groundwater-flow and seven fate and transport model parameters were varied. Results of the sensitivity analyses showed that some parameters—specific yield, storage coefficient, and molecular diffusion—were insensitive to change, even when varied by factors of 10 and 20 (Table A14). Other parameters, for example, horizontal hydraulic conductivity for model layer 1 and infiltration (groundwater recharge), were extremely sensitive to values less than the calibrated values. Reducing the calibrated values for these parameters resulted in wells drying up during the simulation process. Generally, increasing or decreasing a calibrated parameter value by 10% (ratio of varied to calibrated parameter value of 0.9–1.1) resulted in changes of 6 months or less in terms of the date that finished drinking water first exceeded the current MCL of 5 µg/L for PCE. Results of parameter variations were used, in part, to assist in selecting parameters considered for a probabilistic analysis.

A probabilistic analysis approach was used to investigate model uncertainty and parameter variability using MCS and SGS. For the groundwater-flow and contaminant fate and transport models (Faye and Valenzuela In press 2007, Faye In press 2007b), eight parameters were assumed to be uncertain and variable: (1) horizontal hydraulic conductivity, (2) recharge rate, (3) effective porosity, (4) bulk density, (5) distribution coefficient, (6) dispersivity, (7) reaction rate, and (8) the PCE mass loading rate. With the exception of horizontal hydraulic conductivity, PDFs were generated for the remaining seven parameters of variation using Gaussian pseudo-random number generators. Horizontal hydraulic conductivity is a parameter for which there were spatially distributed field values. Therefore, an alternative method, SGS, was used to estimate the distribution of horizontal hydraulic conductivity for model layers 1, 3, and 5. The probabilistic analyses indicated that 95% of Monte Carlo simulations show the current MCL for PCE (5 µg/L) was first exceeded in finished water during October 1957–August 1958 (Figure A26); these solutions include November 1957, the date determined from the calibrated contaminant fate and transport model (Faye In press 2007b) that was based on a deterministic (single-value parameter input and output) approach. The PCE concentration in Tarawa Terrace WTP finished water during January 1985, simulated using the probabilistic analysis, ranges from 110 to 251 µg/L (95 percent of Monte Carlo simulations). This range includes the maximum calibrated value of 183 µg/L (derived without considering uncertainty and variability using MT3DMS) and the maximum measured value of 215 µg/L.

As part of this investigation, field tests were conducted on the present-day (2004) water-distribution system serving Tarawa Terrace. Data gathered from the investigation were used to construct a model of the water-distribution system using the EPANET 2 model code. Based on reviews of historical maps and information, the present-day (2004) water-distribution system is very similar to the historical water-distribution system. Thus, the operational and water-delivery patterns determined for the present-day (2004) water-distribution system from field investigations (Sautner et al. 2005, In press 2007) were used to characterize the historical water-distribution system. Using a calibrated water-distribution system model and an initial source concentration of 173 µg/L

at the Tarawa Terrace WTP (Figure A18), an extended period simulation of 744 hours (31 days), representing December 1984, indicates:

- 100% of the concentration of PCE in finished water at the Tarawa Terrace WTP (173 µg/L) reached locations F05 and F07 (Figure A27), located in the Tarawa Terrace housing area within 2 days,
- 100% of the concentration of PCE in finished water at the Tarawa Terrace WTP (173 µg/L) reached the Camp Johnson elevated storage tank within 3 days, and
- 100% of the simulated concentration of PCE in finished water at the Tarawa Terrace WTP (173 µg/L) reached the Montford Point area (farthest point from the Tarawa Terrace WTP) within 7 days.

These results confirm the assumption that on a monthly basis, the concentration of PCE at residential housing areas throughout Tarawa Terrace would be the same as the concentration of PCE in finished water at the Tarawa Terrace WTP. Therefore, using a mixing model based on the principles of continuity and conservation of mass (Equations 2 and 3, respectively) was appropriate for reconstructing the historical concentrations of PCE in finished water delivered from the Tarawa Terrace WTP.

In summary, 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:

1. 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.

2. Simulated PCE concentrations exceeded the current MCL of 5 µg/L in finished water at the Tarawa Terrace WTP 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.

3. Simulation of PCE degradation by-products—TCE, *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride—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.

4. Maximum concentrations of the degradation by-products in finished water at the Tarawa Terrace WTP 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.

5. PCE concentrations in finished water at the Tarawa Terrace WTP exceeding the current MCL of 5 µg/L could have been delivered as early as December 1956 and no later then December 1960. 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 first exceedance date of November 1957.

6. Exposure to PCE and PCE degradation by-products from contaminated drinking water ceased after February 1987; the Tarawa Terrace WTP was closed March 1987.

Availability of Input Data Files, Models, and Simulation Results

Calibrated model input data files developed for simulating predevelopment groundwater flow, transient ground-water flow, the fate and transport of PCE as a single specie, and the distribution of water and contaminants in a water-distribution system are provided with this report in a DVD format. Public domain model codes used with these input files are available on the Internet at the following Web sites:

- Predevelopment and transient groundwater flow
  - Model code: MODFLOW-96
  - Web site: *http://water.usgs.gov/nrp/gwsoftware/modflow.html*

- Fate and transport of PCE as a single specie
  - Model code: MT3DMS
  - Web site: *http://hydro.geo.ua.edu/*
- Distribution of water and contaminants in a water-distribution system
  - Model code: EPANET 2
  - Web site: *http://www.epa.gov/nrmrl/wswrd/epanet.html*

Specialized model codes and model input data files were developed specifically for the Tarawa Terrace analyses by the MESL at the School of Civil and Environmental Engineering, Georgia Institute of Technology. These specialized codes and input data files were developed for simulating three-dimensional multispecies, multiphase, mass transport (TechFlowMP) and pumping schedule optimization (PSOpS) and are described in detail in the Chapter G (Jang and Aral In press 2007) and Chapter H (Wang and Aral In press 2007) reports, respectively. Contact information and questions related to these codes are provided on the Internet at the MESL Web site at: *http://mesl.ce.gatech.edu*.

Also included on the DVDs accompanying this report is a file that contains results for monthly simulated concentrations of PCE and PCE degradation by-products (TCE, 1,2-tDCE, and VC) in finished water at the Tarawa Terrace WTP for January 1951–March 1987. This file (also provided in Appendix A2) is prepared in Adobe® Portable Document Format (PDF).

Readers desiring information about the model input data files or the simulation results contained on the DVDs also may contact the Project Officer of ATSDR's Exposure-Dose Reconstruction Project at the following address:

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Acknowledgments

A study of this complexity and magnitude is dependent upon the assistance, input, and suggestions of many colleagues. Thus, the authors of this report and all chapter reports acknowledge the managers and staff of the U.S. Geological Survey Water Science Centers in Raleigh, North Carolina, and Atlanta, Georgia. In particular, the contributions of Melinda J. Chapman, Douglas A. Harned, and Stephen S. Howe are acknowledged for providing the majority of well, water-level, and pumpage data used in this study. Keith W. McFadden is acknowledged for assistance with spatial analyses in preparing illustrations and with developing geodatabases, Web-based applications, and the querying system contained on the electronic media accompanying Chapters A and K. Gregory C. Mayer and Edward H. Martin also are acknowledged for their administrative assistance.

The authors acknowledge the staff of the Environmental Management Division, U.S. Marine Corps Base Camp Lejeune, North Carolina. In particular, Scott A. Brewer, Brynn Ashton, Scott R. Williams, and Rick Cheng for their assistance and cooperation during the course of this study, especially for providing a large number of technical reports, maps, and historical documents, which summarize the results of groundwater remedial investigations at and in the vicinity of Tarawa Terrace. The authors also acknowledge Joel Hartsoe and Danny E. Hill of the Camp Lejeune Public Works Department Utility Section.

The authors acknowledge the contributions of the USEPA, Region IV, Atlanta, Georgia, for providing reports and documents summarizing the results of investigations of groundwater contamination in the vicinity of ABC One-Hour Cleaners and in the northern part of Tarawa Terrace.

The authors acknowledge colleagues at ATSDR, Eastern Research Group, Inc., the Multimedia Environmental Simulations Laboratory at the Georgia Institute of Technology, and the Oak Ridge Institute for Science and Education for providing assistance and advice with all aspects of this study.

Thomas M. Plummer, Commander, U.S. Public Health Service, Indian Health Service, U.S. Department of Health and Human Services, assisted with planning, field instrumentation, and conducting tests of water-distribution systems serving Camp Lejeune, August 18–28, 2004.

Caryl J. Wipperfurth, Bonnie J. Turcott, Patricia L. Nobles, James E. Banton, and Kimberly A. Waltenbaugh, U.S. Geological Survey Enterprise Publishing Network, assisted with the preparation of text, illustrations, and electronic media.

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Appendix A1. Summaries of 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—this report) 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 In press 2007a) 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 composed 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 In press 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. Comparison of 59 observed water levels representing estimated 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 In press 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 K_{ow}), and organic carbon partition (log K_{oc}) 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 In press 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 Terrace 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 In press 2007b) 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 transport 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 Tetrachloroethylene (PCE) and Associated Degradation By-Products (Jang and Aral In press 2007) 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 maximum concentrations of PCE degradation by-products, TCE, 1,2-tDCE, and VC, generally ranged between 10 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 In press 2007) 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 Environmental 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 Transport, and Distribution of Drinking Water (Maslia et al. In press 2007b) 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 [In press 2007b]) occurred during November 1957.

Chapter J: Field Tests, Data Analyses, and Simulation of the Distribution of Drinking Water (Sautner et al. In press 2007) describes field tests, data analyses, and the simulation of drinking-water supply at Tarawa Terrace and vicinity. Details of the development and calibration of a water-distribution system model for Tarawa Terrace and vicinity are described based on applying the model code EPANET 2 (Rossman 2000) to the study area. Comparisons are provided between the PCE concentrations computed by Faye (In press 2007b) using a simple mixing model and the more complex and detailed approach of Sautner et al. (In press 2007) that is based on a numerical water-distribution system model. Results of simulations conducted using extended period simulation confirm the assumption that, on a monthly basis, the concentrations of PCE in drinking water delivered to residential housing areas throughout Tarawa Terrace are the same as the concentrations of PCE in finished water at the Tarawa Terrace WTP. Therefore, a simple mixing model based on the principles of continuity and conservation of mass was an appropriate model to use for determining the concentration of PCE in finished water delivered from the Tarawa Terrace WTP.

Chapter K: Supplemental Information (Maslia et al. In press 2007a) presents additional information such as (1) a tabular listing of water-supply well pumpage by stress period (month and year); (2) synoptic maps showing groundwater levels, directions of groundwater flow, and the simulated distribution of PCE; (3) a tabular listing of simulated monthly concentrations of PCE dissolved in groundwater at Tarawa Terrace water-supply wells; (4) a tabular listing of simulated monthly concentrations of PCE and PCE degradation by-products—TCE, 1,2-tDCE, and VC at the Tarawa Terrace WTP; (5) a complete list of references used in conducting the water-modeling analyses and historical reconstruction process; and (6) other ancillary information and data that were used during the water-modeling analyses and historical reconstruction process.

Appendix A2. Simulated PCE and PCE Degradation By-Products in Finished Water, Tarawa Terrace Water Treatment Plant, January 1951–March 1987

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 A3. Questions and Answers

What is the purpose of the ATSDR health study?

Two of the three drinking-water systems that served family housing at U.S. Marine Corps Base Camp Lejeune were contaminated. One system, the Tarawa Terrace drinking-water system, was mostly contaminated with tetrachloroethylene (or perchloroethylene, PCE) from off-base dry-cleaning operations. The other system, the Hadnot Point drinking-water system, was contaminated mostly with trichloroethylene (TCE) from on-base industrial operations. The contaminated wells were continuously used until 1985 and sporadically used until early 1987. ATSDR's health study will try to determine if there was a link between in utero and infant (up to 1 year of age) exposures to drinking-water contaminants and specific birth defects and childhood cancers. The study includes births occurring during 1968–1985 to mothers who lived in base family housing during their pregnancy. The birth defects and childhood cancers that will be studied are:

- neural tube defects (spina bifida and anencephaly),
- cleft lip and cleft palate, and
- leukemia and non-Hodgkin's lymphoma.

Why is ATSDR studying exposure to VOC-contaminated drinking water since other studies have already done this?

Only a few studies have looked at the risk of birth defects and childhood cancers among children born to women exposed during pregnancy to volatile organic compounds (VOCs) such as TCE and PCE in drinking water. This study is unique because it will estimate monthly levels of drinking-water contaminants to determine exposures.

What is in the ATSDR reports about the Tarawa Terrace drinking-water system?

Chapter A provides a summary of detailed technical findings (found in Chapters B–K) for Tarawa Terrace and vicinity. The findings focus on modeling techniques used to reconstruct historical and present-day conditions of groundwater flow, contaminant fate and transport, and distribution of drinking water. Information from the water-modeling analyses will be given to researchers conducting the health study. (Future analyses and reports will present information and data about the Hadnot Point drinking-water system.)

Why is ATSDR using water modeling to estimate exposure rather than real data?

Data on the levels of VOC contaminants in drinking water are not available before 1982. To determine levels before 1982, ATSDR is using a process called "historical reconstruction." This process uses data on the amount of the chemicals dumped on the ground. It also uses the properties of the soil, the groundwater, and the water-distribution system. These data are then used in computer models. The models estimate when contaminants first reached drinking-water wells. The models also estimate monthly levels of contaminants in drinking water at family housing units. This information is important for the health study. It can also be used by those who lived in base family housing to estimate their exposures.

What is a water model?

A water model is a general term that describes a computer program used to solve a set of mathematical equations that describe the:

- flow of groundwater in aquifers,
- movement of a contaminant mixed with groundwater,
- mixing of water from contaminated and uncontaminated water-supply wells at a water treatment plant, or
- flow of water and contaminants from reservoirs, wells, and storage tanks through a network of pipelines.

What information did ATSDR use to develop the water models and what were the sources of the information?

The historical reconstruction process required information and data describing physical characteristics of the groundwater-flow system, conservation principles that describe the flow system, the specific data on the contaminant (PCE) and its degradation by-products, and the water-distribution system. The following specific data needs were required:

- aquifer characteristics: geohydrologic, hydraulic, water production, fate, transformation, and transport;
- chemical properties characteristics: physical, fate, transformation, and transport; and
- water-distribution system characteristics: pipeline characteristics, storage-tank geometry, pumps, water-production data, and water-quality parameters.

Information and data used to conduct the historical reconstruction analysis were obtained from a variety of sources. These sources included ATSDR, U.S. Environmental Protection Agency, 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. Chapters A and K of the Tarawa Terrace report provide searchable electronic databases—on DVD format—of information and data sources used to conduct the historical reconstruction analysis.

How can ATSDR be sure that water-modeling results represent historical "real-world" conditions?

A water model requires information on the specific properties or "parameters" of the soil, groundwater, and water system at the base. Often assumptions are needed because complete and accurate data are not available for all the parameters that must be modeled. In particular, historical data are often lacking. To be sure that water-modeling results are accurate and represent historical "real-world" conditions, a model needs to be calibrated. A calibration process compares model results with available "real-world" data to see if the model's results accurately reflect "real-world" conditions. This is done in the following way. Models are constructed using different combinations of values for the parameters. Each model makes a prediction about the groundwater-flow rate, the amount of water produced by each well, and the contamination level in the drinking-water system at a particular point in time. These predictions are then compared to "real-world" data. When the combination of parameter values that best predicts the actual "real-world" conditions are selected, the model is "calibrated." The model is now ready to make predictions about historical conditions.

Why did ATSDR develop and calibrate two models for simulating the migration of PCE from ABC One-Hour Cleaners to Tarawa Terrace water-supply wells?

At first, ATSDR developed a model that simulated the fate and transport (migration) of PCE that was completely mixed in groundwater in the saturated zone (zone below the water table). The model code used is known as MT3DMS. ATSDR developed a second model because of suggestions from a panel of experts and requests from former marines and their technical advisers. The second model is capable of simulating the fate and transport of PCE and its degradation by-products of TCE, *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) in the unsaturated zone (area above the water table) and the saturated zone. This model, known as TechFlowMP, is based on significantly more complex mathematical equations and formulations. This highly complex model also can simulate PCE and its degradation by-products in both the vapor and water phases. Values of simulated PCE concentrations in the saturated zone obtained using the two different models (MT3DMS and TechFlowMP) are very close.

Why is ATSDR providing simulated PCE concentrations in finished water at the Tarawa Terrace water treatment plant (WTP) rather than at locations of specific family housing units?

ATSDR did in-depth reviews of historical data, including water-supply well and WTP operational data when available. ATSDR concluded that the Tarawa Terrace water-distribution system—including the WTP—was *not* interconnected with other water-distribution systems at Camp Lejeune for any time longer than 2 weeks. All water arriving at the WTP was obtained solely from Tarawa Terrace water-supply wells. Also it was assumed to be completely and uniformly mixed prior to delivery to residents of Tarawa Terrace. On a monthly basis, the concentration of PCE delivered to specific family housing units at Tarawa Terrace was assumed to be the same as the simulated concentration of PCE in finished water at the WTP.

Can ATSDR water modeling results be used to determine the concentration of PCE that my family and I were exposed to on a daily basis?

No. The available data are not specific enough to accurately estimate daily levels of PCE in the Tarawa Terrace water system. The modeling approach used by ATSDR provides a high level of detail and accuracy to estimate monthly PCE exposure concentrations in finished water at the Tarawa Terrace WTP. It is assumed that simulated monthly concentrations of PCE represent a typical day during a month.

Were my family and I more exposed to contaminated drinking water than other families because we lived near one of the contaminated Tarawa Terrace water-supply wells?

No. Water from all Tarawa Terrace water-supply wells (uncontaminated and contaminated) was mixed at the WTP prior to being distributed through a network of pipelines to storage tanks and family housing areas. On a monthly basis, the concentration of PCE delivered to specific family housing units at Tarawa Terrace has been shown to be the same as the concentration of PCE in finished water at the WTP.

Were my family and I exposed to other contaminants besides PCE in finished drinking water while living in family housing at Tarawa Terrace?

Yes. A small amount of PCE degrades in the groundwater to other VOCs. These include TCE, 1,2-tDCE, and VC. Degradation by-products of PCE were found in water samples obtained on January 16, 1985, from Tarawa Terrace water-supply wells TT-23 and TT-26. Historical reconstruction analyses conducted by ATSDR and its partners provide simulated monthly concentrations of PCE and its degradation by-products in finished water at the Tarawa Terrace WTP.

How can I get a list of the monthly PCE (and PCE degradation by-product) concentrations in finished water that my family and I were exposed to at Tarawa Terrace?

ATSDR and its partners have developed a Web site where former Camp Lejeune residents can enter the dates they lived on base and receive information on whether they were exposed to VOCs and to what levels. The Web site will list the simulated monthly concentrations of PCE and its degradation by-products in finished water at the Tarawa Terrace WTP. The Web site can be accessed at *http://www.atsdr.cdc.gov/sites/lejeune/index.html.*

ATSDR's historical reconstruction analysis documents that Tarawa Terrace drinking water was contaminated with PCE that exceeded the current maximum contaminant level (MCL) of 5 micrograms per liter (µg/L) during 1957 and reached a maximum value of 183 µg/L. What does this mean in terms of my family's health?

ATSDR's exposure assessment cannot be used to determine whether you, or your family, suffered any health effects as a result of past exposure to PCE-contaminated drinking water at Camp Lejeune. The study will help determine if there is an association between certain birth defects and childhood cancers among children whose mothers used this water during pregnancy. Epidemiological studies such as this help improve scientific knowledge of the health effects of these chemicals.

The National Toxicology Program of the U.S. Department of Health and Human Services has stated that PCE "is reasonably anticipated to be a human carcinogen." However, the lowest level of PCE in drinking water at which health effects begin to occur is unknown. The MCL for PCE was set at 5 µg/L (or 5 parts per billion) in 1992 because, given the technology at that time, 5 µg/L was the lowest level that water systems could be required to achieve.

Many factors determine whether people will suffer adverse health effects because of chemical exposures. These factors include:

- dose (how much),
- duration (how long the contact period is),
- when in the course of life the exposures occurred (for example, while in utero, during early childhood, or in later years of life),
- genetic traits that might make a person more vulnerable to the chemical exposure, and
- other factors such as occupational exposures, exposures to other chemicals in the environment, gender, diet, lifestyle, and overall state of health.

What is soil vapor?

Soil vapor or soil gas is the air found in the open or pore spaces between soil particles in the soil above the water table (also called the "unsaturated zone"). The source of the soil vapor is the contaminated groundwater. PCE and its degradation by-products are VOCs; therefore, some amounts of these chemicals volatilize (or vaporize) off the groundwater plume and enter the soil in the unsaturated zone as gases. The soil vapor plume (also known as the "vapor-phase" plume) is the area where the gases or vapors have entered the soil in the unsaturated zone above the water table.

Could the soil vapor enter buildings at Tarawa Terrace?

Soil at Camp Lejeune is sandy, so the vapors can readily vaporize up to the surface. The buildings are on concrete slabs, so soil vapor can enter these buildings through cracks or perforations in slabs or through openings for pipes or wiring. In addition, because the vapor enters the building due to pressure differences, the operation of heating or air-conditioning systems can create a negative pressure in the building that draws the vapors from the soil into the building. This is similar to the situation with radon gas.

Could historical exposure to soil vapors contaminated with PCE and PCE degradation by-products affect the current ATSDR epidemiological study?

The results of the PCE and PCE degradation by-product soil vapor modeling will not have a major impact on the current epidemiological study of specific birth defects (neural tube defects, cleft lip, and cleft palate) and childhood cancers (leukemia and non-Hodgkin's lymphoma—also known as childhood hematopoietic cancers). The focus of the study is on drinking-water exposures to the fetus up to the child's first year of life. The drinking-water exposure is considerably greater than any exposure that might occur due to soil vapor infiltration into a home. However, the analysis may incorporate the soil vapor results to determine if these exposures significantly change the results obtained from the analysis of drinking-water exposures.

How certain is ATSDR that finished water exceeding the current MCL for PCE of 5 µg/L was delivered from the Tarawa Terrace WTP beginning in November 1957?

Historical data on the levels of contaminants in the drinking water is very limited. That is why there is uncertainty and variability concerning when the MCL of 5 µg/L was reached at the Tarawa Terrace WTP. Therefore, ATSDR and its partners conducted exhaustive sets of simulations to quantify this uncertainty and variability. Based on these analyses, finished water contaminated with PCE exceeding the MCL of 5 µg/L could have been delivered from the Tarawa Terrace WTP as early as December 1956 but most likely during November 1957.

How does ATSDR know where all of the Tarawa Terrace water-supply wells were located if they have been destroyed? What is the accuracy of this information?

ATSDR relied on a variety of sources to obtain information on the location of Tarawa Terrace water-supply wells. These included historical water utility maps, well construction and location maps, aerial photographs, use of geographic information system technology, and assistance from Environmental Management Division staff at U.S. Marine Corps Base Camp Lejeune. The accuracy of this information is believed to be within ± 50 feet of the actual well location.

What did ATSDR do to be sure that water-modeling analyses are scientifically credible?

Throughout this investigation, ATSDR has sought external expert input and review. Activities included convening an expert peer review panel and submitting individual chapter reports to outside national and international experts for technical reviews. For example, on March 28–29, 2005, ATSDR convened an external expert panel to review the approach used in conducting the historical reconstruction analysis. The panel also provided input and recommendations on preliminary analyses and modeling. ATSDR used a number of recommendations made by the panel members. ATSDR also used technical comments from outside expert reviewers when finalizing reports on Tarawa Terrace water-modeling analyses.

Where and how can I get a copy of this ATSDR report and the information and data that were used in the Tarawa Terrace water-modeling analyses?

A small number of printed copies of this report and subsequent chapter reports (A–K) will be available to interested parties and placed in public repositories. Electronic versions of all chapter reports will be available on the ATSDR Camp Lejeune Web site at *http://www.atsdr.cdc.gov/sites/lejeune/index.html*. Chapters A and K provide a searchable electronic database—on DVD format—of information and data sources used to conduct the historical reconstruction analysis for Tarawa Terrace and vicinity.

Cannot redisplay /tmp/9290766-3--102553.pdf, it has already been shown once.

EXHIBIT 21

DEPARTMENT OF THE NAVY
NAVAL FACILITIES ENGINEERING COMMAND
1322 PATTERSON AVENUE, SE SUITE 1000
WASHINGTON NAVY YARD DC 20374-5065

IN REPLY REFER TO:

June 19, 2008

Thomas Sinks, Ph.D.
Deputy Director
National Center for Environmental
Health/Agency for Toxic Substances and
Disease Registry
1600 Clifton Road, Mail Stop E-28
Atlanta, Georgia 30333

Dear Dr. Sinks,

I am writing this letter to you to reiterate our continued support for working with the Agency for Toxic Substances and Disease Registry (ATSDR) to complete the in-progress groundwater modeling effort that addresses health concerns from past drinking water contamination at U. S. Marine Corps Base in Camp Lejeune, North Carolina. The best way to do this is to support the most scientifically and technologically sound study methods available in order to get answers that are meaningful and scientifically valid.

In March 2008, ATSDR presented its Tarawa Terrace 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". Ideally, we would have specific, water sample results that could be used to determine potential exposure levels. Unfortunately this information does not exist. Because it doesn't, ATSDR undertook this water modeling effort as a means to approximate the historical results over a 35 year time frame. As with all modeling efforts, there is a great deal of uncertainty in trying to re-create the past. ATSDR has gone to great efforts to test and validate the model, and the resulting estimated results, using the limited available data. Attached are some specific concerns and recommendations related to this matter. We look forward to discussing them with you at our next meeting.

We are committed to working with you to improve the scoping of work efforts, researching and reviewing technical information, and achieving consensus of these critical efforts. We have a common responsibility to ensure the technical and scientific information is effectively communicated to our Marines, Sailors and families, and the public. It is imperative to carefully and accurately characterize and communicate results of the water modeling studies so the results will be understood within the context of the study's limitations and uncertainties.

My point of contact to coordinate discussion of these issues is Ms. Kim Brown, who can be reached at (202) 685-0096 or kim.brown@navy.mil.

Thank you for your attention to this matter.

B. P. HARRISON, M.P.A., P.E.
by direction

Copy to:
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MCHB-TS-E (M. White)
ASN(E) (R. Mach)
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NAVFACHQ (K.Brown, M. Dumenigo)
USMCHQ (C. Sakai, K. Dreyer, S. Williams)
NAVFAC ATLANTIC (D. Waddill, B. Brant)
NMCPHC (Y. Walker, M. Simmons, C. Rennix)

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

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.

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.

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.

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.

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

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.

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.

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, 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, 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.

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.

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.

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.

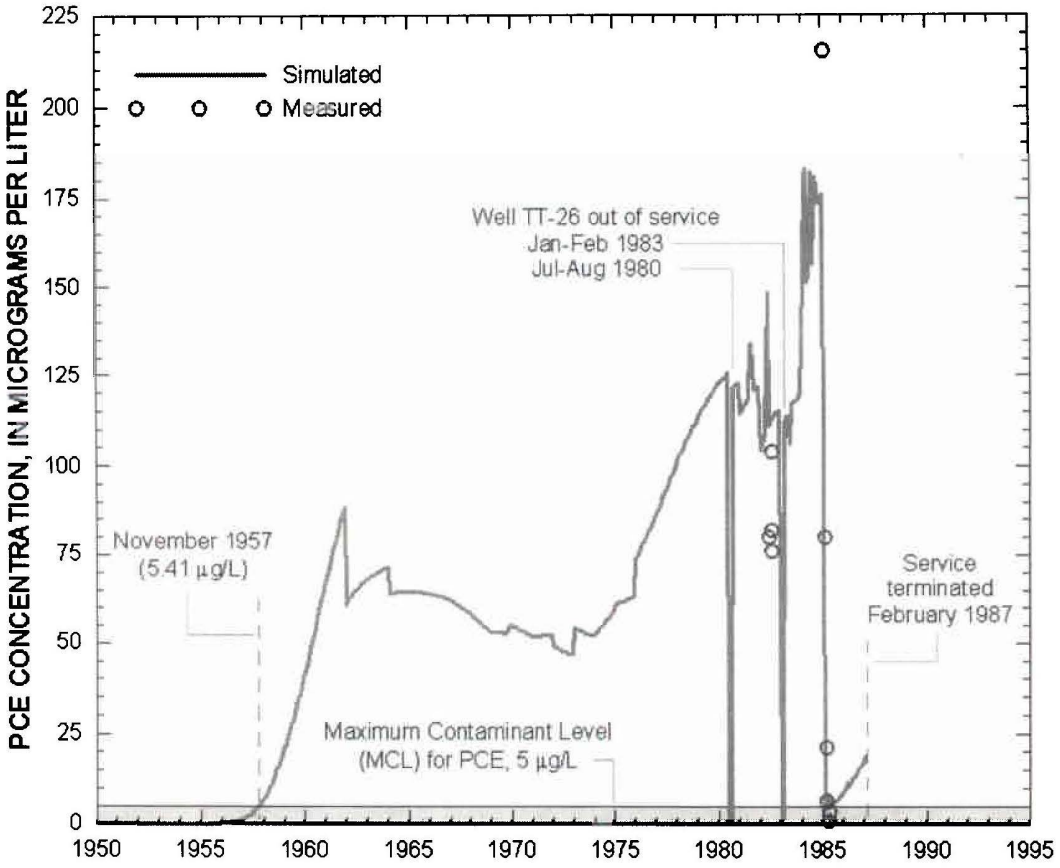

Figure 1. Simulated and measured concentration of tetrachloroethylene (PCE) in finished water at the Tarawa Terrace water treatment plant (from Tarawa Terrace Chapter A report).

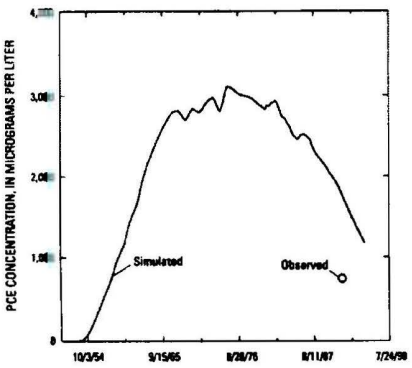

Figure F13. Simulated and observed tetrachloroethylene (PCE) concentrations at local water-supply well RW2, near ABC One-Hour Cleaners, Jacksonville, North Carolina, January 1951–December 1994 (see Figure F6 for location).

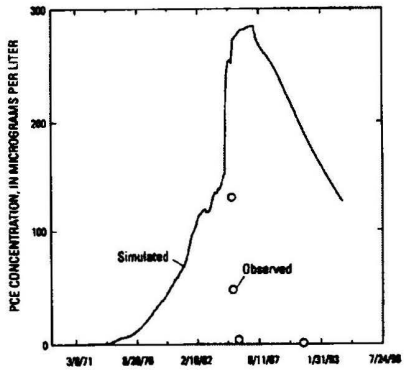

Figure F14. Simulated and observed tetrachloroethylene (PCE) concentrations at water-supply well TT-23, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1969–December 1994 (see Figure F6 for location).

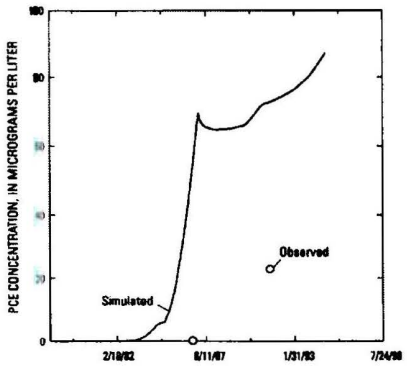

Figure F15. Simulated and observed tetrachloroethylene (PCE) concentrations at water-supply well TT-25, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1978–December 1994 (see Figure F6 for location).

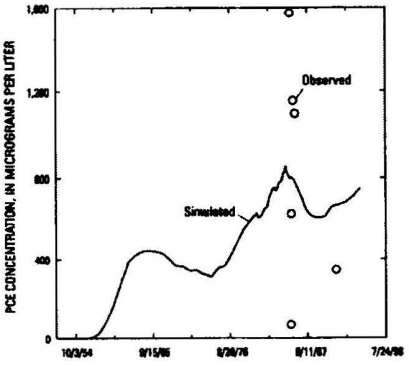

Figure F16. Simulated and observed tetrachloroethylene (PCE) concentrations at water-supply well TT-26, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1952–December 1994 (see Figure F6 for location).

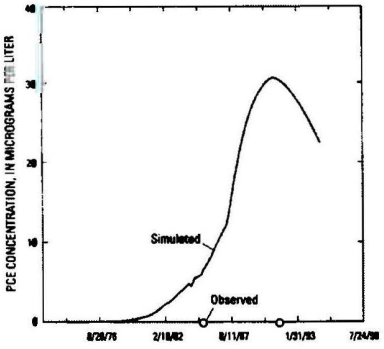

Figure F17. Simulated and observed tetrachloroethylene (PCE) concentrations at water-supply well TT-54, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1970–December 1994 (see Figure F6 for location).

EXHIBIT 22

UNITED STATES DISTRICT COURT
FOR THE EASTERN DISTRICT OF NORTH CAROLINA
SOUTHERN DIVISION

LAURA J. JONES, Plaintiff,	)	
vs.	)	
UNITED STATES OF AMERICA, Defendant.	)	CASE NO. 7:09-CV-106-BO

* * *

Deposition of
MORRIS L. MASLIA P.E., D.WRE, DEE

June 30, 2010
9:18 a.m.

Centers for Disease Control and Prevention
1600 Clifton Road, N.E.
Atlanta, Georgia

By Amy L. Dunning, CCR B-2079

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I N D E X T O E X H I B I T S

PLAINTIFF'S EXHIBITS	DESCRIPTION	PAGE
P-1	Booklet entitled Chapter I: Parameter Sensitivity, Uncertainty, and Variability Associated with Model Simulations of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water	53
P-2	Booklet entitled Chapter A: Summary of Findings	76
P-3	TTHM Surveillance Report Form Date collected October 21, 1980	121
P-4	TTHM Surveillance Report Form Date collected December 18, 1980	121
P-5	TTHM Surveillance Report Form Date collected February 26, 1981	121
P-6	August 10, 1982 letter from Bruce A. Babson to Commanding General	121
P-7	Memorandum From Ms. Betz to Mr. Sharpe dated August 19, 1982	123
P-8	Notice to Residents of Tarawa Terrace	
P-9	Letter dated January 24, 1986 from Director, Natural Resources and Environmental Affairs Division	166
P-10	Letter to Ms. Yvonne Walker from Carol H. Aloisio	
P-11	Letter to Lt. General Kramlich from Howard Frumkin, M.D., Dr.P.H.	138

I N D E X T O E X A M I N A T I O N S

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Examination By: Mr. Bain 182
Examination By: Mr. Anderson 184

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MORRIS L. MASLIA, P.E., D.WRE, DEE,
having been first duly sworn, testified as follows:

EXAMINATION

BY MR. ANDERSON:

Q State your full name, please, for the record, sir.

A Full name is -- first name is Morris, M-o-r-r-i-s; middle name, Lavi, L-a-v-i; and last name is Maslia, M-a-s-l-i-a.

Q And what is your residence address, sir?

A 2681 Canna, C-a-n-n-a, Ridge Circle, Atlanta, Georgia 30345.

Q All right. Thank you. Have you had your deposition taken previously?

A No.

Q Okay. The first time.

A First time.

Q Let me just tell you -- I'm sure you've been advised of this by counsel, but from my perspective, it's very important that you and I communicate effectively here today and that we take care to listen to each other so we're sure we have precision in both the questions and the answers. Will you work with me to try to accomplish that?

A Yes, sir.

Q If I ask you a question and you don't understand it, just let me know, and I'll try to restate it someway to make sure we're communicating. Okay?

A Okay.

Q Because I think it's in the interest of everyone that we have a clear record.

A Okay.

Q If you need to take a break or anything like that, just let us know. This is not an endurance contest. I'm not here to try to be hard on Morris Maslia.

What, if any, preparation have you had for talking with me today?

A I met yesterday for about two hours with Mr. Bain and just went over the rules of the deposition, just as you explained them with that, and basically was told to answer as technically correct or with my knowledge that I have.

Q And obviously truthfully.

A Yes, yes.

Q You're aware this is a case in federal court, are you?

A I have not been told the specifics of the case. I have just been told that there's litigation

involved.

Q Okay. Well, it is a case in federal court. And under the rules of federal court, although you're certainly entitled to preparation and breaks and so forth, once the deposition begins, it's improper to talk about the answers and questions that I pose with your lawyer, with the exception of very limited privilege-related issues.

You realize obviously you're under oath.

A Yes, sir.

Q And you realize that the penalties of perjury would apply to your testimony here today.

A Yes, sir.

Q Okay. Fair enough. Tell me a little bit --

A Can I just make sure my cell phone is on vibrate?

Q Oh, yeah. In fact --

A I apologize, but --

Q Let's all do that.

I'd like to talk with you for a few minutes at the beginning here about your background.

A Okay.

Q Tell me a little bit about your education, if you would, sir.

A Got a bachelor's degree in civil

engineering -- it's actually a BCE -- from the Georgia Institute of Technology. I was awarded that in March of 1976. I have a Master's of Science in civil engineering from the same institute, that was awarded in March of 1980. I have subsequent courses towards a doctorate in civil engineering. I do not have a doctorate of any kind, but I -- course work towards that.

Q Okay. Any other education or particular training that would be relevant to the work that you did here?

A Well, in terms of -- basically worked for the U.S. Geological Survey, developing groundwater -- they transport models and applying them.

Q How long were you with them?

A I was with them for a little over nine years. Began in 1980 and then left the U.S. Geological Survey in -- I think it was November of 1989. And then I worked with a consulting firm, Geosyntech Consulting Engineers, for a couple of years, establishing their water resources department. I was the manager of the water resources department there, bringing online codes and things of that nature.

And then in January of 1992, I accepted a

position over at the Agency for Toxic Substances and Disease Registry as an environmental engineer. And I then developed and was one of the principal coauthors of the agency's exposure to Dose Reconstruction Program. And I have since been classified as a research environmental engineer under the Research Grade Evaluation program that runs throughout the civil service or the government.

Q What was your role when you were at the U.S. Geological Survey those nine years? What did you do?

A There were a couple of things. I worked on some studies in Southwest Georgia looking at the impacts of agricultural pumping. Southwest Georgia, at the time in the early eighties, was one of the last untapped resources for groundwater for large-scale irrigation practices, and there was an interest as to see what the impact that would have, and, of course, fertilizers and things like that. I also worked on the USGS's regional aquifer system analysis programs, which Congress had mandated them to do in the late seventies and throughout the eighties. And I worked on the Florida aquifer, which is basically Southwest Georgia and Northwest Florida.

And at the same time, I became involved with

a case just because of the modeling ability that I had, or specialized modeling ability, in a case to assist USEPA up at Love Canal in Hyde Park, New York. That was the precursor of Superfund, and they used part of our analysis to, in fact, promulgate Superfund.

Q So your analytical techniques and methodologies in that instance became part of the basis for the Superfund system?

A I would not go that far. I would say that the modeling that we did -- that we did because of the area that it was located in -- it was Love Canal in Hyde Park area in New York -- was the impetus for Congress passing Superfund legislation. So we were a technical consultant to EPA.

Q In connection with the passage of Superfund.

A No. It was in connection with a lawsuit. From what I understand, we were being sued by the Canadians because of supposed contaminated water coming over Niagara Falls, because it's a fractured dome right there and Hooker Chemical Company had some waste there. And so the U.S. was being sued by the Canadians, or a group within Canada. And so a colleague of mine was requested to provide testimony in a court hearing.

And one of the things that came out of that is that he suggested in 1980 that we could use computer methods to answer some questions rather than speculating based on limited field data. So that's when he brought me in, and we did a computer model of the area.

Q You must have been using big-box hardware like AS/400s and things like that.

A No. Actually we were renting computer time. At that time you used to have to rent computer time.

Q I remember, yeah. I was at Berkeley at that point.

Mike wants me to ask you about your business card, and I should have done that. It says here "PE." Could you just tell me what that is.

A Sure. PE is a professional engineer, and I'm registered and current in the state of Georgia as a professional engineer and have been for a number of years. And then the DEE means I'm a diplomat of the American Academy of Environmental Engineers. And then does it say "D.WRE" on there? Yes. Okay. And that's a diplomat of the water resources -- I forget the exact title. But there's the Academy -- American Academy of Environmental Engineers. And then there's the American Society of Civil Engineers, and that's

their equivalent diplomat designation.
Q And what does it mean to be a diplomat?
A Basically you can -- it's based on the number of years of experience you have in a certain specialty area. And then they can -- depending on the organization, they can put you in front of a panel to answer specific questions to test your knowledge.
Q Have you been through those processes?
A Yes.
Q And you passed?
A Yeah. That's what they tell me. Yes, I have.
Q How long have you been a licensed professional engineer here in the state of Georgia.
A I'm trying to think. Let's see now. I graduated in 1980, I believe, because you had to have four years of practice with a master's degree. So I believe it was 1980. You can probably go through the Secretary of State's office and pull it up online.
Q And have you consistently been licensed since that time?
A Yes. It's never lapsed.
Q Returning to the subject of Love Canal and Hyde Park which we were talking about before, you

twice mentioned that as somehow, in your mind, connected to the advent of Superfund. Can you explain that relationship.

A Well, just if you look at the history of the Superfund legislation, what promulgated the congressional action was the press, the notoriety of Love Canal. And the reason we mentioned Hyde Park is because actually Hyde Park was significantly more contaminated and more toxic than Love Canal. However, Hyde Park was an industrial area owned by Hooker Chemical, whereas Hyde Park, you had citizens living -- you know, it was a residential area.

Q You mentioned that in connection with those contaminated sites, you apparently for the first time recommended the use of what were then new computer modeling techniques to answer some of the questions associated with those sites?

A I did not recommend. My colleague, Richard Johnson, who has just deceased this past December, actually was an engineer/geologist back in the 1960s when they were digging the power canal for the Mohawk Power Company. And so he saw the geology and how the water was flowing and all of that. And this is in deposition, so you can pick that up. But they were asking him questions that you really could not answer

without a computer simulation program.

And so that's -- he and I worked on the Florida Rassa, so he was head of the Florida Rassa. So that's why I was working with him at the USGS. And so as sort of a side project, he suggested to them that computer simulation could address a lot of the questions that they were being asked in court under litigation, rather than speculating.

Q And were those models, in fact, put together?

A We put a model together. We put a cross-sectional model together.

Q And the computer model that you and Dr. Johnson put together, did it generate data results?

A Yes.

Q And the data and results that were generated from that computer model, did they become part of the data set that represented the findings with respect to what had happened at Love Canal?

A They represented the -- at that time, current 1980 to 1982 conditions of groundwater flowing through a section of limestone that exited to the gorge of Love Canal, of which the Hooker Chemical Company landfill was sitting on top. And it

presented results of how long it would take a particle of water -- and, hence, a particle that may have been contaminated -- to flow from the landfill to the gorge. And it provided different ranges of values depending on the different geologic medium, whether it was glacial till or fractured rock.

Q And did those results from that computer model then go on to be relied upon by people making decisions about --

A They were presented to EPA, and then they, I assume, were -- they were presented to EPA, and EPA used them -- or used the results in their legal briefs. I did not ever see the legal briefs.

Q Of course. But the results were used.

A Yes, the results were used.

Q And then subsequent to that whole Love Canal use of those results, politically we then see Superfunds spring up from that?

A That's correct. That's correct.

Q And that was really my question.

I want to return back to the subject of your work in Georgia when you were dealing with that situation where you had historically significant agricultural pumping from that aquifer and you were studying the effect of that.

Was what you were studying have been fate and transport?

A We did not study fate and transport for a couple of reasons; the first being, we had a cooperative agreement with the State of Georgia, and our specific task was to look at the impact of pumping in terms of water withdrawal, okay, not in terms of, say, pesticides and all of that. Secondly, at that time the State of Georgia did not acknowledge that there was any pesticide contamination. Okay. We obtained samples with pesticide contamination in there, and I don't recall which ones they were. It's in a report that I did, and I have that.

But it was really our task -- the motivation was, you had at that time the banks requiring, as collateral, farmers installed irrigation systems. And these are not small irrigations. These are center pivot systems that can be a mile in diameter. And from the area you see the big circle in the ground. And they withdraw, you know, hundreds of thousands of gallons of water. And in South Georgia, you could drill down, you know, a couple of hundred feet to just a thousand feet, which is very inexpensive, and sink a well and irrigate.

So the State was concerned about ordering

the aquifer. And so as part of the USGS cooperative agreement with them, we had this study to go on to assess what impact the current pumping -- at that time, 1980 -- and what potential there was for further development of the agricultural lands.

Q And what methods did you use?

A We used a computer model. We used a two-dimensional finite difference computer model at the time that the USGS had developed, and gathered field data and calibrated the model and produced the results and produced a couple of reports.

Q The use of these computer models that you've described now in a couple of different contexts, is that a standard practice in your professional field?

A Yes.

Q Are these accepted methodologies?

A Yes.

Q And how are their reliability -- how is their reliability assured?

MR. BAIN: Objection; vague.

BY MR. ANDERSON:

Q Well, how is the reliability of these types of computer models tested?

A The models are calibrated, meaning that you have gathered or have obtained some field

information, that data. And the model --

Q Let me stop you there. And just so this record is clear, when you say you've obtained some field information, some data, are you talking about actual sample results?

A Yes.

Q Okay. Go ahead.

A And depending on the purpose of the model, you will obtain different types of data.

Q For instance, if you're trying to just figure out whether you're draining the aquifer, you might obtain samples showing the quantity of water. But if you're trying to determine pollution, you might take samples of the contaminants?

Is that what you mean?

A Qualitatively, that's correct. Technically, we would go and measure water levels and wells. They may be existing wells. Or if we want to make sure we have accurate water level readings, we will go and install what we refer to as monitor wells, where there are standards for properly constructing them and so on. And then you will obtain water level readings from them. And depending on the focus of your study and the characteristic of the aquifer you're looking at, you may do repeated sampling, you

may do continuous sampling. It's very broad, and the nature and character of the study would dictate how -- the frequency and what type of sampling you would do.

Q Fair enough. And I distracted you a little bit from the main question, which was: How is the validity, accuracy, and scientific reliability of these computer models assured?

MR. BAIN: Objection to form.

BY MR. ANDERSON:

Q How do you check to see if these models are going to give you accurate data?

A The models will give you results, and then there are numerous statistical methods to compare them with the data that you have collected. The model results -- you would compare the model results with the data that you've collected. And you may decide a priori that you want to be within a certain range.

For example, at water levels I may want to be within plus or minus 10 feet of what I measure. It depends on the size of the model of the area that you're modeling and the purpose of the model. And you will use different statistical and visualization techniques to demonstrate that, in fact, the model

provides an acceptable range of reliability compared to the data that you have collected.

Q Okay. These statistical methods that are used to calibrate, are these used to calibrate the model? Is that correct lingo?

A No. They are used to assess the calibration.

Q Okay. All right. I think I understand. These statistical methods that you use to assess the calibration of your computer model, how long have those statistical methods been used?

A They have been used since the beginning of time for -- to compare other techniques and other areas, not just modeling, in other words. So since modeling began, we have needed -- in the late fifties or early sixties, we have needed to test the results of the models because the purpose of developing the model is to obtain information where you have limited or nonexisting data.

Q Is it fair to say that these statistical methods that are used to check the calibration of your computer simulation, to compare the model results of the field data, are based in statistics, the science that is well known to many of us?

A Yes.

Q Founded on that science. It's fine. I'll withdraw the question. When you went to Geosyntech Consulting Engineers, you mentioned you had some role having to do with getting the codes online.

What was that?

A They were a small consulting company, and their primary business was in design and installation of liners for landfills, sanitary landfills. And in doing that, of course, you have to demonstrate that the liner is going to leak, how much it's going to leak over time. And so one way of doing that, you can test that in the lab, but you can also show what's going to happen when you design a landfill where the groundwater is going to flow. And so you need models to do that.

Again, you can instrument beforehand, but most state regulators would like to see some evidence that the liner is going to work. And so they did not have -- their primary business was a liner design, not modeling. And so they brought me in along with another colleague, an older colleague of mine that had retired from USGS. And I set up some computer codes and some analysis methods so that we -- you know, when they needed to assess a design or they needed to answer some litigation, then we could run

the models.

Q Is it fair to say that at Geosyntech you used the same essential techniques that you had used at the United States Geological Survey -- that is, computer modeling, statistical analyses -- to check the calibration of the model?

A Yes.

Q Are those well-established techniques that people in your profession use?

A Yes, they are well established.

Q And how long have they been established, 30, 40 years?

A At least, yes.

Q And then when you moved to the Agency for Toxic Substance and Disease Registry in 1992, you came in, I believe you said, as an environmental engineer.

A That's correct.

Q And you told me, I think, you developed and coauthored the exposure and dose reconstruction program?

A That's correct.

Q Tell me a little bit about that.

A Okay. At the time that I came in in 1992, the agency was right in the midst of answering a GAO.

At that time, I think it's Government Accounting Office. I think now it's Government Accountability Office. They have changed names. Basically critiquing the agency because they had reviewed something like 900 NPL sites. And basically, Congress gave them a limited number of -- a couple of years to review like all 900 of them. And obviously they could not answer certain questions based on, say, one data point at a site who may have been exposed or when they were exposed.

And so the science director of my division as well as the assistant administrator of my agency at the time saw the need to have some quantitative computational ability to predict or reconstruct -- for my agency, primarily reconstruct historical conditions, perhaps predict current conditions and/or -- or predict future conditions. And so we wrote a -- out a plan to have such a program funded that would bring in different techniques, state-of-the-art techniques, impart some of this knowledge on the health assessors of the agency, as well as establish, say, a cooperative agreement with a university partner who develops models all of the time.

And if we need a certain model that we don't

have in hand and we don't have the personnel or the funds to dedicate to developing it, we could go to a university partner through a cooperative agreement and work with that. And that program, I think, was established in 1993, and it goes every five years. And it was just renewed again for -- a couple of years ago for the next five years.

Q You used an acronym NPL sites. Do you mean National Priority List?

A Yeah, the list --

Q The federal list of sites?

A Yes.

Q Contaminated sites?

A Put on by EPA.

Q The answer is yes?

A Yes.

Q And in terms of the exposure, slash, dose reconstruction program, was the purpose of your work in connection with that to aid in the assessment of how much people had been exposed to various chemicals in various situations?

A It was more general than that.

Q Tell me what you mean.

A It was to assist the agency in quantifying exposures where we had limited or nonexisting data or

information, and also to develop techniques, these type of computational techniques, so that the health assessors at the agency would have these tools available to them.

Q All right. But in terms of its function, ultimately it had do with the exposure in dose reconstruction. That's what its name was.

A That's what its name was. Okay.

Q And why was it called exposure and dose reconstruction?

A It was basically to try to provide a program for two different disciplines. The area that we worked in, exposure analysis, is really at the intersection between environmental science and health science and toxicology. In environmental science, we speak about concentrations and exposure to that. Can be exposure. And toxicology and health science, you speak about doses, internal doses. And so the program was really meant to help bridge a gap in there so the engineers could sort of speak to the toxicologists on the same level or understand each other.

Q And your computer models would provide the reconstruction of information to allow the connection between exposure and dose?

A Yes.
Q And in doing that work at the Agency for Toxic Substances and Disease Registry, were you working on behalf of the federal government?
A Yes.
Q And you were doing that work within the course and scope of your duties?
A Yes.
Q And the methods that you employed in the course of that work were the same methods that you described before; statistics-based, computation-based models?
A Yes.
Q And they were reliable for the same reasons that you described previously?
A Yes.
Q And, in fact, the U.S. Geological Survey is also an agent of the federal government, correct?
A That's correct.
Q And you, as you told me before, used those same methods within the course and scope of your work as an agent of the federal government during those nine years that you worked for U.S. Geological Survey, correct?
A Correct.

Q Nowadays you're a research environmental engineer?
A That's correct.
Q Could you tell us what that means.
A That's a classification in the civil service part of the government. The Office of Personnel Management has a classification that is referred to as a research grade system. And under that system, you can be both promoted and, I assume, demoted based on certain criteria of the position, as opposed to just a standard civil service position. For example, on the complexity of the research project that you're working on, on the colleagues internally and externally that you associate with. And probably the heaviest, weighted -- there are four factors to assess you, and the fourth one being -- which is weighted twice as much -- is the publications that you produce in both peer-reviewed to non-peer-reviewed outlets.
Q Through that process that you just described, have you ever been promoted?
A Yes, I have.
Q Has that been repeatedly?
A Yes.
Q And that's been within the course and scope

of your work for the United States Government?
A That's correct.
Q Have you ever been demoted?
A No, I have not.
Q And what is the total number of years of experience that you have, as you sit here today, with the computer models and the statistical methods used to check their reliability?
A Approximately 34 to 35 years. That's going back to my bachelor's degree.
Q And your publications -- have you published anything?
A Yes, sir, I have.
Q Have any of your publications been peer reviewed?
A Yes; many of them.
Q Have any of your peer-reviewed publications dealt with the methodological techniques you described previously, the computer models and the statistical methods used to check their reliability?
A Yes, they have.
Q And have those techniques been peer reviewed? That is, your --
A The techniques themselves have not because those are established techniques. The use of those

techniques described in the peer-review publications have been peer reviewed and published.

Q Thank you for the precision of that. Repeatedly, I take it.

A Yes.

Q In what areas would you consider yourself to have expertise at this point?

A Numerical modeling -- broad category -- environmental engineering, environmental fate and transport analyses, and scientific report writing.

Q What is fate and transport?

A Fate and transport describes the process that a contaminant undergoes irrespective of the media it's in, whether it's air, soil, water, groundwater; where transport refers to the movement of a particle of contaminant with, say, a drop of water; and the fate refers to either chemical degradation, decay, different properties, chemical properties, that a compound may undergo as it's moving along a path.

Q Would that include breakdown products?

A Yes.

Q We'll come back to that subject a little later on. And you mentioned scientific report writing. Certainly having read some of your work, I

can see that that, in and of itself, is quite an undertaking.

What, if any, basic ground rules are there that you have learned with respect to scientific report writing?

MR. BAIN: Objection; vague.

BY MR. ANDERSON:

Q You can answer. He can object for the record. It's okay.

MR. BAIN: Go ahead and answer.

THE WITNESS: Oh, okay. I wasn't sure.

BY MR. ANDERSON:

Q Here is the question again: What are the rules, if any, for writing one of these scientific reports?

A There are no rules, but there are general guidelines to go by. That is, clearly state the problem that you're writing about, present the data as field data and clearly identify it as field data, clearly identify what is computer simulation, state the assumptions and limitations that you are using, and justify why you are making those assumptions and limitations. And then finally draw the conclusions based on the problem, the data, the assumptions, and the results that you reviewed.

Q You mentioned clearly identifying the field data. I note that you and your work on the Marine Corps base at Camp Lejeune, which obviously we're going to talk about, you cite repeatedly to the source material, identifying the field data and other documents reviewed in footnotes and by name.

Is that part of the method that you have employed in the course of your scientific report writing?

A That is a more specific method that we used in this particular case.

Q Okay.

A And other cases like journal articles, you may just reference other peer-reviewed documents and not go into quite as much detail as we have done with the Camp Lejeune publications.

Q Are there internal rules or advisories from the Agency for Toxic Substances and Disease Registry with respect to citing documents in studies like these?

A They have policies.

Q Could you tell me about those.

A The policy is to reference the information and identify the source.

Q Is it correct that the policy, in fact, is

to reference each and every source that you rely upon?

A I could not state that specifically because it's been a while since I've actually read their policy, so I can't speak about the agency's specific policy.

Q How would that policy be described if we wanted to request a copy of it from Mr. Bain?

A I would say it would be their scientific publication policy.

Q Okay. And in terms of the work you actually did regarding Camp Lejeune, did you, in fact, attempt to cite everything you were relying upon?

A We cited everything that we used in a specific report. So although the Tarawa Terrace analysis is compromised of, say, 11 different reports, different reports might not use the same -- Chapter A may not use all of the references that Chapter B or Chapter C, so I would not need to reference those documents unless I was referring to out of Chapter B or C in Chapter A.

Q Sure. And I understand that.

But with respect to whatever it was that you were referring to, you cited it, didn't you?

A Yes, sir.

Q And anything that you relied upon in any of those 11 reports as part of the basis for your scientific study, you cited it.

A Yes, sir.

Q What was your role with regard to that study? And I'm just going to -- if it's all right with you, I'm going to call it the Camp Lejeune study. Can we agree to call it that, or how would you --

A Can I just see what --

Q I'm looking right now at the summary of findings --

A I would call that the Tarawa Terrace analyses because there is a difference, if that's okay.

Q Yeah, that's better. And let's use Tarawa Terrace -- T-a-r-a-w-a, Terrace -- to refer to, if we can, all of the work you did on that. And I know it comprises a whole body of reports, you'll be glad to know we're not going to cover every page of every one of them.

A Thank you.

Q Can we call it the Tarawa Terrace report?

A That's acceptable.

Q What was your role in the Tarawa Terrace

report?

A My role was really three-fold, from a -- and I'll start with a larger or systematic overview -- was to provide results for the epidemiological case control study in terms of monthly concentrations of specific contaminants in the drinking water at Tarawa Terrace.

Q Did you do that?

A Yes, we did.

Q Did you do any sort of probabilistic analysis to determine the reliability of your results?

A Yes, we did.

Q And what was the outcome of that probabilistic analysis?

A And that is actually published in Chapter A as well as a subsequent chapter in more detail. And those results and those chapters show that there was a range of between two and a half and three, meaning that for whatever concentration the model came out with at a certain given point in time -- let's just say 50 micrograms per liter, and I'm using that just as an example -- then the rage of that value -- that value could range anywhere from two and a half -- higher to two and a half times lower than that value.

Q So if we had generated model results of -- we used the words "micrograms per liter" -- say you had 81 micrograms per liter, it could actually be two and a half times that much or it could be two and a half times smaller.

A That is correct.

Q That, to me, sounds very loosey-goosey.

A In fact, it's not.

Q Explain.

A It's considered a -- what we refer to as a very tight range, because typically when we're dealing with water quality, type of data or simulation, the general rule of thumb is to be within one order of magnitude or a factor of ten. So the fact that we were well within the level factor of five even, we felt provided a very robust reliability for the model.

And, in fact, we were told by the senior epidemiologist on the Camp Lejeune project that that was well within acceptable ranges that they could use to work with. It was, as they put it, much more refined than the crude epidemiological methods that they used.

Q And you're referring to Frank Bove and his team?

A That is correct.
Q All right. Now, you used the phrase "micrograms per liter," and I -- forgive me. If I was really capable at math, I would probably be a doctor at this point.
How does that relate to parts per billion?
A That's the equivalent. We use them interchangeably.
Q Okay. So if something says 80 micrograms per liter, that's 80 parts per billion?
A In this situation, it is. With these contaminants in the situation at Camp Lejeune, that is correct.
Q And explain that to me so that I understand. When would it not be correct, and why is it correct here?
A Well, there -- to do the calculations, it involves density properties and temperature, standard temperature, standard things. And if those -- and under these conditions, we do not have density effects --
Q I see.
A -- in other words, dissolved in water. So we can make an equivalent computation to show that it's the same.

Q Okay. So if there were density issues, you could not make the -- you could not just assume that micrograms per liter equals parts per billion, but because they are not here, you can. Is that fair?

A You would have to have a conversion factor -- a conversion factor. Here the conversion factor is one, okay, in other words. But you would have to have a conversion factor, and then you can convert micrograms per liter to parts per billion.

Q Will the same be true for benzene?

A Yes, it will.

Q And is the fact that the conversion factor with these chemicals -- now I'm talking about benzene, trichloroethylene, and tetrachlorethylene -- is one, that is, from micrograms per liter to parts per billion as a equivalency. Is that a generally scientifically accepted fact?

A Yes.

Q What was the goal of the Tarawa Terrace study? What was it trying to do?

A It was -- the goal was to quantify monthly concentrations of specific contaminants in drinking water.

Q Why?

A The epidemiological study being conducted is

referred to as a case control study. And for that, they needed to know what the concentration of the water that people who were exposed to contaminated water ingested so they could compare that to the concentration of water that people who were not exposed, or in their analysis. And so they have to have the -- since we're doing in utero and up to one year of age study, they needed to know per month what the concentration of the drinking water that the mother and/or fetus and/or child up to one year of age ingested.

Q Why did they want to know that?

A They need that to do the case control study to compare experiences or diseases -- experience of those people with disease against those people who do not have the disease.

Q Is a simple way to say this, that this whole Tarawa Terrace study and the epidemiology that it relates to is trying to figure out how much disease the water has caused, if any?

MR. BAIN: Objection to form.

BY MR. ANDERSON:

Q Is that what this is about?

A That has never been stated to me in that way.

Q Why are they doing an epidemiological study with mamas and babies and trying to determine how much chemicals they were exposed to in the water and then talking about the disease history?

MR. BAIN: Object to form.

BY MR. ANDERSON:

Q Help me understand that. What's your understanding of it?

MR. BAIN: Same objection.

Go ahead.

THE WITNESS: My understanding is, the reason you do a childhood in utero study, because we're studying rare diseases. And rare diseases, you need to take out confounders that adults would experience, such as life experiences; smoking, where you live, drug usage, legal and otherwise. And so children do not have those experiences, so you can take those confounders out of the calculations.

And so -- so you look at -- so from that standpoint, you can get a much better understanding of any associations between exposure to contaminated media and rare diseases such as birth defects, childhood cancers. And that is the purpose of our current study, is to

establish, in fact, are there associations between ingesting contaminated drinking water and a higher prevalence of childhood birth -- specific childhood birth defects and specific cancers.

BY MR. ANDERSON:

Q Why did they wonder about that? In other words, why was there even a question about whether there might be associations between exposure to these types of chemicals and these diseases in children?

MR. BAIN: Objection; lack of foundation. Go ahead.

BY MR. ANDERSON:

Q Well, I mean, I'm just parroting the last answer you gave. You told me there's an inquiry into whether there are associations between exposures in these chemicals and certain diseases in children. And I'm wondering: Why did that question arise?

MR. BAIN: Objection.

BY MR. ANDERSON:

Q You can answer.

A That was a recommendation out of the 1997 public health assessment that recommended that there was lack of knowledge of the effects of compounds -- certain compounds described in the health

assessment -- on children. And so it recommended follow-up studies of -- follow-up health studies, of which the current study is just one part, one particular study, to address that.

Q Had there been prior indications in the literature that these chemicals were harmful or might be?

A That's really outside my area of expertise. You need a toxicologist to answer that.

Q And I understand. I'm just -- I'm asking you based on what you read in connection with your work. I mean, did you read the 1997 public health assessment?

A Yes, I have.

Q And so you know, don't you, Doctor, that there were prior studies and scientific reports suggesting an association between exposure to these chemicals and various types of disease? You know that, don't you?

MR. BAIN: Objection. Document speaks for itself.

Go ahead and answer if you know.

THE WITNESS: The reason our current study is being done is because there's a lack of studies. In other words, the studies are

inconclusive to date. There are very few of them. And so one of the reasons this study is being done is to try to build that scientific body of knowledge.

BY MR. ANDERSON:

Q Right. I mean, it's not every day that you get a whole bunch of people exposed to these kinds of chemicals to where you can actually study them, right?

A That is correct.

Q And so that's one of the reasons why there's not a lot of studies.

A That is correct.

Q But in terms of the studies that there are, you know, as you're sitting here now, that some of those studies suggested associations between exposure to these types of chemicals and various diseases, don't you?

MR. BAIN: Same objection; lack of foundation.

THE WITNESS: Some have established that, yes.

BY MR. ANDERSON:

Q Yeah. Now, in terms of the database for the Tarawa Terrace work that you did, what have you

reviewed and studied in preparing those reports?
A We have gathered, reviewed, extracted field data from the Tarawa Terrace area; basically, hydraulic data, hydrologic data, geohydrologic data, contaminant data, and -- at Tarawa Terrace and outside of Tarawa Terrace, as well as other analyses of similar fate and transport and modeling analyses.
Q Obviously you knew that this was very important work you were doing.
A Yes.
Q And you understood that it could potentially have an impact on perhaps even millions of people's lives.
MR. BAIN: Objection; lack of foundation.
BY MR. ANDERSON:
Q You realize there's about 1.3 million people who potentially were exposed to this contaminated water at Camp Lejeune?
A I have not heard that figure being that high.
Q Well, you knew it was important to get it right.
A I know it's important -- this goes for anything that we do -- to have a product that is scientifically defensible.

Q And you -- from what I can tell reading it, you took every step you could to ensure that that was the case.

A That is correct.

Q Okay. And you employed methods that you believe, as you're sitting here now with 34, 35 years of experience, were scientific valid.

A Correct. That's correct.

Q And they were the same methods that you had utilized at the other agencies of the United States Government such as the U.S. Geological Survey, correct?

A That is -- generally speaking, we used, I believe, more sophisticated methods.

Q Well, were they in any way so sophisticated as to be, you know, novel and unreliable?

A Not unreliable. Novel application, yes.

Q Tell me about that.

A We were predicting -- or reconstructing backwards in time for 30, 35 years at a monthly interval, which is a -- from a groundwater modeling standpoint, a fairly fine timeline, typically. And in terms of, say, remediation practices where they use these similar models, you may look at years -- or five -- of years trying to clean up. So you do not

necessarily see published results in terms of monthly values. So that was a very refined time step in terms of a groundwork model.

So from that standpoint, that's probably, you know, edge of the envelope of what's been done. And we also went to numerous methods to look at some different aspects. Once we obtained initial reports, calibrated results, we then went to look at, well, what happens if the wells pump at a different rate than we assumed; also looking at the degradation byproducts and things like that. So we employed numerous models to, again, not only refine our understanding but also may show that our results were scientifically defensible.

Q Okay. There's a law called Daubert which says that the only kind of evidence that a federal court will consider that has a scientific aspect to it is evidence that's scientifically reliable.

And when you say that the getting down so fine as to determine monthly exposure values is, quote, edge of the envelope, is that scientifically indefensible, edge of the envelope, or is that just -- tell me -- explain to me and explain to the judge who may be reading your words someday why we can rely on the monthly results you obtained.

MR. BAIN: Object as to form.

You can go ahead and answer it.

THE WITNESS: We could rely on the results because we followed a scientific practice, as we previously discussed, of laying out all of the data, the information, showing the assumptions -- clearly stating the assumptions we made, clearly stating the limitations, and calibrating the model to compare the model stimulated results with the field data; and then also conducting sensitivity analyses, which means -- part of that is the probabilistic analysis that shows that the model does produce different values but they are contained within a certain envelope or a certain range. And that range is within an acceptable limit for anybody who does this or is involved in this type of work, not just the epidemiologist but I'm talking about the environmental engineers.

BY MR. ANDERSON:

Q Did you use in preparing this report the same essential tools of your career, that is, the computer models, the calibration of the models, the statistical analyses?

A Yes.

Q Generally accepted scientific techniques.
A Yes.
Q And was your work peer reviewed?
A Yes, it was.
Q And was it found to be scientifically reliable by the peer-review process, or was it peer approved, I guess?
A It was peer approved.
Q I noted that in the forward to the summary of findings, it says that the study protocol received approval from the Centers for Disease Control and Prevention institutional review board.
Is that correct?
A That is correct.
Q Tell me what that involved.
A You would have to ask Dr. Bove because that involves human subjects and the epidemiological side.
Q But your study protocol did receive approval.
A The entire study, not the modeling. The health study received.
Q Okay. And then it says that you used -- it says: ATSDR is using water-modeling techniques and the process of historical reconstruction to quantity concentrations of particular contaminants in finished

water and to compute the level and duration of human exposure to contaminated drinking water.

Is that a true statement?

A That is a correct statement.

MR. BAIN: Counsel, can you tell me what page you're reading from.

MR. ANDERSON: III.

THE WITNESS: The forward.

BY MR. ANDERSON:

Q In terms of the peer review you described, was there peer review of the results of your study or a peer review of the techniques used to do your study?

A Peer review of the report. When a report -- a draft report is completed, we will send it out -- or it's my practice to send it out to colleagues -- they can be internal or external; in this case it was external -- who have expertise in these methods and these types of analyses. And so we sent this report out.

Chapter A, let's talk about Chapter A. And offhand I can't remember if it's two or three different people that I sent it to, the documentation. But I don't recall how many people I sent it to. It was at least two. To review the

report, both -- you will choose whether you want to review it from the report entity itself, from a public health standpoint, from a technical modeling standpoint.

So you will send it to different people like that, and they will provide you comments back on it. And, of course, you are free to accept or not accept the comments depending on what their particular comments are. But we do -- for these all -- the Tarawa Terrace series reports, they all underwent peer review.

Q And all were peer approved?

A Yes.

Q Now, you mentioned Chapter A as having been through the peer review process as well, and that is the summary of findings for Tarawa Terrace.

A That is correct.

Q And so your actual report findings on Tarawa Terrace have been peer reviewed.

A That is correct.

Q And peer approved.

A I would say peer reviewed is the correct term that I've always used. Never heard the term "peer approved."

Q Well, I just made it up. What I mean to

suggest is, when you had your peer review, they didn't tear the thing up and throw it in the trash. They came back and said, Well, we may comment here and there, but we're peer reviewing it in a positive fashion.

A That is correct.

Q Okay. That's all I meant.

A That is correct.

Q And you reached results obviously.

Am I correct that the monthly results that we have mentioned several times are included in Appendix I-5?

A I've have got a copy -- oh, okay, since you've got that. I-5 is from Chapter I, I believe. Oh, maybe not. Let me. Appendix I-5.

Q There's a front page to that.

A Okay. Because I think -- oh, Appendix I-5. Yeah. If I can, I've got both Chapter A and Chapter I here, and I forget how we named the appendices.

Q Why don't you just show me where your bottom-line results are, and we'll use your copy.

A Chapter I is really the enhanced sensitivity analysis, whereas Chapter A is the summary. So, yeah, Chapter I -- the -- Chapter I -- Appendix I is

from Chapter I.

Q Okay.

A And, yeah, that's the probabilistic analysis, which I do not believe we put in Chapter A in its entirety. So that's the difference. The same -- the same, what I call, mean value results that are shown in Chapter A in the appendix, like A-2 and so on, are also in Chapter I, but what Chapter I does is give the range of values.

Q Okay. Well, if a person wanted to know, for instance, what he or she was exposed to living at Tarawa Terrace at a particular month that was covered by your study, where would we look?

A The best place to look is in Chapter I because it would give you the 50 percent or median value and then it would give you the range with the high and with the low. Again, if you just wanted to speak about an average value, then you could refer to Chapter A because it's the equivalent, basically, to the median value in the statistical analyses presented -- probabilistic analyses shown in Chapter I.

Q Well, in terms of -- since you suggest Chapter I as more complete --

A It is more informative.

Q Let's use that. Let's use the most informative.

Is the copy that I have here, is that the most informative and complete that you're referring to, or do I need to use the copy you brought?

A That should be. If you pulled it off the Web or made a copy of the published report, then that's the same that we have sitting right here on the table, and that is for PCE. Okay.

Q Would it be all right with you if I used your published report as an exhibit?

A Sure, sure.

Q Thanks. I will just mark it as --

MR. BAIN: It's not your only copy, is it?

THE WITNESS: No, no, no. I mean -- no, no, we got a couple hundred more at the office. But it's my own copy too.

MR. BAIN: Let's go off the record.

(Brief discussion ensued off the record.)

BY MR. ANDERSON:

Q I'll just mark it as Exhibit 1 to your deposition. And I appreciate you letting me have it.

(Plaintiff's Exhibit Number 1 was marked for identification.)

THE WITNESS: I would -- if I could just

preface that, is, Chapter A was meant to give a complete summary of all of the analyses we did; geohydrologic, water quality, and things of that nature. Whereas Chapter I was specifically targeted to assess the model simulations.

BY MR. ANDERSON:

Q In what sense? What do you mean by that, to assess?

A Well, good modeling practice requires that you conduct -- after you calibrate a model, you conduct a sensitivity analysis; that is, how sensitive are model parameters, because we don't have data for each parameter, that if you change -- if you happen to a year from now get some additional information that changes a value of a parameter that you coded into the model, how would that impact your final results.

And so we provide a quick summary in Chapter A, but Chapter I is the more in-depth analysis. And it not only does the groundwater flow model, fate and transport, it also does the water distribution system model.

(Brief discussion ensued off the record.)

BY MR. ANDERSON:

Q What is this -- I'm now looking at the

Appendix I-5 -- what do those numbers reflect?

A Okay. In Appendix I-5, basically the stress period is model jargon. That's equivalent. One stressor is equal to a month of a year. So stress period number one would be like January 1950, I think -- January 1951 would be stress period one. And then it goes each month -- each stress period. That's so that we could easily identify in the model. The model doesn't know about months.

Q Right, right.

A So that's what that means. The month and year corresponds to the month and year that the model simulation was applied to, starting in January '51 and going all the way through -- in this report, we stopped at March '87 which is when the last water supply well was operated.

Q And then the next one?

A Then the calibrated PCE concentration. That is the mean value that came out of the model of the original mod flow MT3DMS models. We have always said that represented a mean value.

Q And --

A Or an average value.

Q And you mentioned mod flow and MTDMS.

A MT3DMS.

Q MT3DMS. Are those models?
A Those are computer codes. Mod flow is produced by the U.S. Geological Survey and publicly available. And MT3DMS is a fate and transport model code, I believe, out of the University of Alabama. And it, to use layman's terms, hooks on or uses the results out of mod flow to do the fate and transport.
Q And have both of those -- that is, mod flow and MT3DMS -- have both of those been utilized in other studies and other settings?
A Yes.
Q Are both generally accepted?
A Yes.
Q All right. Go on and tell me now. It says: Calibrate PCE concentration --
A So those are the values also reported in Chapter A that represent the mean or average monthly concentration of PCE.
Q Are those reported in micrograms per liter?
A Everything I talk about will be in micrograms per liter.
Q Which is in this case the same as parts per billion?
A Parts per billion; that is correct. Then the remaining columns represent the probabilistic

analysis that we conducted, that is described in detail in the main text of Chapter I. And we used the terminology and approach that is similarly used in other branches of science like petroleum engineering when they want to know what's the probability of finding oil. There is no one value. There's a median value, and then there's a two and a half percent and 97.5 percent range.

Q Okay.

A And so we used the same approach. That's a standard way of presenting this in tabular form. And so that gives you the low range -- low value and the high value of what the concentration could have ranged at any particular month and time that the simulation was applied to.

Q All right. Let's break that down a little bit. There's a scenario one and a scenario two. Tell me about those two different scenarios?

A In scenario one, we varied number model parameters, but we kept pumping. The amount of water was drawn from the ground -- from the water supply wells the same as we did in our original model. We assumed that it was not probabilistically distributed. That is, there was no uncertainty to the pumping.

Q It was static?
A The pumping changed month to month, but the value of the pumping, there was no uncertainty about it.
Q Okay.
A Okay? And that's what --
Q I see.
A -- we did, okay, in other words. That was scenario one. Scenario two assumed that even pumping was uncertain, so that if someone was pumping, you know, 2000 gallons per minute, that may have been a mean value, but that could have a range on either side.
Q By a factor of what?
A We used a normal distribution, and I couldn't -- there's a graph -- there's a typical graph in there. I couldn't really tell you a factor. But we generated a probabilistic distribution for pumping for each month.
Q Okay. And these two scenarios are called Monte Carlo simulations.
A That's -- I think that's used.
Q Sure. And I understand it. I'm wondering -- for the Court, can you just explain what a Monte Carlo simulation is.

A It gets it's name obviously from Monte Carlo, gambling casino, because you've got different odds of winning or losing. And it uses the same technique. It generates many, many -- in this case, several hundred -- five or six hundred different times. So for each month, the model is run over and over and over again with different parameter values based on different probabilistic distributions, not just the mean value but a range of probabilistic distributions. And so you can get different combinations of values.

And what we want to see, again, does that infinite range of parameter combination and values -- does that give you reliable results, or does that give you such a large range that you can say the results are not necessarily reliable.

Q And in this case, what did you find?

A We found out that our results were very consistent and had a very narrow spread or a very narrow range in value for each given month about the mean.

Q All right. How should we understand this in terms of what you're actually saying? If you could turn to stress period 350.

A Okay. Right here. Got it.

Q This is the February 1980 set of values.
A Right.
Q Now, the mean value is -- I'm going to use parts per billion.
A That's fine.
Q 122.98 parts per billion. And just for the record, what does mean value indicate?
A Mean is the average -- average value. Let me --
Q Go ahead.
A Let me explain something. Look at -- we've got one thing that says it's calibrated as mean value, and we also have a column that says "P50," which is a 50 percent value.
Q Yeah, I see it.
A We are assuming that our results -- and this is a typical assumption -- that they are normally distributed. Many things in science and engineering behave according to a bell-shaped curve. Okay? And so what we are assuming is that the mean, the median, and the mode are the same value, meaning it's a normal distribution. It's not going be exactly that. But you can see, for example, the mean value or the average value is 122.98, which we can say 123 for argument sake, round it off. And the P50 is 122.

Q Right.
A They are nearly -- you would call that the same value. Okay?
Q Right.
A And that's just a reference and, again, presenting the P50 as a standard practice in other sciences. It basically shows you the spread about a middle value, and we're assuming that spread is bell-shaped curve.
Q Okay. And you have P2.5 --
A Right.
Q -- and P97.5. Those are at the outer edges of --
A Those are at the -- what we refer to as the tails of the distribution if you have a bell-shaped curve. So the P50 is right at the center and then the other two at the other two extremes.
Q Okay. And that's the -- what you told me about before when you said it could be off by an order of magnitude of two.
A I said it could be off by a factor of two, two and a half, like that. That's basically --
Q That's what's reflected here?
A That's where we derive that general number from, is we went through all of these and looked at

the spread on that. And I'm using two and a half as a round figure. It could be less than that. In this case, it's, you know -- that's right in there to -- to -- in other words, 123. The high is 171. So it's much narrower than that. But there are some places where that does spread out. But it was well below five and well below an order of magnitude.

Q And so, therefore, useful for the epidemiologist.

A Yes.

Q In looking at this now, I see that the mean value is 122.98, and I'm going to go ahead and use the precise figures because of the record. I'm looking at stress period 350. The mean value is 122.98. The P50 value under Monte Carlo simulation, scenario one, is 121.80, which you indicated for practical purposes is essentially the same thing.

A Right.

Q And then if you go over to Monte Carlo simulation two, the mean value -- the P50 -- excuse me -- is 131.23, again, right in there.

A That's correct.

Q The other figures on that line, you know, the outliers obviously somewhat mirror each other.

But does the fact that the mean value and

the P50 under both Monte Carlo simulations is so consistent -- does that tell us anything?

A It basically confirmed to us that, in fact, assuming a normal distribution was appropriate, that it was behaving that way, appropriately.

Q Does it tell us that --

A The model was behaving appropriately and that we did not make an assumption that it was normally distributed parameters. And then the results are way out in left field.

Q Okay. So it tended to confirm the reliability of your assumption of a normal distribution.

A That is correct.

Q And, therefore, tended to confirm the validity of the work you were doing, the results you were getting.

A That is correct.

Q Does the fact that the mean value, the Monte Carlo scenario one P50 value and the Monte Carlo simulation scenario two P50 value, are so similar tell us anything about the actual -- the likely actual exposure -- or I should say the likely actual quantity of contaminants in that month?

In other words, does the fact that those

things are similar numbers give us any information about what the actual numbers should be? I'm trying to ask: Does it help us rule out, for instance, the 206.13 and the 77.7?

A No, it does not --

MR. BAIN: Wait a minute.

Objection as to form.

Go ahead.

BY MR. ANDERSON:

Q Go ahead.

A No, it does not; because all of those numbers -- basically in the probabilistic distribution, we're saying those numbers are equally likely. Okay? In other words, that's what we're saying, and that's why that's important for the epidemiologist to use. They can use that range -- that range in there. What it does say to me is that, in fact, yes, there is some uncertainty associated with pumping, with the actual pumping, because it is a slightly different number.

Q Right.

A And that we should take into account the variability and uncertainty with all model parameters, which is what we did. Pumping, just like any other model parameter, contaminant source, or

anything is subject to uncertainty because we do not have -- even when we have measured data, we do not have a complete set of information. So it's important to conduct these analyses. But it does give us confidence in our results.

Q So all we know -- and I don't mean to suggest that this is not a lot -- but at the end of the day, we know that for stress period 350 from February 1980, the amount of contaminants in the water at Tarawa Terrace ranged from 77.70 to 206.13.

MR. BAIN: Object to form.

BY MR. ANDERSON:

Q Is that the truth?

MR. BAIN: Object to form.

BY MR. ANDERSON:

Q Is it somewhere in between those?

A That's a factual statement based -- that's what these numbers represent.

Q Right. And you're talking about, in this one, PCE only; is that right?

A This is only PCE.

Q Is there a table in there for any other contaminant like TCE?

A I do not believe we conducted this for -- for the degradation products. I did not publish a

probabilistic analysis for the degradation products of PCE and TCE, DCE, and vinyl chloride, although the same technique could be used.

Q Is there a reason why that wasn't done?

A Just space and time. We presented the mean values of those degradation products in Chapter A as well as Chapter G, which was specifically on the degradation products. And my feeling was, if I could demonstrate how to apply this method just to PCE, the same technique could be applied to the -- to the other values, and you could generate ranges as well.

Q What is your understanding of the contaminants in the water at Tarawa Terrace? I'm understanding that there is both TCE and PCE. Is that your understanding?

A There's PCE and TCE. We also had measurements of DCE.

Q Which is -- for the record, it's 1,2-dichlorethylene?

A That's right. And there's two different congeners, a trans and A Syst. And if I can look in here and see which ones we did, because one was not -- it was the trans that was predominantly at Tarawa Terrace.

Q Now, let me come back to that in a second.

I just want to ask you: Is it your understanding that all of the TCE at Tarawa Terrace was as a result of degradation of PCE?

MR. BAIN: Object to a lack of foundation.

BY MR. ANDERSON:

Q You can answer.

A Our assumption was that, in fact, the PCE at Tarawa Terrace was a degradation product, not a source contaminant.

Q What are sources of TCE other than as a PCE degradation byproduct?

MR. BAIN: Objection to form.

Go ahead.

THE WITNESS: A puriform TCE is used as an industrial solvent. So in many industrial settings, they will use TCE as a solvent.

Q Degreaser?

A Yes, degreaser. It is also used -- just for the record, so we're clear -- TCE can also be used as a dry-cleaning product just like PCE. And, in fact, that issue was raised by our office of science when they were reviewing the report, who asked if we had considered TCE. And since we were dealing with one dry cleaner, the ABC Dry Cleaners, that we knew from their deposition specifically what compound they

used. And that was tetrachlorethylene and perchloroethylene. And so --

Q PCE?

A PCE. So there was no source that we could locate or find for trichloroethylene.

Q So you made the assumption in your work based on that that whatever trichloroethylene we see there is a PCE degradation byproduct.

A That is correct.

Q Did you make inquiries as to whether there were any use of industrial solvents that contained TCE in the Tarawa Terrace area? Did you inquire as to that?

A We looked at the literature and source documents to see what industries may have been in there and all of that, and Tarawa Terrace is primarily a residential area. And so with the exception of, say, a gas station, something like that, there was no industry there. And, in fact, the state of North Carolina in 1985 -- the Shiver Report, in fact, pointed to that ABC One-hour Cleaners, was, in fact, the source for the PCE in the -- in one water supply well on base.

Q Did you, in the course of requesting documents from the Department of the Navy and the

folks at Camp Lejeune, ask to see any documents that had to do with TCE usage at Tarawa Terrace?

A We asked for -- not specifically. Not specifically.

Q Why not?

A Because we wanted to be the ones to determine how different compounds may have gotten into the soil, the groundwater. What we wanted to see was -- and we asked for this -- any and all documents that may contain relevant information for water modeling, that is, documents containing geohydrology, geophysical logs, water-level readings, water-quality sampling. They did provide us -- we asked for building use on base, things like that. But we -- it's important not to sort of -- I tell them I want Document X so I can prove Z. Okay.

In other words, we need to be the ones -- meaning ATSDR -- to make -- read that document and make that understanding. So we ask for every -- all documents that we could use in our water modeling analyses. And we provided them on several occasions with the type of documents and/or the type of data these documents might contain.

Q Would it have been your understanding that your request for documents were broad enough that

they would have included any documents that would have shown, for instance, the disposal of TCE in the Tarawa Terrace area?

A Yes.

Q Would your documents requests have been broad enough to also have covered the presence of fuel tanks in the Tarawa Terrace area?

A Yes.

Q Containing fuel that contains benzene?

A Yes.

Q Did you receive from the government, in the course of those document requests, any information about presence of fuel tanks in Tarawa Terrace?

A Yes, we did.

Q You were aware at the time that this Tarawa Terrace study was published, that there was, for example, a 10,000-gallon fuel tank near the school?

MR. BAIN: Object as to form; lack of foundation.

Answer if you know.

BY MR. ANDERSON:

Q Did you know about that?

A I can't specifically say that I personally knew about it. But we have a Chapter E report, and in Chapter E we discuss with me the benzene

occurrences at Tarawa Terrace.

Q Okay. And did your report on Tarawa Terrace, the one we have been discussing this morning, take into account all that was known to you and your team about the underground storage tanks in Tarawa Terrace in terms of the results here?

A We did not simulate or conduct model simulations for benzene at Tarawa Terrace.

Q Why not?

A After reviewing the data and the analyses that we did based on the underground storage tanks, we did not -- number one -- we felt, number one, that whatever gasoline -- because at Tarawa Terrace there was gasoline holding tank leaks -- was small enough in nature that it did not impact any of the supply wells. So there was no major source of benzene.

And, in fact, the results -- there are, I think, two or three samples at the water treatment plant that are, say, 1 to 4 -- maybe there's a 7 -- micrograms per liter, were substantially low, that it did not, again, indicate that there was a source at Tarawa Terrace for benzene contamination of groundwater supplies that would impact drinking water.

Q So you just said, I believe, that there were

gasoline holding tank leaks at Tarawa Terrace?

A Yes. That's documented in Chapter E.

Q And the treatment plant found benzene in the water, but you felt it was a sufficiently low quantity.

A That's correct.

Q That it would not impact your study.

A That's correct. That's correct.

Q Were the wells actually tested for benzene at Tarawa Terrace?

A I do not -- I do not know if they were tested or not.

Q Now, we've been talking about Chapter I, and you showed me some data there. Can you show me how that relates to the data that you described as being in Chapter A.

A Sure. And I will just go to the results here. If you go to Appendix A -- yeah, Appendix A-2, example in Chapter A. I'm on page A82. Or, for example, let's use the one we've been talking about, stress period 350, just so we can compare apples and apples. And that's on page A91. If we look at February 1980 in Chapter A --

Q Can I come around and stand by --

A Oh, sure, yeah.

Q My copy doesn't go that far. If you don't mind, I won't loom over you, but I just want to see what you're talking about.

A In fact, if we go here to my same stress period, same month and year -- and here we've got single specie using MT3DMS model. So that is the concentration, as a model, PCE in micrograms per liter, parts per billion. And then we go to stress period 350, and we get 122.98. If we go to Chapter I where it says calibrated PCE concentration, stress period three -- 122.98. So this column in Chapter I is the same as this column in Chapter A, identical. I mean, we didn't make additional models. That is those results.

Q Right.

A The rest of the columns are the degradation product in Chapter A.

Q Are they a subset of the PCE single-specie number?

A Not a subset. It's using -- you have to use a more sophisticated model and degrade the PCE.

Q Sure. Are these figures in addition to the PCE, or are they the PCE as degraded?

A It's the PCE as degraded.

Q Okay.

A And, in other words -- so this is why you'll see -- and we'll go back to 350, whereas our single specie -- look only at PCE -- is 122.98. For the degradation model, PCE has to be lower because there's other mass for other products. Okay.

In other words, we're -- in the single specie, we are lumping all of the degradation products. And in the same, PCE does not degrade. That is what we call the most conservative approach. In other words, that would give you the maximum hit of PCE in the water.

Q Right.

A This is a refined and a -- well, not a preferred approach but a more sophisticated approach. And in doing these analyses, that is something that you want to do. This also says that this is in check because we should have a higher value of PCE for the single species as opposed to the degraded value.

Q I understand. And so taking that page A91 in Chapter A for stress period 350, February 1980, your values are, single-specie PCE was 122.98. As we discussed in Chapter I, the PCE component of the multi-species would be 98.2.

A That's correct.

Q And then you have 1,2-DCE at 13.49 --

A That's correct.
Q -- TCE at 4.04, and vinyl chloride at 7.56.
A That's correct.
Q And so assuming -- I take it this assumes that the -- that PCE underwent a normal biodegradation process.
A That is correct. That is correct.
Q So assuming that the PCE at Camp Lejeune underwent a normal biodegradation process, you have a chemical cocktail in the water.
A That is correct.
MR. BAIN: Objection to form.
BY MR. ANDERSON:
Q That's the truth, isn't it?
MR. BAIN: Objection to form.
Do we have an answer?
BY MR. ANDERSON:
Q Can we have an answer.
A Yes. It's underwent, and you had multiple compounds in the water.
Q Right. Multiple contaminants.
A Multiple contaminants.
Q Multiple chemical contaminants.
A That is correct.
Q Yeah. Would it be all right if I also mark

the Chapter A? I'm sorry for marking your copies.

A Go right ahead.

(Plaintiff's Exhibit Number 2 was marked for identification.)

MR. BAIN: Do you want to take a break about now? It's about 11:00 o'clock.

MR. ANDERSON: Can I ask him one or two more questions?

BY MR. ANDERSON:

Q Chapter A is going to be Exhibit 2 to the deposition. And what I wanted to ask you before we go out for our break is just a couple of quick things.

What, if anything, do you know about the health risks associated with these other chemicals in the water, for instance, vinyl chloride? Does that have any health-effect history that you're aware of?

MR. BAIN: Object to foundation -- lack of foundation.

Go ahead.

THE WITNESS: I'm not a toxicologist, and I could only answer in very generalized terms. Not specific health impacts.

BY MR. ANDERSON:

Q Right. And I'm not looking for more than

what you know. I'm just asking based on what you've read in the field that you are in, does vinyl -- is vinyl chloride in the water a good thing? Is that something we want, strive for?

A No, no. You do not want vinyl chloride in the water.

Q And trichloroethylene, do you want that in the water?

A You don't want any chemical compound in the water.

Q So you don't want trichloroethylene, and you don't want 1,2-TDCE.

A That is correct.

Q And obviously you don't want all of those things together, right?

A You don't want any compound contaminants in the water.

Q Why not?

MR. BAIN: Object as to form; lack of foundation.

BY MR. ANDERSON:

Q Why not?

A They have certain compounds that have been shown to be carcinogens.

Q And then the last thing I wanted to ask you

so I can think about it, frankly, when we're on our break is: How am I to understand this data and these tables that we have been discussing? Say, for instance, I was at Camp Lejeune, living in Tarawa Terrace from stress period 350 to stress period 390. Okay?

A Okay.

Q How do I quantitatively deal with the numbers in that box? You would just draw a box around it like I did on my copy. Do you add those up in terms of your exposure? What do you do with that data?

MR. BAIN: Object as to form.

BY MR. ANDERSON:

Q I was there, I drank this water, I showered in this water. I want to know how much I was exposed to. Do I get out a calculator and start adding month upon top of month?

MR. BAIN: Object as to form.

THE WITNESS: You would have to ask really an epidemiologist that specific question because that is not what I do nor what I was tasked with doing.

Q Okay.

A We have provided a similar table like this

on our Web site for anyone to access. And we state there -- it just says the likelihood and the range of what a person may have been -- we use the word, I believe, may have been exposed to in their drinking water at that particular month and day. And that's all I can say, and that's all the modeling results presented in this can say.

Q Okay. That Web site -- there was a Web site at one time where you could actually go in and put in your physical address. Do you remember that?

A Yes.

Q And then it would tell you how much of these various chemical contaminants were in your water at your house?

A That's correct.

Q And then that Web site got taken down.

A That's correct.

Q Why?

MR. BAIN: Objection; lack of foundation.

BY MR. ANDERSON:

Q Just tell me what you know. I'm not asking you for anything you don't know. I'm just getting inside your head and trying to find out what you do know.

A It was -- in working with the Department of

Navy, they expressed some reservations that there were insufficient qualifiers on the data, not the table itself. But when somebody just put in an address and got a value out, it did not explain to them the limits of the data or the simulated data. And they objected to that -- it was the actual application that got taken off of that.

And in working with -- which we want to do working as a -- with a partner, and the Navy being one of them. We decided that the reports were out there. Anyone could grab the reports. We put the table out there. So we took it down off that. The Department of Navy requested that that application, you know, be taken off of the Web site.

Q When did they make that request approximately?

A I really don't recall, but it was after this report was published.

Q So recently, I mean, within the last couple of years.

A Yes, yes.

MR. BAIN: Can we take a break?

MR. ANDERSON: Just one more, one or two more. I'm sorry. All right, all right. I don't want to lose my train of thought.

BY MR. ANDERSON:

Q When the DON objected to that application and asked that it be taken down, was that objection stated in writing?

A Not to my knowledge. I never received a written request.

Q Who would have received that at the ATSDR if there -- if there was a request that that Web site be taken down?

A They probably would have communicated to the deputy director or the assistant administrator at the time. It was more discussed. We have monthly conference calls with the Department of Navy and other -- and that may have been discussed at that time. There were several repeated references by DON to that application on the Web site.

And, in fact, now that I recall, there probably is a letter where they critiqued the Tarawa Terrace model, or reviewed it. I don't mean critiqued it. But they reviewed the model, and they may have said something to that effect in that letter.

Q What is that letter called if I wanted to request it from Mr. Bain?

A It's the Navy's review of the Tarawa Terrace

model, and it's dated 2007 or '8, something like that. And we have -- we responded to that letter point by point on --

Q I remember.

MR. ANDERSON: Okay. Let's take a break.

(A brief break was taken.)

MR. ANDERSON: Okay. Let's go back on.

BY MR. ANDERSON:

Q Dr. Maslia, before we took a break, we talked about the -- some of the various chemicals that were combined -- chemical contaminants combined in the drinking water at Camp Lejeune. And when we listed those several chemicals, first of all, those were in the finished water that comes through a person's tap, right?

A That is correct.

Q And you mentioned that in addition to those there was also some benzene in that water.

A No. What I said was that we had two or three hits at the water treatment plant there. And I just could not say what happened to the benzene because it was such low -- low concentrations of it.

Q Based on the documents that the government gave you.

A That's correct, yes.

Q And if you found benzene at the water treatment plant, is there any reason to think it somehow gets taken out of the water once it leaves the treatment plant and flows to the consumer?
A No. It may have been diluted, though.
Q Right. Sure. And we don't know.
A That's correct.
Q And then you mentioned also that the study assumed no additional source of TCE on Tarawa Terrace. And just to be clear for the Court, the multi-species, multi-phase model in Appendix A2, when it includes TCE as an assumed breakdown product from PCE, that doesn't encompass if, in fact, there was another source of TCE like industrial solvents onsite.
A That is correct. That model, again, uses PCE as the source, the same value we use for the single species. It just let's it break down through the breakdown process.
Q So if it would be shown by the evidence and from its greater weight that there was actually TCE degreasing done on Tarawa Terrace, that would not yet be taken into account by the multiple chemicals you found in the water in your model.
A Another source of TCE was not -- a source,

not another one -- a source of TCE was not taken into account because we did not see any evidence of a source like there was for PCE.

Q And that, again, as with the benzene, was based on the documents that the government gave you.

A That is correct.

Q Now, who at the Department of the Navy asked that that Web site for the families to type in their addresses be taken down?

A It was just in general conversation. Again, we have monthly conference calls, and they also critiqued the Tarawa Terrace model, and I cannot put a name, that I specifically remember that person said X, Y, and Z, but that definitely Navy and/or Marine Corps staff expressed that sentiment.

Q That they expressed their displeasure with that Web site and asked that it be taken down.

A With that application.

Q Okay. The one that allowed family members to type their address in --

A Yes.

Q -- and find out how many chemicals they had.

A That is correct.

Q Now, you mentioned that the Department of Navy critiqued your model. You said that.

A That is correct.
Q They did that in writing, didn't they?
A Yes, they did.
Q And they sent that to you.
A Yes.
Q What is that document called, or how would I ask for it to get it from Mr. Bain?
A You could ask for it in two ways. One, you can see it on our Web site. We have our response to it. We have the ATSDR -- I think it's called response. If you go under the water modeling for Tarawa Terrace and go down through all of the publications and stuff, you'll see something to the effect of ATSDR response to the Department of Navy review of Tarawa Terrace model. And in that, we include their letter because we refer to certain sections of their letter. So you'll see their letter there.

And you could then see the date of their letter and just ask them for the date of that letter. And offhand I do not remember if they sent it directly to me or they sent it to Dr. Frumkin who was the assistant administrator of ATSDR at the time. I just don't recall that.
Q Who wrote that attack on your model?

MR. BAIN: Object to form.
BY MR. ANDERSON:
Q Who wrote it?
MR. BAIN: Objection.
THE WITNESS: The cover letter was signed by, I believe, Mr. Harrison.
BY MR. ANDERSON:
Q Is he part of the Department of the Navy?
A Yes.
Q Is he a scientist?
A He has a "PE" after his name, so I'm assuming he's a registered engineer. I really would like to look at the letter again, if I can see that. We deal with him and also Richard Mock who is his supervisor.
Q Do you have a copy of that with you?
A No, I do not.
Q Well, we can get it on this computer in a minute. The -- maybe at our next break so we're not wasting time. I'll dig it out with your assistance.
The critique of your model, was it -- that is the critique peer reviewed?
A Their letter or --
Q Their letter.
A I don't know. You would have to ask them.

Q Did you agree with their critique of your model?
A We disagreed with many of their points that they made in their letter, and we addressed each one.
Q Did you, as a result of going through that process, become convinced that there were problems with the work you had done on Tarawa Terrace?
A No. I was convinced even more strongly that we did a scientifically defensible work.
Q Why more strongly?
A Because we were able to, in addressing some of their critiques, point out where in the literature elsewhere these techniques had been used. And, in fact, some of the critiques that they provided, we were able to show that, in fact, at other locations the Department of Navy used the exact same approach that we had used and it was acceptable to the Navy at that location.
Q And did you point that out in your letter?
A Yes.
Q So that's available to me on the Web site?
A Yes. Yes, it is.
Q And those are the same methods and techniques that you utilized in your study.
A That is correct.

Q Going back now to the tables indicating the multiple chemicals to which people at Tarawa Terrace were exposed in their drinking water, I just want to talk to you for a second about the routes of exposure.

Given that these several chemicals are coming out of the tap, is it fair to say, based on your understanding, that people would be exposed to these chemicals through drinking, inhalation, skin absorption?

A Yes; all three.

Q So if somebody was living there on the base in base housing at Tarawa Terrace, they would be exposed whenever they drank, cooked, bathed, washed clothes.

A Yes.

Q And the routes of exposure would include not only the actual drinking of it but inhaling the volatile heated water, for instance, when you're standing in the shower and all that steam is in your face?

A Yes.

Q Or when the washer or dryer is running?

MR. BAIN: Object to lack of foundation.

THE WITNESS: I really could not answer that

specific question.
BY MR. ANDERSON:
Q Skin absorption when you're washing dishes --
A Yes.
Q -- and have your hands in the hot water, steam coming up, inhalation?
A Yes.
Q And best of your understanding based on the work you did, that would have been day in and day out, right?
A Yes.
Q Are these chemicals additive in the adipose tissue?
MR. BAIN: Objection; lack of foundation.
THE WITNESS: This is outside of my area of expertise.
BY MR. ANDERSON:
Q You don't know if they are bioaccumulators?
A No.
Q Do you know whether these chemicals are interactive, that is, whether vinyl chloride in the context of PCE interacts?
MR. BAIN: Objection; lack of foundation.
THE WITNESS: I have no expertise in that

area.
BY MR. ANDERSON:
Q So when it comes to just how toxic this chemical cocktail is, you couldn't say.
MR. BAIN: Objection for lack of foundation.
THE WITNESS: That's, again, outside my area of expertise.
BY MR. ANDERSON:
Q And you've talked now about the routes of exposure. What is your understanding about who was exposed?
A Anyone who was living in Tarawa Terrace housing, because the water distribution system provided water to Tarawa Terrace housing. So that would be, you know, children, adults, workers. In other words, if there's a restaurant or whatever on base or shopping center, people who -- you know, there is a swimming pool there. People who went swimming.
Q Marines?
A Yes.
Q Their wives?
A Yes.
Q Their children?
A Yes.

Q Pregnant wives of Marines?
A Yes.
Q Infants?
A Yes.
Q Pouring this water in an infant formula and so forth.
A I have no knowledge of the feeding practices back then. So --
Q Or through the breast milk.
A Yes.
Q Now, in terms of these tables, you know, now the DON has got that site taken down, and the families can't go on there anymore and type in their address. But they can get ahold of your study. And if they want to -- if they do find your study and want to read about their exposure -- let's just go to that, if you would, stress period 349 again, January of 1980, when Laura Jones -- actually February 1980, 350 stress period when Laura Jones came on base.
She could look and she could see her exposure to total PCE and then the other chemicals that you listed as breakdown products. For that month, you see under stress period 350, and she would know she had those exposures in that month. Is that how we read this?

A That would be her average exposure.
Q In that particular month.
A That is correct.
Q So each day of that month on average, she would have been exposed to that much of those chemicals; is that the understanding?
A No, no. I would say over a month period, the average exposure would be this value. We cannot go down -- the model does not go down to a day.
Q No, I understand that, Morris. But I'm asking -- what I'm asking -- I want to make sure that the record is clear. You're saying and you already told me it would be each and every day that this exposure occurs.
What I'm asking you is: You're saying here on average in February of 1980, she's exposed to these chemicals throughout the month.
A No, no. I'm saying the average exposure which is different than on average.
Q Okay. The average exposure per month.
A Yes.
Q Okay. So this is a monthly value?
A That is correct. That is correct.
Q Okay. So the average exposure per month for February 1980 is this series of numbers.

A That is correct.
Q Okay. And then let's say she stays for stress period 351. Then the next month the average per month is, she's exposed to the next set of values.
A That is correct.
Q And so on and so forth throughout the entire time she's there.
A That is correct.
MR. ANDERSON: Let's go off the record for a second.
(Brief discussion ensued off the record.)
BY MR. ANDERSON:
Q And just for final clarification on the issue of exposure, if there is another source of TCE, she would have been exposed to that in addition to what you have here.
A Not unless it got in through the water treatment plant.
Q Right.
A Okay. And, again, that really would be speculating based on here, because our model is based on only one source and that's PCE and degraded TCE.
Q Right. And that's the only one you know about.

A That is correct.
Q And if it were shown from the evidence that there was another source that got into the water, then that would be in addition to what is reflected?
A If it got into the supply well and then into the water treatment plant, then that would be an addition. But it would be -- you could not defend just taking that value and adding it to this model, because then the model would not have incorporated that other source. We would have to rerun the model to do that.
Q Understood. And the same would be true if there was a significant source of benzene. You would have to rerun the model.
A We would have to rerun the model with a caveat that if we could assume it was dissolved, low enough concentration, in other words, not floating above the water table but just dissolved like these were, then you could rerun the same model that we had. If, in fact, it is substantial enough that it's floating on top of the water table, then you have an entirely different complicated model. You could not use these models.
Q And if, in fact, you were running a model for TCE or PCE and you were about finished with the

model years into it and somebody told you, Hey, there's a million gallons of benzene that have not previously been accounted for, would that mean you would have to start a lot of work over?

A It means you would have to look at what assumptions the model that you have developed thus far -- what assumptions you have made and see if, in fact, you could include that, or, in fact, you would have to bring in a more complicated model.

You would have to evaluate that because benzene also has -- even if it's dissolved, it has different, what we would call, retardation factors, the speed or lack thereof that it moves once it's mixed with water. It would move at a different rate than PCE would. So you would have to rerun the model and take that into account, and there would be some time involved in doing that.

Q He's asking -- Mike Pangia wants me to ask you: If, in fact, there was found to be benzene in this water, does that mean that your -- the work you did and the model you ran is inaccurate?

A No, not at all.

Q Now, stepping back again from the data itself and so forth to the subject of your model more broadly with regard to Tarawa Terrace, did you check

the results of your simulations against any actual data points, that is, known data like you described doing in Georgia?

A Yes, we did.

Q Were they -- were your simulation results consistent or inconsistent with the known levels of contamination?

A We were very consistent.

Q What did that tell you?

A It told us that we had a reliable and, more importantly, what we believe is a scientifically defensible product.

Q All right. So that gave you added assurance of the accuracy of your results because of the fit between the study results and the known levels of contaminants.

A That is correct.

Q Were there any other checks on methodological reliability that you did after you had run your simulations?

A Well, Chapter I, which is the probabilistic and sensitivity analysis, is another check because, again, it demonstrated that the range of values were fairly narrow, were within acceptable limits for the epidemiologist to use. And we felt that they showed

that our results were consistent over time.
Q So that was another confirmation of the reliability.
A Yes.
Q And then you've already told us you had the study peer reviewed.
A Yes.
Q You mentioned that the Department of the Navy had criticized your study. Has the study been criticized by anybody else?
MR. BAIN: Objection to the form. The word used was critiqued.
MR. ANDERSON: All right. Well, I'm not going to get into that level of semantics.
BY MR. ANDERSON:
Q By whom?
A The National Research Council.
Q All right. Tell me about that.
A About the council or about --
Q About the criticism or critiquing of your model by the National Research Council.
A Okay. They produced a report in June of -- is it 2009 or 2010? I forget the year. And they spent an entire -- Chapter 2 is what they referred to as their exposure assessment chapter, and they spent

the entire chapter critiquing the modeling approach, the model that we used.

One of their biggest critiques that they made -- not only did we disagree with but the data contradict their critique -- is that we did not analyze the VOCs as DNAPL, which are dense non-aqueous phase liquids, which means they have a density of greater than one or they are denser than water. And they indicated that that was a severe limitation. That was one.

They also critiqued in a different chapter -- Chapter G, I think -- we do a vapor analysis, look at the vapor of the different constituents going into the soil above the water table. And they critiqued that by comparing it to vapor intrusion in a dry cleaner in New York City. And, again, we were baffled as to why they would compare soils, sandy limestone soils in North Carolina with an urban dry cleaner in New York, but that's the comparison they made. And, again, we addressed all of their -- internally we addressed all of their critiques. But they critiqued it.

Q When you addressed these internally, were there documents generated that -- where you addressed these critiques?

A I generated a document and sent it to my branch chief and division director as an e-mail attachment.

Q Who is that person?

A My branch chief is Susan Moore, M-o-o-r-e; and my division director is Dr. William Cibulas, C-i-b-u-l-a-s.

Q And so you attached that response to the National Research Council and gave it to your superior.

A That's correct.

Q How did you deal with the issue of your supposed failure to treat the contaminants as dense, nonaqueous-phase liquids?

A Well, in fact, they used data that we published in Chapter E, which is the water quality chapter. And I think the highest value was 20,000 micrograms per liter. And what we said was, all that is is an indication of a source but there's no other data anywhere near there and so they could not prove that that was DNAPL. In other words, that does not prove there's DNAPL there. And so they used the data that we published.

That was one of our -- if you want to call it -- complaints about -- internally our senior

leadership is that they took data that we published, misinterpreted it, and then put it out there for the public as scientific gospel, because they are the National Research Council.

Q Who are they anyway? I mean, you know, who are those people?

A National Research Council is an independent agency that is contracted out by any -- typically by any agency within the U.S. Government. If they want, you know, high-level scientific work or analysis, they do many types of different analyses.

Q So they are paid for hire, available to be hired by some agency, for instance, the Department of Navy?

MR. BAIN: Object as to form.

THE WITNESS: The Department of Navy did pay for the National Research Council review. My understanding is that they were mandated to do so by Congress in one of the defense authorization bills.

BY MR. ANDERSON:

Q Do you know who introduced that --

A No, I don't.

Q -- amendment to the legislation?

A No, I do not.

Q That's interesting. In expressing your concerns internally about the fact that, as you put it, the DNR -- or DRC -- excuse me -- let me start over.

In expressing your concerns here internally about the fact that the National Research Council had, in your words, misinterpreted our data and represented it to the public as scientific gospel, did you and others within the ATSDR write e-mails and memos about that subject, discussing it?

A We wrote a formal -- at my level, response. I did it for my particular chapter of interest which is the Chapter 2. I know Dr. Bove did the toxicology and epidemiology. And, like I said, I sent mine by e-mail. But we had numerous discussions with agency leadership -- at that time, Assistant Administrator Dr. Howard Frumkin and Deputy Director Dr. Tom Sinks -- and we were told on several occasions in no uncertain terms that the agency would not respond the NRC report.

Q Why?

A They said these were scientists of national repute, okay, and that the agency was not going to respond to the NRC report.

Q So you were ordered not to respond.

MR. BAIN: Object as to form.
BY MR. ANDERSON:
Q Were you ordered not to respond?
A I was told the agency would not respond.
Q Did you have any choice? Did you have a choice to respond anyway?
A I wrote -- I wrote my document and sent it by e-mail to my branch chief and division director, and that's as far as I could go --
Q So if you --
A -- as an employee of ATSDR.
Q So the public only sees one side of the story. They see what the National Research Council has misinterpreted from your data --
MR. BAIN: Object as to form.
BY MR. ANDERSON:
Q -- but they don't see your response; is that the truth?
A The public has not seen my response as an official ATSDR response to that section of my expertise in the NRC report.
Q How about Bove's response to the NRC's toxicology stuff: Has the public seen that?
A No, they have not.
Q So the public has seen one side of the story

and not your side of the story?

MR. BAIN: Objection as to form; argumentative.

BY MR. ANDERSON:

Q I'm just asking: What is the truth? Is that the truth?

A Our internal scientific response to the document -- both epidemiology, toxicology, and exposure assessment -- was not released -- were not released as ATSDR responses to the NRC report.

Q Were they released in any form to the public?

A The agency did release a -- if you want to call it a work plan, okay, or a plan going forward. And in it, they did not subscribe to all of the NRC's recommendations. Okay. In other words, however, we always felt from the technical and scientific standpoint that that significantly watered down our work because it did not, you know, go point by point. But the agency did put forth a plan going forward in which the agency did not accept all of the recommendations of the NRC.

Q And I believe you said that the NRC misinterpretation was funded by the Department of the Navy?

A The NRC work -- the work the NRC interprets or cites, there's a committee there, and they do what they do to get the ball running. In other words, to get funding to look at the water contamination at Camp Lejeune, that product was -- my understanding -- was funded through authorization in one of the defense authorizations.

Q And that was by the Department of Navy, right?

A I'm not clear if it's the Department of Defense or Department of Navy. In other words, I don't recall specifically.

Q One or the other or both.

A Right, that's correct.

Q When you read what the National Research Council had come up with about your model, did you come away from that feeling that your model was invalid in some ways, or did you come away from that convinced of your model's validity?

A Neither. I was convinced there was significant misunderstanding and misinterpretation of information and, in fact, lack of understanding of the whole Camp Lejeune issue on the part of the NRC committee and specifically those people on the committee who were responsible for doing, say, the

exposure assessment part.

Q Why do you say that?

A I had several e-mails back and forth from one particular individual on the committee.

Q Who was that?

A Dr. Prabhakar Clement. Last name is C-l-e-m-e-n-t. And I think he's out of Auburn University. Early on when -- in 2007, 2008, asked me -- asking me about what -- what particular approaches we were using and, for example, how we were treating the PCE source and the model, what option in the model we were using. I'm putting this in layperson's terms, if that's okay.

Q I appreciate it.

A And I explained and all of that. And, in fact, I have an e-mail from him saying, Boy, this is great. You know, the public is lucky to have an agency like -- ATSDR is doing such a good job and all that sort of stuff.

And then somewhere along the line in 2008, 2009 -- it was after we published these results for Tarawa Terrace -- I didn't hear anything, but then the NRC came back. And it was like totally opposite of what we had been communicating in an e-mail, and I wasn't sure where the change -- and, of course, the

reports -- a committee report. And somewhere in -- I think it was 2008 or so -- I had sent an e-mail to the chair -- oh, not the chair of that committee but the NRC staff person who oversees the committee.

Q Who is that?

A Susan Martel.

Q M-a-r-t-e-l?

A M-a-r-t-e-l. Susan.

Q Okay. Keep going.

A Suggesting that it would be good for the committee or for us to meet with the committee again because I thought there were political budget and scientific issues that perhaps the committee needed more clarification on.

And so I sent her that e-mail. We met once with the NRC committee. They had a public meeting in Washington. I forget the date of it. That's public record. And, you know, I presented a 20-minute presentation of what we were doing with Florida modeling. Dr. Bove presented 20 minutes on the EPI side. The Marine Corps -- one Marine Corps general -- I do not recall his name, but I have got the -- there's a an agenda of who spoke -- got up and stated what the Marine Corps was hoping to get out of the NRC committee and all of that sort of stuff.

And so the rest of it -- that's the only time we presented details of what we were doing. The rest of these are through e-mail requests of the results or whatever or data that we had. And, as I said, as things progressed, I felt that the -- I felt personally or professionally -- professionally that the -- it was a lack of understanding, as I said, of the politics, the complexity, budget issues, and approaches that we were using and that it would behoove the committee just to hear from ATSDR on those subjects. And I sent that e-mail to Susan Martel.

Q What was the response?

A Her response was that she would forward my e-mail to the chair of the NRC committee but it would be up to the chair of the NRC committee to make a decision if they wanted additional information from ATSDR or additional -- I don't know if it's called testimony or not but, you know --

Q And what happened after that?

A Nothing.

Q You mean, you -- so you never heard back from the chair of the --

A No.

Q -- NRC?

Who was it that told you that the rebuttal that you had produced to the NRC interpretation could not be made public?

A We were told that ATSDR was not going publicly rebut, and that was Dr. Sinks, Dr. Tom Sinks, as well as my division director and the division of health studies director, which is Dr. David Williamson. They are obviously one level bureaucratically below Dr. Sinks.

Q So he was the top man responsible for that decision?

A I couldn't say if he was personally responsible or not. I'm not involved in those discussions at that high level. But he was the -- at the time, assigned to oversee the whole Camp Lejeune health study, and that's what we were told on several occasions.

Q The question that comes to mind is this, you know, the government spent a lot of money to allow you to do the study that we have talked about, and it's printed in these beautiful reports. First of all, how much money -- how much money did your study cost?

A It's been averaging about 1.5 to 1.8 million per year.

Q How long has it been going on?
A Since 2004.
Q So the -- and the government is paying for that, the taxpayers are paying for that study, correct?
A That is correct.
Q So the government -- help me understand -- the government spends many millions of dollars to support your work because you guys are the experts.
A That is correct.
Q And they fund you. And now the Department of the Defense or the Department of the Navy comes along and gets another organization. This -- uses another organization also funded by the government, funded by the taxpayers, to attack the work that you did, funded by the taxpayers, right?
MR. BAIN: Object to form.
Q Is that true?
MR. BAIN: Objection.
THE WITNESS: They used another scientific body to critique our work. That's fine. And our work is public information, so anybody can critique it, whether it's an individual or consulting company or any other organization. I believe it's scientifically defensible. And what

I asked for and what my colleagues at ATSDR and, in fact, our cooperators like Georgia Tech requested, that we be allowed to defend it on the same playing field.

BY MR. ANDERSON:

Q And that was the request that was denied.

A That's correct.

Q I mean, you know, just kind of simplistically, if, say, Toyota did this, you know, they fund a study of their gas pedals and then they hire -- they also fund a study to critique their study of their gas pedals, that would be nonsensical.

How does it make sense that we're paying, as taxpayers, for a multimillion dollar study by you guys who are the experts and then we're also paying for the National Research Council to come along and critique that? How does that make sense?

MR. BAIN: Object to form; lack of foundation.

THE WITNESS: I haven't got an answer for that.

BY MR. ANDERSON:

Q In reviewing the documents that cover the known data regarding the actual contamination that were provided to you by the Department of the Navy,

were you relying on the Department of the Navy to provide you with everything that they had?

A Yes.

Q And what documents did you see?

A We saw anything from handwritten notes to lab reports to engineering reports to remedial investigation reports to unidentified slips of paper.

Q Did you see these documents that were attached to our lawsuit. I'm going to show you exhibit pages E, F, G, also known as CLW4306, 438, 443. Did you use those as known data points?

A These are -- actually what these are -- CLW, we have termed -- and it's in our reference section as Came Lejeune water document, and they are all listed, not necessarily in sequential order, all in the DVDs.

Q Right.

A And what these particular ones -- let's looks at CLW0436. At the time, this is 1980. And this is how the volatile organic compounds were actually discovered at Camp Lejeune. Because at the time they were looking for trihalomethane constituents, and that's what's listed here: CHCL3; CHCVR is the bromide; and so on and so forth. Because they were -- these were byproducts of --

disinfection byproducts, and they were concerned about high levels. And so they --

MR. BAIN: Excuse me. You got to listen to his question, and answer. He's just asking you if you saw these and used these.

THE WITNESS: Oh, okay, okay. Well, I was getting to why we did not -- sorry -- it's elongated -- why we did not use as data in our model. So the answer to your question, we did not use these particular documents as data in our model.

BY MR. ANDERSON:

Q Okay. Go ahead and tell me why not, just in the interest of hearing that.

A Because they relate to trihalomethanes and this is infection of byproducts. They do not relate to volatile organic compound contamination. However, they were having difficulty with the analytical methods in there, and they had indicated possible or likely VOC interference.

Okay. So while it does not give us a value to put in or compare the model with, it does tell us that in 1980 there were most likely high levels of VOCs in the water. And, in fact, the model confirms from a quantitative standpoint. So we used them

indirectly in our model.

Q And they were consistent with what you found.

A Yes.

Q Okay. And I guess that document, that first one there, says: Water is highly contaminated with low molecular weight halogenated hydrocarbons of strong interference, et cetera, et cetera.

Do you know who prepared these documents, these -- I guess it says William Neal, chief of laboratory services.

A It was prepared by the laboratory section of Camp Lejeune. And Elizabeth Betz was a chemist whose name you will see many times on such documents.

Q So these documents in 1980, which you indicate reflect high levels of volatile organic compounds in the water, also reflect an awareness, a knowledge, on the part of the Department of the Navy's staff, Marine Corps staff, of the presence of those chemicals as of that time; is that true?

A Let me put it this way: I don't know how the Department of Navy handled its internal communications. They indicate that a lab analysis was done and a chemist provided an information sheet to someone in their environmental management

division. That's all I can say from that document and their repeated references to interference with VOCs.

Q Right. But, I mean, these documents -- CL436, 438, and 443 -- based on your knowledge, your training, and your experience, these were documents generated by the Department of the Navy.

A No, no.

Q Or the Marine Corps.

A Marine Corps.

Q Right there at the base --

A That is correct.

Q -- in 1980.

MR. BAIN: Do you want to look at all of the pages that he referenced to see --

THE WITNESS: Yeah --

MR. ANDERSON: Yeah, and then give me the answer after you look at them all.

THE WITNESS: Yeah, these are -- these are all part of the CLW documents. CLW number was put on subsequent to -- probably during the time that we started our health study. These particular documents were prepared locally at Camp Lejeune.

BY MR. ANDERSON:

Q And so they're government documents; they're documents of the United States Government?
A Yes.
Q An agency of the government.
A Yes.
Q Is the Marine Corps a part of the Department of the Navy?
A Yes.
Q And just to come back to my question because it got a little interfered with, ironically, those documents reflect that the Marine Corps knew as of 1980 that there were high levels of volatile organic compounds in the water at Camp Lejeune.
MR. BAIN: Object to form; lack of foundation.
BY MR. ANDERSON:
Q Isn't that the truth?
MR. BAIN: Same objection.
THE WITNESS: The chemist and the person that she provided these documents were made aware of it.
BY MR. ANDERSON:
Q They knew it.
A Where it went -- I mean, I cannot speak for the entire Marine Corps or the Navy.

Q But some agent of the Marine Corps knew as of 1980 that there were high levels of volatile organic compounds in the water.

MR. BAIN: Object as to form and lack of foundation.

BY MR. ANDERSON:

Q Answer?

A They -- they were told that there was interference with their mass spectrometer on there.

Q Did you tell me before that this indicates high levels of volatile organic compounds?

A High level of VOC that's interfering with an analytical test. It is not a direct confirmation that there are VOCs in the water.

Q But it ended up being consistent with what you found.

A That is correct.

Q Which was high levels of VOCs in the water.

A That's correct.

Q So some agent of the Marine Corps knew in 1980 that there were high levels of VOCs interfering with their samples at Camp Lejeune.

A That is true.

MR. BAIN: Object as to form and lack of foundation. The document speaks for itself. He

wasn't --

MR. ANDERSON: Let's have him testify here. I want this on the record.

BY MR. ANDERSON:

Q Is that the truth, sir?

A Could you repeat the question.

Q Yeah, yeah. Some agent or agents of the Marine Corps working in their lab in 1980 knew from these documents that there were high levels of volatile organic compounds in the water interfering with their sampling.

MR. BAIN: Object as to form and lack of foundation.

Go ahead and answer it.

THE WITNESS: That is correct.

BY MR. ANDERSON:

Q That's is the truth, isn't it?

MR. BAIN: Objection, same objection.

BY MR. ANDERSON:

Q Simple.

A I wouldn't phrase it as truth or not. I'd say the facts based on those --

Q All right. That's the facts.

A That is what those sheets or those lab results are showing. That is that chemist's

interpretation.
Q An interpretation which was subsequently borne out by what you studied and what you concluded.
A That is correct.
Q And peer reviewed.
A That is -- yes, it was peer reviewed, yes.
Q Did you also review the Grainger report from August of 1982 in connection with the review of the known data points?
A Yes.
Q And was that one of the data points that you use as a check on your simulation?
A Yes.
Q And were those data points consistent with what your simulation discovered?
A Yes.
Q And it indicates here Bruce Babson had prepared that Grainger report and sent it to the commanding general of Camp Lejeune.
Did I read that correctly?
A That's how all we even address things to the commanding general.
Q Did I read it correctly?
A Oh, yeah, you read it correctly. It says it's sent to the commanding general.

Q Does this document also indicate that, again, now, two years later, the Marine Corps is aware of high levels of volatile organic compounds in the drinking water at Tarawa Terrace and now even the quantities of some of these?

A Yes.

Q Did you see documents contemporaneous to this document indicating any knowledge on the part of the Marine Corps of the health risks associated with exposing the Marines and their wives and children to these chemicals at that time?

A The Grainger letter in the first paragraph or second -- I don't have it in front of me, so --

Q Now you do.

A Okay. Thank you. Yeah, what I said -- what brought this particular letter to our attention is their statement in there basically stating that the Marine Corps should not be so much concerned with the earth environmental issues but with the health issues, because it said in here, these appeared -- meaning the concentrations of the -- albeit high levels -- and, hence, more important from a health standpoint than the total THM content. Okay?

And so that's what caught -- from both my standpoint and the epidemiologist's standpoint is

that the -- a lab -- I assume this is a contract lab to the Marine Corps -- had informed them of in the first paragraph of that.

Q Of the health risks; is that right?

A Well, the health concerns. They did not quantify. We tend to talk in terms of risks in quantifiable numbers. They did not quantify that, so I would say that's, you know, health concern.

Q Right. And they said that the interferences which were thought to be chlorinated hydrocarbons hindered the quantification of certain trihalomethanes: These appear to be at high levels and, hence, more important from a health standpoint than the total high trihalomethane content. For these reasons, we called the situation to the attention of Camp Lejeune personnel.

Is that what we're talking about?

A That's what I just read from.

Q Okay. So bottom line, again, here, the folks at Camp Lejeune are being put on notice that not only are there high levels of volatile organic compounds in the water but that these raise human health concerns?

A That is how we interpreted -- or interpret that.

Q All right. And I just want to put these documents into the record so that the record is complete.

(Plaintiff Exhibit Numbers 3, 4, 5, and 6 were marked for identification.)

BY MR. ANDERSON:

Q I'm going to put in as Exhibit 3 the CLW436; Exhibit 4 to your deposition, CLW438; Exhibit 5 to your deposition, CLW443. And Exhibit 6 is a two-page document, CLW5177 and 5178, the Grainger report, G-r-a-i-n-g-e-r.

And you mentioned Elizabeth Betz. And in August of 1982, she, in the course of reviewing the Grainger letter that we just saw, remarked, did she not, on some of the health -- human health effects of exposure to this group of chemicals?

A I need to look at the particular document.

Q Who was Elizabeth Betz?

A She was the base chemist. That's how I refer to her. I don't know her exact title. Okay? But that's in the documents that I've seen. She was always dealing with the water quality analyses.

Q She worked for the Marine Corps and was an employee of the United States Government?

MR. BAIN: Object to form; lack of

foundation.

THE WITNESS: I really could not say. I've just seen her name on internal Marine Corps documents. I do not know if she was a contract employee or a civilian government employee.

BY MR. ANDERSON:

Q Okay. But in whatever specific capacity she worked, she was working on behalf of the Marine Corps, correct?

A That is correct.

Q And she was working over there at the base, from what it looks like in these documents.

A That is correct.

Q And she in August 1982, showing you Exhibit 7, remarked upon the health risks to human beings of exposure to some of these chemicals that you found were, in fact, in the water and that the Grainger report had found in the water.

A That is correct.

Q She found things like liver damage, kidney damage, central nervous system disturbances in humans, correct?

MR. BAIN: Can you refer where you're referring.

MR. ANDERSON: Paragraph 5.

THE WITNESS: That's what she reports and reports about, suggested guidances and things of that nature.

BY MR. ANDERSON:

Q So the answer was yes?

A She stated what she -- I mean, what she states in the letter is what she stated.

Q Well, she, working on behalf of the Marine Corps in 1982, stated in her report that these chemicals can cause in humans liver and kidney damage and central nervous system disturbances, correct?

A That's what she says in here.

Q Do you know of anything that would refute that, say that is not true?

A You would have to ask a toxicologist.

Q And then that, for the record, was CLW606 and 607, which is now Exhibit 7.

(Plaintiff's Exhibit Number 7 was marked for identification.)

BY MR. ANDERSON:

Q So this, again, reflects, you know, in 1982, the knowledge of at least some agents over there at the Marine Corps, of the risk of allowing families -- children, infants, neonates -- to be exposed to these chemicals, doesn't it?

MR. BAIN: Objection to form.
THE WITNESS: Again, it expresses their concerns --
BY MR. ANDERSON:
Q All right.
A -- of health risks, but it does not quantity the risk.
Q Right. They knew there was a risk.
A I would say that's correct.
Q When you reviewed the documents that you reviewed from the time that these people knew there was a risk and knew there were volatile organic compounds and knew they posed a threat to human health, from that time forward, did you see any evidence that the Department of the Navy or the Marine Corps took action to protect the Marines and their families from these contaminants?
MR. BAIN: Objection to form.
THE WITNESS: We were not reviewing the documents to assess what the Marine Corps did or did not do. We reviewed documents to see if they contained pertinent or relevant data or information to use for developing the water -- from the water model.
BY MR. ANDERSON:

Q Did you review a lot of documents?
A Yes.
Q In the course of your review, did you happen to see any documents that showed what action showed them taking action to protect the families?
A There were some memos where there were instructions on how to operate the distribution system.
Q When were those memos?
A I would say around 1985 or so.
Q So five years after the -- Exhibit 3 and three years after Betts's acknowledgment of human health effects.
A Be approximately correct.
Q Did you, in the course of reviewing all of those thousands of pages that your -- that you reviewed, find the Department of the Navy or the Marine Corps taking any step in those intervening years to protect the Marines and their wives and children from these chemicals?
MR. BAIN: Object to form.
THE WITNESS: There were internal memos about replacing certain wells and not operating certain wells.
BY MR. ANDERSON:

Q In '85.
A Again, right around '85.
Q I'm asking you before that. Between 1980 and '85, did you see them take steps, action -- take action to protect the families?
MR. BAIN: Objection to form.
THE WITNESS: I really did not review the documents for what action, again, the Marine Corps took. But, rather, did it provide -- in other words, if they were to take an action where they were to turn on a well or turn off a well, that would have implications for the water --
BY MR. ANDERSON:
Q Right. And you told me that happened in '85.
My question is: Do you know -- can you tell me any action that you know of that the government took to protect the people -- the wives, the children, the Marines -- from this water and its contaminants between 1980 and 1985? Do you know of any?
MR. BAIN: Objection to form; asked and answered.
MR. ANDERSON: It's not been answered.
BY MR. ANDERSON:

Q I want to know what you know --
MR. BAIN: He's answered it.
BY MR. ANDERSON:
Q I want to know if you know of any action that they took to protect the families.
MR. BAIN: He answered it. He didn't review it for that reason. That's what he answered.
MR. PANGIA: Does that mean he doesn't know?
MR. BAIN: He's already answered the question.
THE WITNESS: Again, I reviewed the documents to see particularly, as an example, did they turn a well on and off and when did they do it. We did not have any indication if a well was in existence, that they turned it off, except for maintenance, in other words.
BY MR. ANDERSON:
Q Okay. So let me come at it from that standpoint.
Did you see where after they knew that this water was highly contaminated and they knew about the risks to human heath, that they shut the contaminated wells down and didn't let anybody drink any more of it? Did you see that?
A At '85 and afterwards, they shut down the

wells.

Q But what about in '81: Did they do it then?

A No.

Q Did they do it in '82?

A No.

Q Did they do it in '83?

A No.

Q Did they do it in '84?

A No.

Q So all of those years, based on what you know, the families were drinking this highly contaminated water.

A Water contaminated with volatile organic compounds that we described in our analyses were, in fact, being delivered to the residential housing and other locations at Tarawa Terrace.

Q Did you review the BUMEDs, B-U-M-E-D-s?

A I know what they are. Only after they were brought to our attention in a congressional hearing June of 2007, I believe, June 13th.

Q That was the first time you became of aware of that.

A Yes.

Q Did you learn of the base order at that time with respect to the water?

A Yes.
Q But not before.
A Not before.
Q What did they require?
MR. BAIN: Objection as to form; calls for a legal conclusion.
BY MR. ANDERSON:
Q You can answer.
A I did not review the BUMEDs in detail. We felt they were, for the water modeling, not pertinent because they spoke about water quality onboard ships, and also some of the levels or standards that they described in there having to do with pesticides and things of that nature that we were not analyzing for.
And so we -- again, we reviewed documents to extract data and information specifically to develop and calibrate the groundwater flow and fate and transport model. And they were brought to our attention after we had concluded that. And we looked at them and said that does not change the results or, in fact, the assumptions of our model.
Q All right. They had to do with keeping the water from having contaminants, didn't they?
A That is correct.
Q During those years that they kept pumping

this water to the Marines and their families there at Tarawa Terrace, did the government -- did you see anywhere where the government gave notice to those people that they were drinking water that had these contaminants in it?

A There's a CLW document -- and I do not recall the number on it -- from, I believe, the base commander, and I think that was in 1985 where they were having water shortage. And going over how they were going to conserve water. But assured residents that there were only minute or trace amounts of contaminants in the water and it was safe to drink.

Q And that wasn't true, was it?

A There were not minute amounts in the water.

Q And that document is Exhibit 8, isn't it?

A Yeah. This is the one I'm thinking of, yes.

Q And he told him, Go ahead and drink it and go ahead and swim in it.

A And this was actually just for the record, because I don't see a CLW document. This is one of the CERCLA administrative records files, and I'm trying to see the number on it. But it doesn't have a CLW stamp on it, but there's probably a similar one with a CLW in these documents. But looking at the number on top, I can tell you that's a CERCLA

administrative record file.
Q And that's the document you were talking about.
A Yes.
Q And told them, Go ahead and drink it and go ahead and swim in it.
MR. BAIN: Objection as to form. The document speaks for itself.
BY MR. ANDERSON:
Q These are minute quantities.
A It was minute quantities that caught our attention. I think they used the word "trace amounts."
Q And that caught your attention?
A Yes.
Q Why?
A Well, to us, a trace amount would be less than the MCL which would be less for PCE, less than 5 micrograms per liter.
Q So that document is not accurate, is not true.
MR. BAIN: Object as to form.
THE WITNESS: It contradicts what has been -- what was measured, and it contradicts what the model shows.

BY MR. ANDERSON:

Q And it even contradicts the Grainger report, doesn't it?

A It does, yes.

Q Which was three years before.

A That is correct.

Q Other than that misleading notice that you indicated was given in 1985, Exhibit 8, did you, in your review, see anywhere during those intervening years that the government was sending this poisonous water to the people any notice of the true situation?

MR. BAIN: Object as to form.

THE WITNESS: I do not recall any -- any documents that I have -- I have reviewed or my staff have reviewed to that effect.

BY MR. ANDERSON:

Q Now, I understand that there was a memorandum of understanding -- I believe it was in 1991 -- between the ATSDR and the Department of the Navy so that the ATSDR would have access to all of the relevant documents for its water model.

Is that my --

A That is correct.

Q Did the ATSDR rely upon base personnel to provide all of the relevant documents?

A Yes.
Q Did the ATSDR ever have trouble getting information out of the Department of the Navy or the Marine Corps?
MR. BAIN: Object to lack of foundation.
MR. ANDERSON: I'm just asking.
MR. BAIN: Well, you haven't established that he speaks on behalf of the ATSDR.
MR. ANDERSON: Come on.
BY MR. ANDERSON:
Q Did you ever have trouble getting documents from the Marine Corps or the Department of Navy?
MR. BAIN: Can you limit it to him, then?
MR. ANDERSON: Okay.
BY MR. ANDERSON:
Q Are you aware -- I'm not going play games -- are you aware of the ATSDR and its agents, to include yourself, having any trouble getting documents you needed to do your work here from either the Department of the Navy or the Marine Corps?
A We have had difficulty in the Marine Corps and Navy identifying documents that we need.
Q Tell me about that.
A We have provided -- since we became involved in the health -- with the health studies in the

summer of 2003 and forward -- the types of data and types of documents that we needed, we have requested inventories or a list. And when we specifically identify, for example, we want a lab report by a certain name, then they will go and look for it. Okay?

But if -- in our general -- our approach is to say -- since they are the experts with their documents and not us -- we want documents for geohydrology, water quality documents that anybody who is trained in environmental engineering or dealing with base documents in their environmental management program, that we believe should know what those are. We have had difficulty and -- until we have specifically identified we want X, Y and Z of obtaining those documents.

Q Has there been correspondence about those difficulties?

A Yes.

Q Is it correct that you maintain a file of e-mails and letters that you've sent trying to obtain information you needed for your studies?

A Yes.

Q What would that file be called?

A Well --

Q How would we describe it to request it?
A I have e-mail files specific to underground storage tanks, okay, because that one I have specifically put together because that has come up most recently. And also the fact that the agency is going to a different e-mail system, I thought I'd better preserve it in a different way.
And so I have a chronology of e-mails back and forth to the Marine Corps, requesting these types of documents. In this case it happened to be underground storage tank documents and information.
Q All right. And you -- have you maintained also other documents relating to request for information that didn't have to do with simply the underground storage tank issue?
A Yes. There are official letters wherein the head -- or Dr. Frumkin or Dr. Sinks have written letters to their equivalent, which would be the -- like deputy or assistant commandant of logistics and installation at Marine Corps headquarters, and we would present what information we were looking for. We would say, What happens if we don't get the information? And there are a series -- or two -- two, you know, back and forth; our letter, their response, our letter, back and forth.

Q Have you got copies of those?
A Yes, I do.
Q Let me show you -- this problem of getting information from the Department of the Navy and the Marine Corps goes back quite a ways, doesn't it?
A Yes, it does.
Q The memorandum of understanding was found in 1991. I'm showing you one document that I just pulled out as an example from 1994. Reading from the second full paragraph, it says -- second sentence says: You are aware we have had much difficulty getting the needed documents from MCB Camp Lejeune. We have sent MCB Camp Lejeune several requests for information. And in most cases, the responses were inadequate, and no supporting documentation was forwarded. For example, ATSDR does not have any of the remedial investigation documents.
Did I read all of that correctly?
A That's correct.
Q It goes on to say: The situation -- and this is the last sentence of that paragraph: The situation at MCB Camp Lejeune is also somewhat complicated, in that several of our public health request questions could not be answered with information from the RI reports, for example, lead in

the drinking water.

Did I read that correctly?

A That's correct.

Q And then the next paragraph, the second sentence: For an ATSDR public health assessment to be useful, it is important that all pertinent information be provided for evaluation.

Is that correct?

A That's correct.

Q And we must rely on the base personnel to identify and provide the documentation; is that correct?

A That's correct.

Q Do you agree with those statements in this letter, Exhibit 11.

A I was not at -- well, that's 1994. I was at ATSDR, but I was not involved in any way with Camp Lejeune at the time.

Q All right. But you know that these problems with getting documents from the Department of the Navy and the Marine Corps continued, don't you? You know those problems continued.

A We had similar requests in the tone or verbiage in the letters that we officially wrote -- I say officially, meaning our agency leadership

wrote -- contained a similar message to this.

Q And those are the letters that you have in that file of yours.

A That's correct.

Q And I misspoke before. I described this as Exhibit 11. It was actually Exhibit 10. I'm going to show you Exhibit 11 which is another letter probably in that file of yours, December of 2005.

(Plaintiff's Exhibit Number 11 was marked for identification.)

BY MR. ANDERSON:

Q This is to the Department of Navy, Lieutenant General Kramlich. I'm reading the first paragraph. It says: The Agency for Toxic Substances and Disease Registry is conducting an epidemiologic case control study of the children whose mothers were pregnant while living on base. ATSDR staff briefed Lieutenant General Kelly and other headquarters Marine staff on the status of the study, including the water modeling, in August 2005. The purpose of this letter is to seek your assistance in resolving outstanding issues that delay ATSDR's ability to complete the current health study on time. ATSDR has experienced delays in obtaining requests for information and data pertaining to water quality

sampling data and site remedial investigation reports. ATSDR has recently been made aware of the existence of a substantial number of additional documents previously unknown and not provided to ATSDR staff. These documents are designated as CLW documents.

Did I read that right?

A Yes. I wrote the letter.

Q Oh, I'm sorry.

A I drafted the letter.

Q Right. It was signed by Frumkin.

A Yeah, but I drafted the letter.

Q All right. Fair enough.

So you were well aware of these problems.

A Yes.

Q So am I to understand that as of December of 2005, you had not been provided the CLW documents?

A We had not been provided some of the CLW documents, or we had not been provided all of their CLW documents. We had been provided some of them.

Q But not all of them.

A But we were aware, from making trips to Camp Lejeune and some inventory that they were doing, that I had noticed that we had not -- we did not have in our possession some additional CLW documents that

some went on base and shown me.

Q A substantial number. That's what you wrote.

A Yes.

Q Who on base showed you the additional -- the existence -- who revealed the existence of the additional CLW documents in 2005?

A It was not -- when you say "revealed the existence," we really did not operate in that manner. We would come up there occasionally. And I was up there in November 2005, and they were inventorying. They were inventorying the base, and they were showing me the CLW documents that were had, because I raised the issue at a meeting, asking if their inventory company was going to inform us of any water-related documents. And that's when I found out that they had this whole listing or drawing, if you want to call it, of CLW documents.

And I could tell by the numbers that they had shown me in 2005 that they had exceeded the numbers, the CLW numbers, that we had in our possession at ATSDR. And so that's when I expressed my concern to both my division director and our agency leadership, concern that we might -- those additional documents might contain information that

we were calibrating the model with and not be aware of.

Q Who at the base was present when you found out about that?

A That was Scott Williams.

Q Scott Williams. And where does he work?

A He's assigned to Marine Corps headquarters. He's our point of contact at headquarters, and that's currently.

Q And you said that there was something about the numbering that let you know that there were documents that had not been provided to you.

Do you recall how high your Camp Lejeune water documents went to, Bates-number-wise, before you got the additional documents in 2006?

A I seem to recall that ours went up to the 3,000s, and I had seen documents when I went on base in the four, five, six, and seven thousands. Again, we recognized they were not sequential. I think that's important to say. But all I knew is that they were not document numbers I had ever seen before.

Q And you mentioned that there were a substantial number missing. That would be in the order of thousands of pages, wouldn't it?

A Potentially, yes.

Q Well, I mean, in fact, you later found out it was on the order of thousands of pages.
A Yes.
Q And that was a discovery you made in 2005, years after your water model had begun on Tarawa Terrace.
A Our water model had -- it was probably in the -- probably been going on for about a year and a half.
Q This is the end of 2005.
A Right, right. We did field testing for a good part of 2004, from the spring through the fall of 2004, and did not really begin water modeling activities until 2005.
Q And these documents that had not been provided previously, they were actually stamped "CLW" for Camp Lejeune water?
A Yes.
Q Would it be too simplistic to say that in all likelihood something called a CLW, Camp Lejeune water document, might well be relevant to a Camp Lejeune water model?
A Would be pertinent, yes.
Q You went on on the second page to talk about the fact that you needed all documents immediately.

Did I read that correctly?

A We requested timely sharing of these documents.

Q "To attempt to meet our project completion timeline, we must be provided all documents that relate to base-wide water issues immediately." First full paragraph.

A Oh, okay. Okay. I mean, I wrote -- drafted the letter, so yes.

Q And that was true.

A That is correct.

Q You indicated that discovery of this documentation must not rely on specific requests from our staff but on our shared goal of ensuring the scientific accuracy of our study and DOD's responsibility to provide the information.

A That is correct.

Q You went on to say that a thorough review and assessment of such a large volume of additional documents at this late date and the incorporation of related information into a nearly complete model may require additional funding to review these documents and modify our model if necessary.

Did I read that correctly?

A That is correct.

Q "Completion of this assessment and required modifications to our model extend the timeline for six months to a year."

A That is correct.

Q Have there been additional problems getting documents from the Department of the Defense and the Marine Corps since then?

A It would be similar of the identification issue. When we specifically mention a document number or document type, they will provide it. But if we say we need -- as we did, you know, just underground storage tank documents, it -- the process is elongated.

Q So the answer is, yes, there have been continued problems.

A Yes.

Q A lot of those problems had to do with the underground storage tanks and the benzene; is that correct?

A That is correct.

Q I thought that the Department of the Navy and the Marine Corps were supposed to be a partner. You were supposed to be partners.

A We are partners. That's the purpose of the memorandum of understanding.

Q Now, we've been talking about a lot of e-mails and so forth that are on your computer and folders and things. And you mentioned that there's going be a new e-mail system at the ATSDR. And I'd like to state on the record that we want them preserved no matter what happens to the computer system. If you have to go home today and burn it onto a CD, every document that we've talked about during this deposition, we intend to request. He has been making a list of them. So I don't want to hear -- and I don't think the federal judge is going to want to hear -- that we had a change in e-mail systems and all of it got gone.

MR. BAIN: Well, we have to have, as we mentioned, a Rule 26 conference, a reasonable scope of request that you produce to us, which was agreed to in our joint status conference report. We still have not received that scope of preservation yet. We have taken steps through the agencies to preserve information that we believe is related. But until you identify what the scope is, you need to do that.

Also, I should say at this point, we did receive the notice of deposition for Mr. Maslia's deposition on Sunday, which should include an

attachment requesting certain documentation. We did not bring any documentation with us in response to that today, other than the report on Tarawa Terrace which Mr. Maslia has brought, because, for one, it was produced on Sunday which was not a reasonable time to comply with the request. Secondly, it was overbroad in that it requested basically everything that could, you know, under the sun, could be related to his work. And finally, it likely requested information that would be subject to privilege. So for that reason, we did not bring anything in response to that today.

MR. PANGIA: Well, that's fair enough. I just hope that the Justice Department doesn't play the same game that the Department of Navy has been playing with the ATSDR.

MR. ANDERSON: Why don't we take a break.

(A brief break was taken.)

BY MR. ANDERSON:

Q Based on the information available to you, what kind of an area is Tarawa Terrace? Is it mostly housing.

A It's mostly housing.

Q Is there shopping, swimming, bowling,

movies, other resources of entertainment there, to your knowledge?

A There's a shopping center. There's a school. I don't know about bowling specifically at Tarawa Terrace.

Q Is the movie theater over at Hadnot Point.

A Yeah. There's a movie theater and bowling at Hadnot Point.

Q And there's a shopping center at Hadnot Point.

A It's the exchange.

Q Yeah. So the answer is yes?

A Yes.

Q If a person was living at Tarawa Terrace and wanted to have access to those resources, they would obviously have to travel over to Hadnot Point if they wanted to go bowling without going off the base, for instance.

A That is correct.

Q And in the course of going over to Hadnot Point, a person who lived at Tarawa Terrace would have had exposure to the Hadnot Point water supply had they, say, for example, ordered a Coke at the Hadnot Point theatre or a drink from the supermarket water fountain.

A If they drank from the supermarket water fountain, yes, that would have been Hadnot Point water at that point.
Q Or if they swam in the Hadnot Point pool.
A Yes.
Q And those exposures obviously would be in addition to any exposure that they had at Tarawa Terrace.
A That is correct.
Q So you would have to add those exposure on top of the figures that is we saw in Exhibits 1 and 2.
A That is correct.
Q Now, I understand that these days you're working on a water model for Hadnot Point.
Is that right?
A Hadnot Point and Holcomb Boulevard.
Q Okay. And you've not finish that yet?
A No.
Q You started that some years ago, didn't you?
A We just recently this past year started the actual model. We've been in a -- putting databases together for the model since about 2007.
Q 2007. And what does that involve, putting data bases together? Gathering data?

A Again, it is going through disparate types of documents, pulling out pertinent data -- geohydrologic, hydraulic, water quality information -- and then putting -- conducting QA/QC on the data before you -- and then developing databases that are appropriate for the model that you're going to use.

Q Okay. And so you've been gathering the documents relating to the Hadnot Point, slash, Holcomb Boulevard water model since 2007.

A That is correct.

Q Were you provided all of the appropriate and necessary information for the Hadnot Point/Holcomb Boulevard water model in a timely fashion?

A We were provided documents when we specifically asked for a specific document type or -- a document type.

Q So if you knew something existed specifically and you were able to ask for it, you would get it?

A Yes.

Q But if you just asked for all documents relating to the water, that's where you would run into trouble.

A Again, we made that request several times,

and we still obtained additional documents after those requests.

Q Had supposedly been fulfilled.

A Say that again.

MR. BAIN: Objection to the form.

BY MR. ANDERSON:

Q And this is now having to do with the -- the next model at Hadnot Point/Holcomb Boulevard.

A Right.

Q So same thing again.

A Uh-huh.

Q Well, let me ask you this: Was the contents or even the existence of the underground storage tank, electronic portal disclosed to you when you began your study at Hadnot Point and Holcomb Boulevard?

A No.

Q Why not?

MR. BAIN: Objection; foundation, form.

THE WITNESS: I have no answer for that.

BY MR. ANDERSON:

Q Because you don't know.

A I can't answer. I mean, you'd have to ask the Marine Corps or the Navy.

Q You don't know why they weren't disclosed.

A No.
Q Did that impact your study?
A Yes.
Q How?
A Well, we had completed a review of what is referred to as the Installation Restoration Program sites, IRP sites, and that is described in an ATSDR-approved report. We call it Chapter C for Hadnot Point. And the data is very voluminous even for that, and so we were under the impression that we had all of the information that we needed to start preparing the databases for the model.
And when we started QA'g/QC'g our own report, we realized that had there were substantial documents, underground storage tank documents, that existed that we did not have possession of nor did we know the quantity or volume of those documents.
Q How did you make that discovery?
A During our QA/QC process -- approximately in January through March of 2009, we were QA/QC'g the Chapter C report. And in checking, for example, we made list of reference in the text. Okay. You want to make sure that you got that reference in the reference section. Okay. So it jives. We came across mention of these particular documents that we

had never seen before, okay, in reading that. And so our contractor sent a request, requesting a half a dozen of these documents.

Q Was that Bob Fay?

A That was Bob Fay. Bob Fay. And he asked me if he could just do it. And I say, Yeah, you don't need to go through me. Just go inform me of what you're doing. So he sent an e-mail request to the folks at -- actually, Scott Williams who was at headquarters. And he sent that request down to the environmental management division folks at Camp Lejeune. And, again, it's because we identified half a dozen, say, documents. They turned out to be UST documents that we mad mentioned or had reports on but we had never seen, the actual document.

And so they sent them, one or two. And then I see these e-mails going back and forth. Well, this document is too large to send by e-mail. Do you have an FTP site? Back and forth. And can you burn it on a CD? And it became apparent that the person Mr. Fay was in contact with was not excited about having to do document after document -- you know, send it by e-mail or figuring out a way to either hard -- print it off and mail it or whatever.

So she said, Why don't I just give you

access to a Web portal, okay, and you can download whatever you want. And that's the first -- and that was right around March of 2009. That's the first that we had heard of a Web portal specifically dedicated towards -- for underground storage tank documents and information.

Q Did you ever come to learn why you weren't told about those benzene documents until then?

A No.

Q The existence of leaking underground storage tanks, did that have, you know, an impact on your work in terms of your modeling the exposure assessment?

A Not on the -- at this point, not on the modeling. And we're talking about March 2009?

Q Uh-huh.

A At that point, not on the modeling work.

Q It was more the data collection.

A It forced us to now put Chapter C as only the installation restoration program sites and make another Chapter D of underground storage tank.

Q And did it ultimately add to the complexity of the model by virtue of the fate and transport characteristics of benzene?

A Would not add to the complexity of the

model. It would make the model take into account all information that's available.

Q Now, I understand that you concluded that approximately 1.2 million gallons of fuel is or may be missing, having leaked out of various tanks at Hadnot Point and Holcomb Boulevard.

Is that accurate?

A That is not our conclusion.

Q What is that based on? Whose conclusion is that?

MR. BAIN: If I can object at this point. And preliminary for purposes of whether it -- a certain privilege. Has there been a conclusion reached about that?

THE WITNESS: No. No conclusion has been reached.

MR. BAIN: So to the extent that you're asking him about a conclusion about that, I'm going to object and instruct him not to answer because it's a deliberative process.

MR. ANDERSON: Okay. I'm not sure I understand the basis for a claim of privilege. But let me just ask a few questions and try to trench around it a little bit and see if I need to worry about it.

BY MR. ANDERSON:

Q Are you telling me that you all are still studying how many gallons of fuel may be missing?

A Yes.

Q Okay. Is part of the reason why you don't know that yet, the fact that the Department of the Defense and the Marine Corps didn't tell you all about the new electronic portal until March of 2009?

A That is part of it.

Q When do you expect to have an answer to how much benzene was -- how much fuel and how much benzene got into the water for those folks?

A We are projecting or estimating at this point that our water modeling will be complete between December of 2011 and March 2012.

Q Well, when do you think you'll have an answer for how much fuel was lost?

A The same time.

Q Is benzene a known human carcinogen?

A Yes.

Q How does the fact of leaking underground storage tanks affect your exposure assessment? Does it affect it beyond what we have already talked about?

A You mean the data itself?

Q Well, just the fact that over at Hadnot Point and Holcomb Boulevard you now have a substantial quantity of benzene apparently that's going be found in the water, does that affect your assessment of people's exposure and their --

A That would be for the epidemiologist to address.

Q Is Camp Lejeune a Superfund site?

A Camp Lejeune is a Superfund site, an NPL site -- NPL site.

Q National Priority List?

A National Priority List site.

Q Is that the same thing as what people call Superfund?

A Yes.

Q And what does it mean exactly to be on the National Priority List?

A Well, EPA conducts an analysis to evaluate the hazard and looks at different pathways, and they've got some scoring mechanism. And then a site has to be proposed for inclusion on the NPL list or Superfund site. They announce it in the federal register, and then it's either put on or not put on.

Q It has to be bad enough to be put on it?

A It has to have a certain hazard ranking.

Q Is it true that CERCLA applies to those sites?
A To NPL sites?
Q Yeah.
A Yes.
Q And, to your knowledge, does CERCLA require that any documents regarding a release of contaminants at an NPL site be made public?
MR. BAIN: Objection; lack of foundation.
THE WITNESS: I'm not CERCLA expert, legal expert.
BY MR. ANDERSON:
Q You don't know the answer?
A I don't know.
Q Have the benzene documents on that electronic portal been released to the public?
A Be more specific, I guess.
Q Sure. You told me before that in March 2009 Bob Fay became aware of the existence of an underground storage tank, electronic portal, and that contained substantial documents previously not disclosed to the ATSDR in the course of its review.
Have those documents been made public?
A Not -- a substantial number of them have not -- a substantial number of them have not.

Q Why?
A Well, we were provided documents by the Navy or Marine Corps under what they call, for official use only, classification, which means we can use them as we warrant. But in order to release them, either as references in a report like this or to the public, we have to ask the Navy or Marine Corps to allow us to release them.
Q Have you asked to be allowed to release those documents?
A Yes, we have.
Q What was the response?
A The response was that they would have to assign somebody to review the documents and see what they needed to or not needed to redact and that they would get back to us.
Q Why would they want to redact stuff from the benzene-related documents?
MR. BAIN: Objection; lack of foundation.
THE WITNESS: I'm not a lawyer. That gets into the legal --
BY MR. ANDERSON:
Q You don't know?
A I don't know.
Q You don't know what part of it that they

want to hide?

MR. BAIN: Objection.

MR. ANDERSON: Well, that's what redacting is, isn't it? You block -- look at this one. Look at this. You block this out, right? Isn't that what it is?

MR. BAIN: Or following the law, the Privacy Act, et cetera.

MR. PANGIA: So nobody sees it.

BY MR. ANDERSON:

Q You don't know which part of it they want to redact.

A They have not indicated what they plan to or plan not to redact.

Q You just know it's going to take a while.

A They said -- they asked us back in January when we needed them by. We said August of 2010. And I sort of checked on that request a couple of months ago, and they said August 2010. So we are assuming that is what they are going to stick by.

Q So you told me before, you know, you can't -- you can't cite documents in your report until they have been made public.

So presumably until you get those documents redacted and given to you, you can't come out with

your report; is that fair?

A We can come out with the report. The issue is on scientific integrity. Anyone has the right to ask us for any of the reference material, and we need to be able to produce it so they can reproduce our analysis or whatever. And so if we can't use a reason, well, we're not allowed to release a certain document that from a scientific -- as I said -- integrity standpoint, that does not hold to the -- any, you know, water. No pun intended.

Q So, you know, your report -- your report can't come out until they review their documents and redact whatever they're going to redact.

A The Chapter D report, which is UST, and the model, the Chapter C report, which is the installation/restoration program sites, is, in fact, in the process of being published. That's using a different set of files that are public.

Q All right. But the other reports can't be published until --

A That is correct.

Q -- the documents are reviewed, redacted, and finally furnished.

Has anybody besides the ATSDR been asking for those documents to be released to the public?

A Yes.
Q Who?
A The community assistance panel. The CAP, the Camp Lejeune committee assistance panel.
Q And that's a group of citizens who are involved in the ongoing study of Lejeune?
A They are not involved in the study itself. They are a citizens group made up by former or past Marines. And they -- at times, we look to them to advise either -- or provide input to us, direction of the study or questions we may have specific to Lejeune. Since obviously the former Marines have been at Lejeune, they may have specific questions about that.
Q Are you aware of any senators demanding the release of those documents to the public?
A I'm aware of discussions with Senators Burr and Hagan. I'm not aware of a specific order or letter or -- that.
Q Just to clarify, are we to understand that as of now the ATSDR has some of the documents from that electronic portal that have not been made public?
A We have all of the documents listed in an index provided to us this year in March 2010, that

lists all of the documents, and we have all of the UST documents in that portal.

Q Okay. And can you describe for me the types and categories of documents that are on that list, that you're aware of.

A They are consulting reports assessing different points of contamination actually all over the base, not just what is relevant to us, in other words, of all of Camp Lejeune.

Q Including Tarawa Terrace?

A Yes.

Q Okay. Those are documents you were not -- obviously were not aware of at the time you completed your Tarawa Terrace model?

A No. Actually on the DVDs and in Chapter E, there are underground storage tank documents for Tarawa Terrace specifically; 30 or so, maybe, 50. And they're on the DVDs. At the time, though, we did not make the connection and we were not informed that they were taken from an underground storage tank portal. We just asked about underground storage tank documents.

We work on Tarawa Terrace specifically because of the benzene hits that we saw, and they provided us some of these documents. They were never

identified as coming from an underground storage tank Web portal or a possible --

Q And the index with all of the documents for that portal, that's something that you currently possess.

A Yes. We received that in March of 2010.

Q And looking through those benzene-related electronic portal documents yourself, is there anything that you see that seems to be missing from what you've gotten?

A We are still going through that because, as I said, that portal provides documents not just for Hadnot Point, Holcomb Boulevard, and Tarawa Terrace, but also other areas of the base like the air station, the rifle range, and all that. So we first have had to separate out those that are pertinent to our area.

Q So the answer is: At this point, we don't know whether anything is missing or not.

A We have a complete set for the portal.

Q Let me give you a for instance.

A Okay.

Q For example, you know, the contractor progress reports for the firm Environmental Science and Engineering?

A Right.
Q Did you notice that some of those are missing, that is, the progress reports from August '84 on? Have you found those?
A I'm really not aware of such things as progress reports. Again, we are still inventorying -- our contractor is still inventorying all of the documents. So --
Q You don't know what's missing?
A I don't know what -- other than the technical consulting-type reports, annual monitoring reports, things like that. When you get down to progress reports, I'm not specifically aware that, in fact, they were even part of that or that -- you know, how many there should be or should not be.
Q Yeah, there were monthly reports from a firm called Environmental Science and Engineering. And, you know, I'm aware that the report dated July 6th, 1984, states that the firm had sampled and was to test immediately thereafter Hadnot Point Well 602. And the August report, if you look at the earlier reports, the way it worked was, they sample one month and report the next.
The August 1984 result -- report would have shown the results of that Hadnot Point 602 test

which, you know, based on what you know as you sit here now, it would have shown benzene, right?

A Yes.

MR. BAIN: Objection.

BY MR. ANDERSON:

Q The answer was yes, wasn't it?

MR. BAIN: Same objection.

MR. ANDERSON: Did you get his answer?

Okay.

BY MR. ANDERSON:

Q And so, you know, I'm puzzled to learn that the August 1984 progress report and actually all of the subsequent progress reports from Environmental Science and Engineering are missing from the set. I just want -- my only question is: Have you noted that at this point?

A I personally have not noted that.

Q You're not aware. This is the first time you're hearing it.

A Yes.

Q All right. Fair enough.

Now, there were yearly summaries you mentioned a minute ago. There was one Camp Lejeune water CLW dock, 1406, which I'm now going to mark out of sequence as Exhibit 9 because I skipped a number

earlier and our good court reporter told me that.

(Plaintiff's Exhibit Number 9 was marked for identification.)

BY MR. ANDERSON:

Q This is CLW1406. It's Exhibit 9, and it's a yearly summary that showed benzene at 2500 parts per billion as of November 1985, on the second page there, CLW1407. Shouldn't there be data sheets associated with this document?

A Yes.

Q Okay. Have you found those?

A No.

Q And then I noted on the cover letter, it says that these enclosures indicate no immediate concern.

Did I read that correctly?

A That is correct.

Q And then it goes on to talk in paragraph 3 about the cost. It says: The cost of analysis of the sampling shown on these enclosures was approximately -- looks like 20 to 30 thousand. I can't read it -- funding by the Atlantic provision. Naval facilities engineering command of this analysis is anticipated to end not later than the end of this fiscal year. And, of course, we're in 1986 here.

NREAD has entered 120,000 in the 1988 POM to reflect the overall loss of funding for laboratory analysis.

And then in paragraph 4: It is apparent that careful planning will be required to absorb this additional cost and to hold actual sampling to the essential minimum.

Did I read that correctly?

A Yes.

Q And then it goes on to say in the next paragraph: Accordingly, the environmental engineers required to -- and then it's blanked out with a pen and redacted.

Have you seen an unredacted copy of this?

A Not this specific document.

Q I mean, do you know what it says underneath?

A No, I do not. I do not.

Q And at -- you know, at 2500 parts per billion of benzene human carcinogen, is that of concern to you?

MR. BAIN: Objection to form.

THE WITNESS: That would really -- again, a toxicologist would --

BY MR. ANDERSON:

Q Could convey about this.

A Yeah.

Q Go ahead.
A I was going to say, these are -- this is a CLW, but it's actually also a CERCLA document. We have no unredacted CERCLA documents. In other words, what they provided us is what we published.
Q And it's redacted.
A Okay.
Q So, again, your data is only what you get from the -- from the defendant at Department of the Navy and the Marine Corps.
A That's right.
Q I mean, you're relying on them.
A That is correct.
Q Right. We talked before about the 10,000-gallon underground storage tank that was near one of the Tarawa Terrace -- near the school over there. And I just -- I forgot to ask you at the time we were talking about it.

But when the children went to school at Tarawa Terrace, they drank the same water from that same Tarawa Terrace water system the whole time they were at school, right?
A That is correct.
Q So that water would have had the same contaminants that are listed in your reports?

A That is correct.
Q Did you see where the Department of the Navy or the Marine Corps took any step between 1980 and 1985 to make sure that the school kids received bottled water instead of continuing to drink the water that the Marine Corps was aware had these contaminants?
A Give the same answer I did that you asked before, of the only thing we note is the memo.
Q Claiming it was a trace amount.
A Of that. And no wells were shut down.
Q So the answer would be, no, you saw no bottled water brought into the school.
A Well, I have no knowledge of any mention of bottled water.
Q With regard to the Tarawa Terrace water system, water treatment system, have you ever heard of people claiming that there were pipes for that water system that used vinyl linings inside of asbestos pipes, linings that had been glued in with glue that had been thinned by PCE?
A No, I have not.
Q Did you ever investigate how the pipes were constructed?
A Do you mean the materials that the pipes are

made of?
Q Yes.
A Well, yes. We did that when we did the water distribution system model, and that's the water that distributes from the water treatment plant. Through the pipes, we classify the types by what types of materials. We need that information to assign certain properties in the -- for the distribution model. And they -- so we do have that information.
Q And, in fact, the pipes were not using vinyl linings, were they?
A The pipes were made from both cast iron and PBC.
Q Oh, so there was probably vinyl chloride piping in --
A The newer pipelines -- they replaced pipelines -- as they replaced older cast iron, they tend to replace them with -- sometimes with PBC.
Q Did you consider that as a potential source of additional contamination?
A No.
Q Did you consider the glue that would be used to glue those pipes together as a potential source?
A No.

Q Regarding the design of the Tarawa Terrace treatment plant itself, if you had a sample showing contaminated water coming out of the treatment plant, what would that tell you about the contamination?

A It would tell you that that's the same amount that anyone within Tarawa Terrace within a week would have received, because at Tarawa Terrace all of the wells are mixed and then it goes into the -- mixed in a raw water tank and then it goes into the treatment process.

So if you have a sample after the treatment process of a certain concentration, we, in fact, in Chapter I show the model results that after a week or so, the concentration stabilizes throughout the entire distribution system to equal the concentration at the water treatment plant.

Q So if the water coming out of that water treatment plant is contaminated, as you found, in order to figure out where the contamination was coming from, you would have to go back behind the water treatment plant to the individual wells for testing.

A That is correct.

Q Do you know why that wasn't done in 1980?

MR. BAIN: Objection; lack of foundation.

THE WITNESS: Be more specific.
BY MR. ANDERSON:
Q Was it done in 1980?
A At Camp Lejeune?
Q Yes.
A In 1980, throughout North American, people were not specifically testing for volatile organics anywhere.
Q After they were alerted to them.
A Oh, okay, okay.
Q And alerted that these things were in the finished water.
To know the source and know which well or wells was causing the contamination to be brought into the treatment plant, you would have, would you not, to test individual wells?
MR. BAIN: Objection; lack of foundation.
BY MR. ANDERSON:
Q Isn't that logical?
MR. BAIN: Objection.
THE WITNESS: You would have to ask the folks at Camp Lejeune because that would be part of the, say, environmental management division or order of quality branch.
BY MR. ANDERSON:

Q I would have to ask them why they didn't do certain things.
A Yes.
Q But in terms of knowing where that contamination was coming from, your model proves beyond any doubt that if we want to know, we have to look back of the treatment plant in the system because all of the wells go in there and mix together. We have to look at individual wells, don't we?
MR. BAIN: Objection to form; lack of foundation.
Go ahead.
THE WITNESS: I would say first that the model presents evidence within the reliability of the model, that certain wells were contaminated and that is what drove the contamination at the water treatment plant.
MR. ANDERSON: Okay. If we can just have a few minutes and maybe we can go off the record for a second.
(A brief break was taken.)
BY MR. ANDERSON:
Q Dr. Maslia, if there were another source of trichloroethylene beyond what you're aware of with

the ABC Dry Cleaners as a breakdown product of PCE of substantial quantities, is that something that you would want to know about?

A Yes.

Q Do you know of any other source -- have you been told about any other source of substantial quantities of trichloroethylene in the Hadnot Point/ Holcomb Boulevard area?

A In the Hadnot Point?

Q Yeah.

A Oh, okay. Because you said ABC Cleaners.

MR. BAIN: Are you talking about Tarawa Terrace?

BY MR. ANDERSON:

Q It's a different question now.

A Okay. Well, we know about sources of trichloroethylene at Hadnot Point.

Q What do you know?

A Well, there is an entire industrial area. And as with any industrial area, there's going be, you know, industrial solvents, TCE being one of them, PCE being another. They may, in fact, have used -- because there was an on-base dry cleaner near in the Hadnot Point area, they may have used both compounds, both industrially and in the dry cleaners too. So we

are aware of TCE at the Hadnot Point. And there's obviously a source or sources for that, and that's what we -- we'll be relying on the model to help refine that understanding.

Q Are you aware of disposal of contaminated used -- trichloroethylene solvents in the Hadnot Point area?

A Yes. There is a landfill there as well, and they used disposable practices at the time to dispose of, you know, industrial waste and stuff like that.

Q What disposable practices are you aware of with respect to the solvents at Hadnot Point?

A Well, all I know in a general sense is that that landfill was used to dispose of, you know, solvents and things of that nature.

Q Are you talking about the volatile organic compounds?

A Yes.

Q And you talking about pouring drums of used trichloroethylene solvents into a hole in the ground? What are you talking about?

A It could be just -- because there's a -- in that area, they, you know, repair vehicles and all of that and all of the military equipment. So it could be just waste from that, and they needed to dispose

of it. How they disposed of it, we don't know. It's a complexity of challenge, unlike the Tarawa Terrace -- or the ABC Dry Cleaners where we know there was like a sledge pit and that's where they put it in there. We don't have specific documentation as to the actual practice of, you know, from point A to point B to point C of what they did with the -- with the waste product.

Q So as far as Hadnot Point goes, as you sit here today, you don't know anything about a sledge pit for TCE waste.

A No.

Q And have you asked for documents that would have revealed the existence of that -- such a pit?

A We have asked for all documents related to Hadnot Point/Holcomb Boulevard and to assist us to reconstruct historical concentrations.

Q Have you been advised, as you sit here today, about efforts to spray the used trichloroethylene waste into the trees along the edge of the base?

A I have not heard that previously.

Q How about burning of the trichloroethylene sledge waste?

A There are some burn pits that I'm aware of,

just in the documents.
Q You have seen documents that confirm the presence of those burn pits, haven't you?
A Yes.
Q Have you seen documents that confirm the burning of trichloroethylene waste?
A Not myself personally, I have not.
Q Have people described to you such documents?
A Former -- not documents. They have described activities. Members of the camp have.
Q Okay. And how do you know about that?
A Well, just in general discussions. As we were formulating our approach to Hadnot Point and what areas we should or should not consider, we had selected three areas to look at in our water model for the Hadnot Point/Holcomb Boulevard area. And there are multiple contamination sites in those general areas. And we had to limit our analyses both because of time and funding and to try to get the epidemiological study concluded. So we limited it to three major areas that we felt would address the epidemiological study and the historical exposures.
Q What three areas?
A The Hadnot Point industrial area, HPIA; the Hadnot Point landfill; and then what we were

referring to as the HP645 area, which is actually at Holcomb Boulevard. It's Building 645, associated with Water Supply Well 645.

Q Why there?

A Benzene.

Q You said you were aware of burning of -- I think you said you were aware of burning of trichloroethylene sledge from people at the camp, in conversations or something.

A No. I was just aware that they used a, quote, burn pit to dispose of waste products. I don't have -- I have not read specific documents, and I have no specific knowledge of specific practices.

Q Have you seen the burn pits?

A I have not, no.

Q The funding for the ATSDR studies -- who controls what funding you guys get for what studies?

A We put in a request along with our Division of Health studies because we are basically technical consultants. My division is. And so they put in how much total money the agency needs. And then we put that in each years what we call annual plan of work, the APOW. Okay? It's what it's called. And we list what we are going to do in general terms.

You know, we've got a water modeling

component. We've got a health study component. And that's what we request from the Department of -- now it's the Department of Navy. At one point, it was the Marine Corps. It switches back and forth.

Q So you -- what you get to study and how much money you get to study is actually controlled by the Department of the Navy?

A Not necessarily what we get to get. But they either approve our budget or don't approve our budget. But, yes, we have to ask -- the money comes through the Department of Navy.

Q Are your analyses of any of the Holcomb Boulevard and Hadnot Point areas that you have told me you're studying -- is any part of that work now complete, complete enough to tell me about?

A No, no. Not -- it's in draft or -- I forget the exact label or term for it. But it's -- what I would consider in draft form, has not gone through any kind of review.

Q Peer review?

A Peer review, agency policy clearance review, or anything like that.

Q All right. Do you anticipate that you will personally look through the documents that we discussed today about Hadnot Point/Holcomb Boulevard

are, for instance, documents having do with burning TCE and all that kind of thing?

A Now that you mentioned it, I will look at them.

Q And the documents relating to pouring it into the ground, will you look at those too?

A It's really a generalized term only because -- I say that because, again, we did not -- we do not have specific documentation of their operational practices, in other words. So it's hard to ask for information or go in and search and say, you know, pour in TCE into the ground.

You're not going to find -- even with the documents we have, it's more of a discovery process of reading documents and saying -- or if it's brought to our attention -- I say former Marine -- that this is what happened, then we may try to find a document that supports that type of operation.

Q If you searched for TCE and pit, can you run a search like that?

A We can run a search on the available CERCLA administrative record documents that's on the DVD in Chapter A.

Q Okay. You mentioned that if a Marine told you that they were disposing of this by pouring it in

sledge pits, then you could go and look for documentation to support that report.

What have you done to interview about that issue?

A About the sledge pit?

Q Yeah.

A I'd really have to ask my other staff if they've had conversations with the -- with the former Marines, only because we're not at the stage of looking at the transport of contaminants at Hadnot Point. We are still working on the actual -- just a groundwater flow model part.

Q I understand.

A And when we get to that part, it would be important to identify how and when sources originate, because we have to tell the model where the source is or the frequency of the source to do that. So we're not at that point yet.

Q But you will get there, and that information would be important.

A That information would be important.

MR. ANDERSON: Okay. Anything else?

MR. BAIN: I just have a few questions of you, Mr. Maslia.

EXAMINATION

BY MR. BAIN:

Q First of all, counsel gave you this notice to the residents of Tarawa Terrace, which is Exhibit Number 8, and asked you about the description in here. I think the word that was used was minute quantities of the contaminants.

Do you remember that?

A Yes. I remember that conversation.

Q And counsel asked you whether that was correct or not. And I believe you said it was not correct based upon the maximum contaminant levels for those contaminants. Is that right?

MR. ANDERSON: Object to form.

THE WITNESS: Yeah. I think we used the word "trace amounts," and I said I would not consider that a trace amount.

BY MR. BAIN:

Q And that was based upon what the maximum contaminant levels were for those chemicals; is that right?

MR. ANDERSON: Object to form.

BY MR. BAIN:

Q That was the basis for your answer?

A Yes.

Q And as of the date of this particular

document, 1985, had a maximum contaminant level been establish for either trichloroethylene or tetrachlorethylene?

A No.

Q Okay. Another subject that I want to ask you about was, there was a lot of discussion about the documents that had been provided you by the Marine Corps and the Department of the Navy.

Have there ever been any situations where you were aware of a particular document or a set of documents and requested it from the Navy or the Marine Corps and they refused to provide it to you?

A No. They have never refused to provide us documents that we have specifically requested.

Q And finally, counsel just asked you about documentation of past practices with respect to the Hadnot Point industrial area, of that area.

And you're aware, aren't you, that that area has been studied as part of the CERCLA process; is that right?

A That's correct.

Q And that would include a review of documentation and, if necessary, interviews with people?

A Right, yes.

Q And that is something that you would rely upon in looking into that question for the purposes of your model at the Hadnot Point area?

A Yes. It would be in, say, remedial investigation reports and/or feasibility studies, that they typically would go back through historically and describe what practices may have occurred or did not occur and document that.

Q Those documents which were produced as part of the CERCLA process or, as the military called it, the installation/restoration program, those are made part of the administrative record; is that right?

A That is correct.

Q And as you mentioned previously, that record is publicly available.

A Yes.

MR. BAIN: Okay. That's all of the questions that I have.

MR. ANDERSON: I just have one or two more last questions.

FURTHER EXAMINATION

BY MR. ANDERSON:

Q Would you consider the amounts that were reported in the Grainger report to be a trace?

A The concentrations of -- I just look at this

letter again just to make sure we are -- the ones where you have an indication of less than one or one would be considered trace amounts.

Q And the others?

A And the others would not be considered trace amounts.

Q And what was the date of the Grainger document?

A The date is August 10th, 1982.

Q And what was the date of the memo saying it was a trace?

A April 1985. I can't read the exact date on here.

MR. ANDERSON: Thank you. That's it.

MR. BAIN: The last thing I would like to -- you have an opportunity read and sign the deposition, and I would request that you do that.

THE WITNESS: What?

MR. BAIN: Read the deposition and sign it.

THE WITNESS: Oh, sure.

(Deposition concluded at 1:50 p.m.)

* * *

C E R T I F I C A T E

I hereby certify that the foregoing transcript was reported, as stated in the caption; that the witness was duly sworn and elected to reserve signature in this matter; that the colloquies, questions and answers were reduced to typewriting under my direction; and that the foregoing pages 1 through 186 represent a true, correct and complete record of the evidence given.

The above certification is expressly withdrawn and denied upon the disassembly or photocopying of the foregoing transcript, unless said disassembly or photocopying is done under the auspices of Professional Court Reporters, LLC, Certified Court Reporters, and the signature and original seal is attached thereto.

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This, the 20th day of July, 2010.

_____

AMY L. DUNNING, B-2079

E R R A T A S H E E T

Pursuant to Rule 30(e) of the Federal Rules of Civil Procedure and/or O.C.G.A. 9-11-30(e), any changes in form or substance which you desire to make to your deposition testimony shall be entered upon the deposition with a statement of the reasons given for making them.

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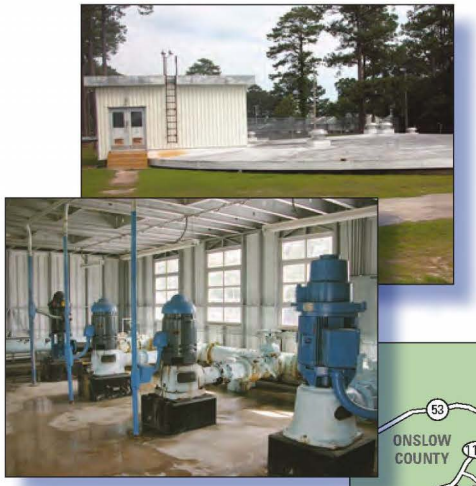
MORRIS L. MASLIA, P.E., D.WRE, DEE

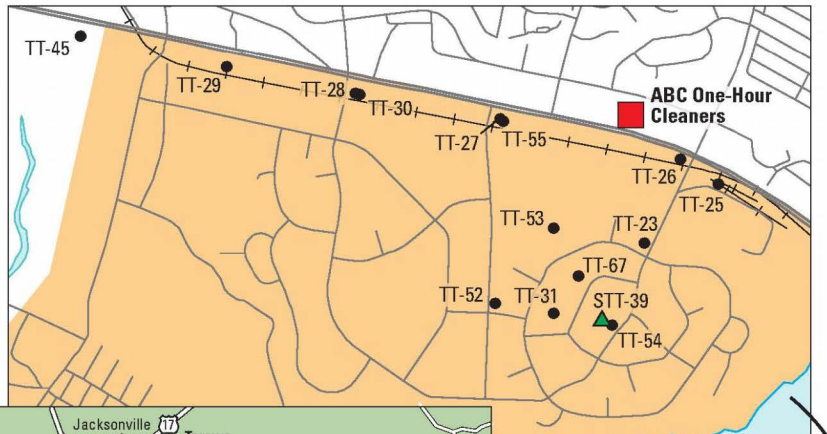
Sworn to and subscribed before me,
_____, Notary Public.
This _____ day of _____, 2010.
My Commission Expires:_____.

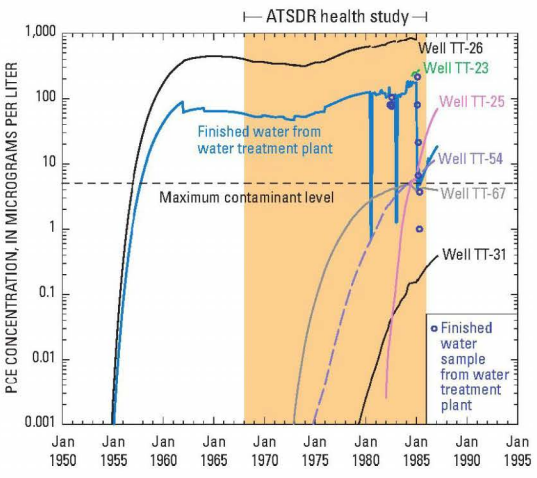
EXHIBIT 23

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

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

Maps: U.S. Marine Corps Base Camp Lejeune, North Carolina; Tarawa Terrace area showing historical water-supply wells and site of ABC One-Hour Cleaners

Photographs on left: Ground storage tank STT-39 and four high-lift pumps used to deliver finished water from tank STT-39 to Tarawa Terrace water-distribution system

Photograph on right: Equipment used to measure flow and pressure at a hydrant during field test of the present-day (2004) water-distribution system

Graph: Reconstructed historical concentrations of tetrachloroethylene (PCE) at selected water-supply wells and in finished water at Tarawa Terrace water treatment plant

DEPARTMENT OF HEALTH & HUMAN SERVICES

Public Health Service

Agency for Toxic Substances
and Disease Registry
Atlanta, GA 30333

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, fbove@cdc.gov
Historical reconstruction/modeling, Mr. Morris L. Maslia, (770) 488-3842, mmaslia@cdc.gov.

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

Enclosure

cc:
H. Frumkin, NCEH/ATSDR/OD
C. Aloisio, NCEH/ATSDR/OFAS
M. Campbell, NCEH/ATSDR/OFAS
J. Masone, NCEH/ATSDR/OFAS
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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.

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.

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.

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.

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 pumping schedule variation on the arrival of PCE at water-supply wells and the WTP (Wang and Aral 2008) and (2) assessment of uncertain

[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 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, $\Delta\overline{C}$; (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 ($\Delta\overline{C}$, $\Delta\sigma_C$, 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 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

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

Attachment 1: Department of the 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

7.1 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 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:

15.1

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.

16.1

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.

Recommendations

As a starting point for further discussions, the Navy/Marine Corps proposes the following recommendations:

17.1

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.

Response to the Department of the Navy's Letter on Assessment of ATSDR Water Modeling for Tarawa Terrace

Attachment 2: Chronology of meetings, presentations, and publications related to the historical reconstruction of contaminated drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina

Attachment 2. Chronology of meetings, presentations, and publications related to the historical reconstruction of contaminated drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina.

[ATSDR, Agency for Toxic Substances and Disease Registry; DOD, Department of Defense; USN, U.S. Navy; USMC, U.S. Marine Corps; USMCHQ; U.S. Marine Corps Headquarters; CL, Camp Lejeune; EMD, Environmental Management Division; GT, Georgia Institute of Technology; AHE, AH Environmental Consultants; USGS, U.S. Geological Survey; PPT, Power Point presentation; N/A, not applicable]

Date	Activity	Location	Attendees	Notes
7 July 2003	ATSDR site visit to Camp Lejeune	Camp Lejeune, NC	ATSDR: Morris Maslia, Jason Sautner CL/EMD: Thomas Burton, Brynn Ashton, Scott Brewer CL/Water Utilities: Mack Frazelle	ATSDR staff described use of water modeling for historical reconstruction approach, requested data and information
8 Oct 2003	Presentation of ATSDR's water modeling approach	ATSDR, Atlanta, GA	ATSDR: Morris Maslia, Jason Sautner, Frank Bove, Wendy Kaye, G. David Williamson GT: Mustafa Aral USMHQ: Nick Ta USMC/CL: Thomas Burton USN: Kim Parker-Brown DOD: T. Michael White	Copies of presentation provided at meeting including CD-ROM containing PPT presentation. See attached meeting sign-in sheet and presentation title slide
11 Mar 2004	Presentation of ATSDR's water modeling approach to USMC/ CL, USMCHQ staff, and USMC contractor	Camp Lejeune, NC	ATSDR: Morris Maslia, Jason Sautner, Frank Bove, Claudia Valenzeula USMC/CL: Scott Brewer, Scott Williams, Brynn Ashton, Thomas Burton, Mack Frazelle, Danny Hill, CAPT Kevin Slates (AC/S I&E) USMCHQ: MAJ Harold Graef CONTRACTORS: Robert Faye (ATSDR), AHE (USMC)	Copies of presentation provided to meeting attendees. See attached meeting sign-in sheet, and presentation title slide
28 Mar 2005	Expert Peer Review Panel to review ATSDR's water-modeling activities at Camp Lejeune	ATSDR, Atlanta, GA	Panel members – See attached list	USMC representative sitting on panel–Dr. Peter Pommerenk of AHE. See Maslia (2005) for peer panel report
26 Aug 2005	Meeting with and presentation to Lt. General Kelly	USMCHQ, Washington, DC	ATSDR: Tom Sinks, Frank Bove, Perri Ruckart, Morris Maslia USMCHQ: Lt. Gen. Kelly and staff, Carla Lucchino (ADC/I&L), Kelly Dryer, Craig Sakai, et al. USMC/CL: Scott Williams, Brynn Ashton	ATSDR presents results of arrival of PCE at TT-26 (May 1960) and TT-23 (Summer 1984) above 5 ppb level. See meeting agenda and talking points

Attachment 2. Chronology of meetings, presentations, and publications related to the historical reconstruction of contaminated drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina—continued

Date	Activity	Location	Attendees	Notes
18 May 2006	Meeting with and presentation to Lt. General Kramlich	USMCHQ, Washington, DC	ATSDR: Tom Sinks, Frank Bove, Perri Ruckart, Morris Maslia USMCHQ: Lt. Gen. Kelly and staff, Carla Lucchino (ADC/I&L), Kelly Dryer, Craig Sakai, et al. USMC/CL: Scott Williams, Brynn Ashton	ATSDR presents approach to water modeling and summary of water-modeling results for Tarawa Terrace area, including graph showing PCE concentrations in well TT-26 and at Tarawa Terrace water treatment plant. Copies of presentation including CD given to Lt. Gen. Kramlich and staff
11 June 2007	Meeting with and presentation to Lt. General Kramlich – Final Tarawa Terrace results (Executive Summary report)	USMCHQ, Washington, DC	ATSDR: Tom Sinks, Frank Bove, Perri Ruckart, Morris Maslia USMCHQ: Lt. Gen. Kelly and staff, Carla Lucchino (ADC/I&L), Kelly Dryer, Craig Sakai, et al. USMC/CL: Fred Cone, Scott Williams, Brynn Ashton	ATSDR summary of FINAL Tarawa Terrace water-modeling results. Provides USMC with copies of Tarawa Terrace Executive Summary report (to be publically released 12 June 2007). Copies of presentation given to Lt. Gen. Kramlich and staff
July 2007 – Feb 2008	Public release of final Tarawa Terrace Chapter Reports (A-H) in hard copy and on ATSDR Web site	Atlanta, GA	N/A	Chapter A (Summary of Findings) released July 2007. Chapter F (Fate and Transport) released February 2008.
26 Mar 2008	Technical information meeting with USN and their consultants	ATSDR, Atlanta, GA	ATSDR: Morris Maslia, Jason Sautner, Frank Bove, Bill Cibulas, Susan Moore, etc. GT: Mustafa Aral ERG: Robert Faye USMC/CL: Scott Williams USN: Kim-Parker Brown, Dan Waddill DOD: T. Michael White USN Consultants: Hall Davis (USGS), Peter Pommerenk (AHE)	ATSDR presents summary details of all Tarawa Terrace water-modeling results. Q&A on technical aspects of historical reconstruction and water-modeling approach. ATSDR also presents work plan for Hadnot Point/Holcomb Boulevard with time line.
19 June 2008	U.S. Navy transmits to ATSDR electronic written comments on: Assessment of ATSDR Water Modeling for Tarawa Terrace	N/A	Letter written to Tom Sinks with copies to H. Frumkin, C. Aloisio, F. Bove, and M. Maslia (and other USN/USMC staff)	Electronic mail transmitting letter from Kim-Parker Brown requests response by 8 July 2008.

Attachment 2. Chronology of meetings, presentations, and publications related to the historical reconstruction of contaminated drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina—continued

Meeting with DOD, US Navy, and US Marine Corps to Present ATSDR's Water-Modeling Approach, 8 October 2003

Historical Reconstruction of Water Resources for Marine Corps Base Camp Lejeune, North Carolina: ATSDR's Approach

October 8, 2003

Sign-in Sheet

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Attachment 2. Chronology of meetings, presentations, and publications related to the historical reconstruction of contaminated drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina—continued

Meeting with DOD, US Navy, and US Marine Corps to Present ATSDR's Water-Modeling Approach, 8 October 2003

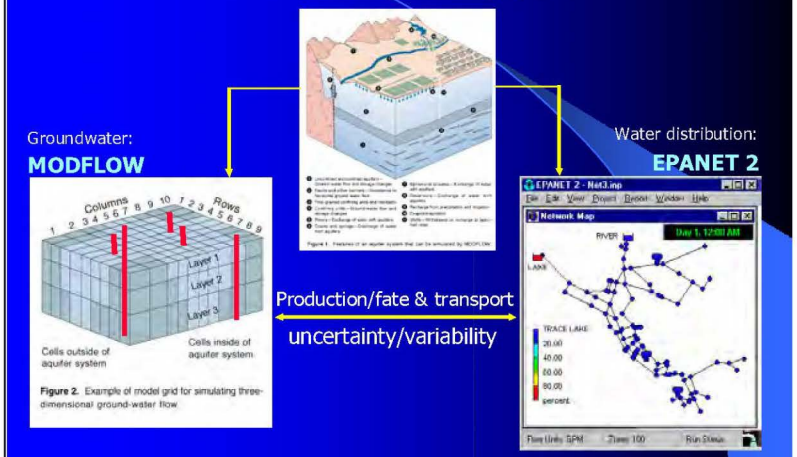
Historical Reconstruction of Water Resources for Marine Corps Base Camp Lejeune, North Carolina:
ATSDR's Approach

Morris L. Maslia, P.E.
Research Environmental Engineer
Project Officer, Exposure-Dose Reconstruction Project
Agency for Toxic Substances and Disease Registry

October 8, 2003
Atlanta, Georgia

08 OCT 03 ATSDR

Models to be applied



08 OCT 03 ATSDR

Critical Data Needs (Model Calibration)

- Hydrogeologic characterization (geophysical logs from drilled water-supply wells or test wells)
- Field-test data of water-distribution system
- Water production from groundwater wells
- Operational data (on/off cycling of wells and pumps)
- Distribution of consumption by consumption type (e.g. residential, industrial, recreational, etc. – Conservation study ??)

08 OCT 03 ATSDR

Project Deliverables

Sep 30, 2004	• Groundwater flow model calibration/simulation • Water-distribution system field tests and network
Sep 30, 2005	• Groundwater transport model calibration/simulation • Water-distribution system: Field-test data reports and model calibration • Groundwater flow and transport model report • Initial sensitivity and uncertainty analysis
Sep 30, 2006	• Water-distribution system: Historical network configuration, spatial distribution of contaminants, and present-day model report
Sep 30, 2007	• Assessment/reduction of uncertainty and variability • Final report

08 OCT 03 ATSDR

Attachment 2. Chronology of meetings, presentations, and publications related to the historical reconstruction of contaminated drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina—continued

Meeting with US Marine Corps and their Consultants to Present ATSDR's Water-Modeling Approach, 11 March 2004

Water Modeling Coordination Meeting
11 March 2004
ATSDR – HQMC/ LFL – MCBCL – AH Environmental

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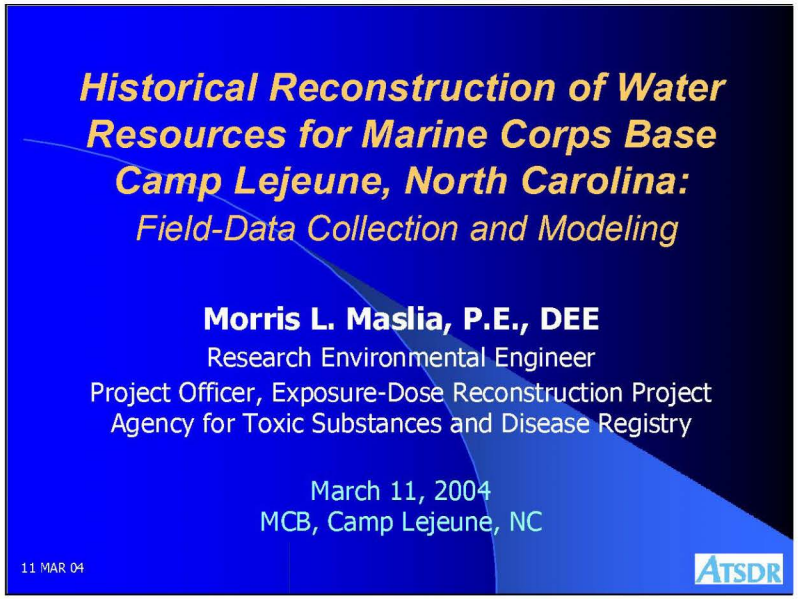
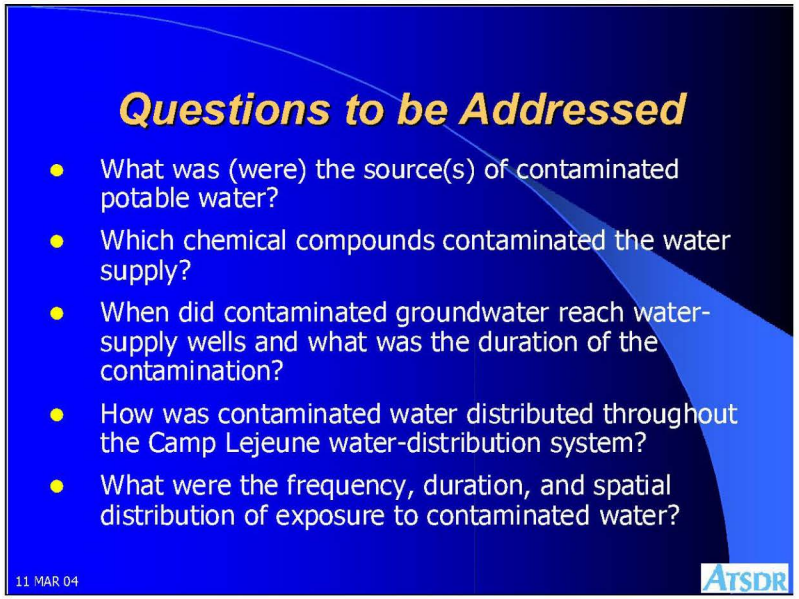
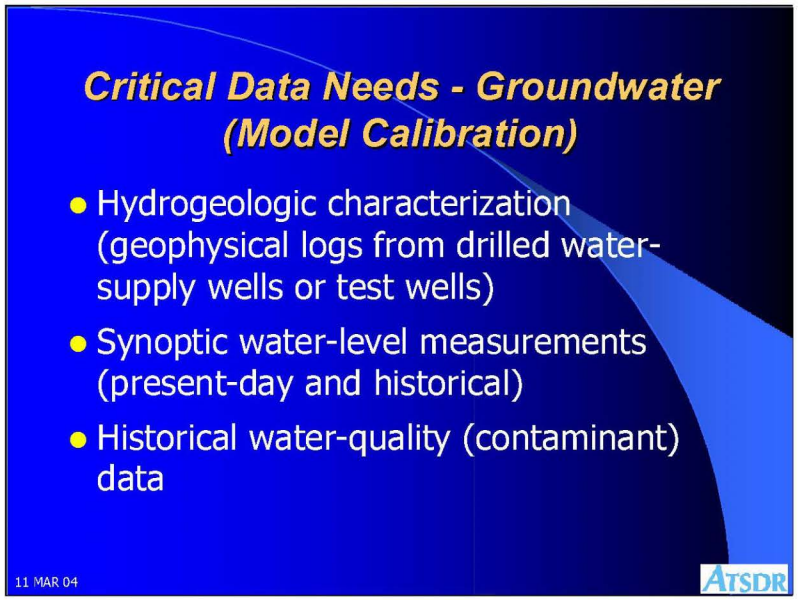
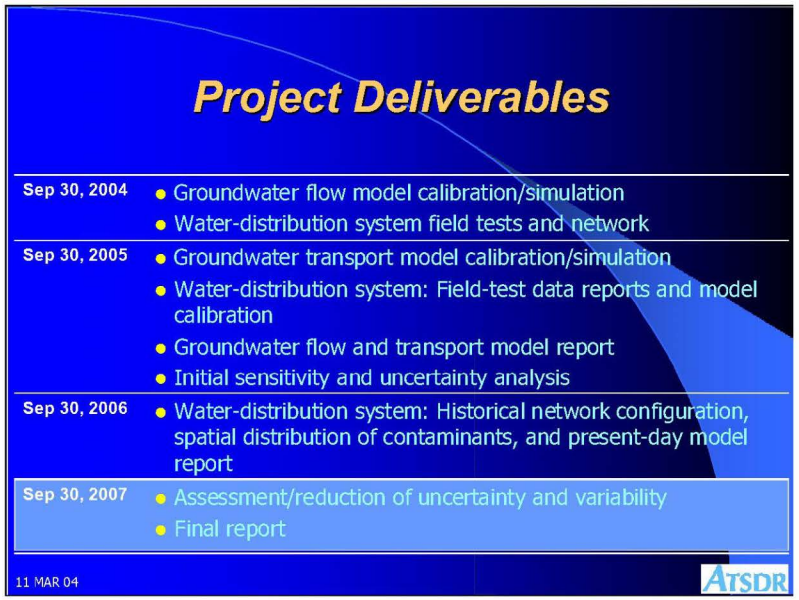
Attachment 2. Chronology of meetings, presentations, and publications related to the historical reconstruction of contaminated drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina—continued

Meeting with US Marine Corps and their Consultants to Present ATSDR's Water-Modeling Approach, 11 March 2004



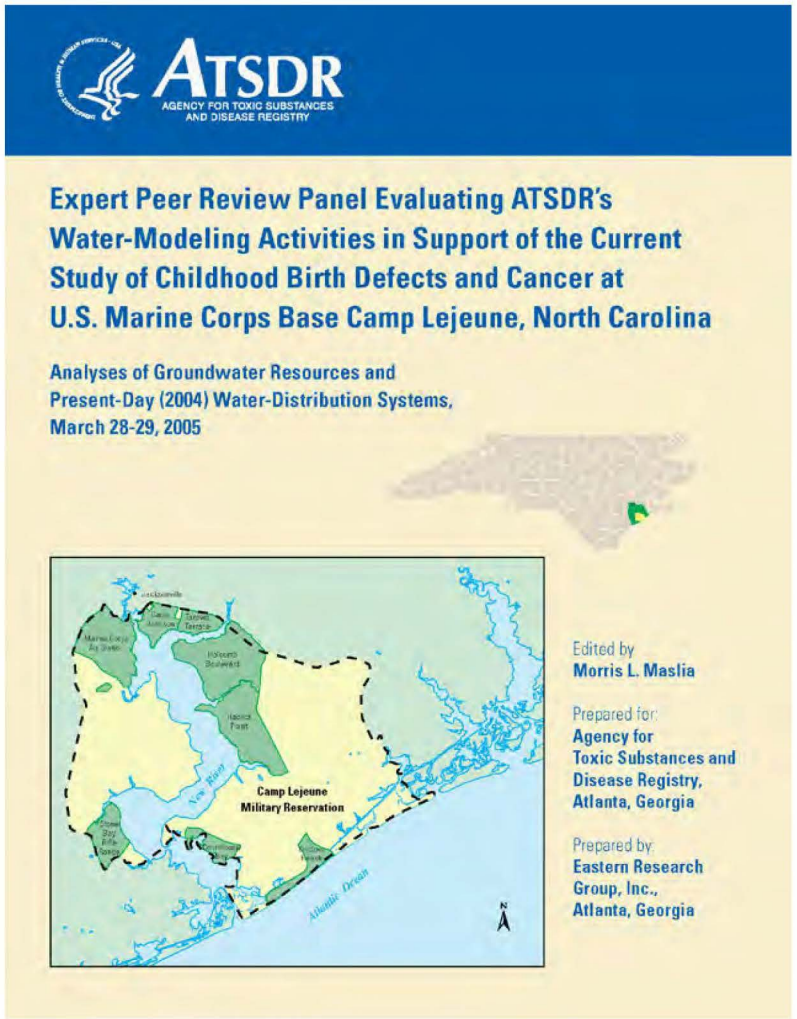






Attachment 2. Chronology of meetings, presentations, and publications related to the historical reconstruction of contaminated drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina—continued

Expert Peer Review Panel Meeting, Atlanta, Georgia, March 28–29, 2005



ATSDR
AGENCY FOR TOXIC SUBSTANCES AND DISEASE REGISTRY

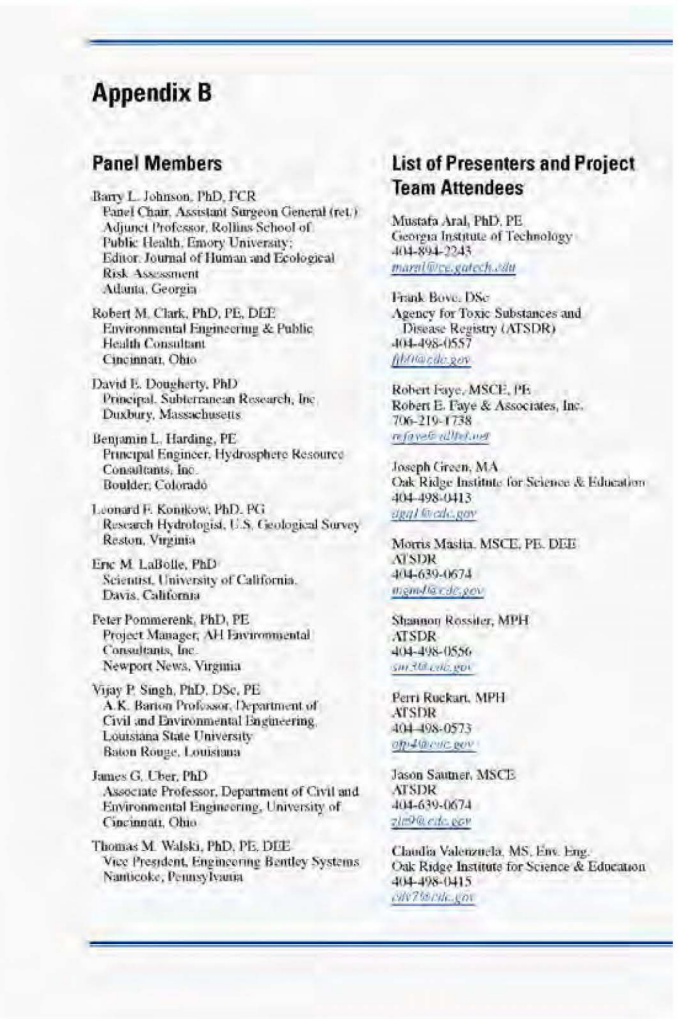
Expert Peer Review Panel Evaluating ATSDR's Water-Modeling Activities in Support of the Current Study of Childhood Birth Defects and Cancer at U.S. Marine Corps Base Camp Lejeune, North Carolina

Analyses of Groundwater Resources and Present-Day (2004) Water-Distribution Systems, March 28-29, 2005

Edited by
Morris L. Maslia

Prepared for:
Agency for Toxic Substances and Disease Registry, Atlanta, Georgia

Prepared by:
Eastern Research Group, Inc., Atlanta, Georgia



Appendix B

Panel Members

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Panel Chair, Assistant Surgeon General (ret.)
Adjunct Professor, Rollins School of Public Health, Emory University;
Editor, Journal of Human and Ecological Risk Assessment
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Attachment 2. Chronology of meetings, presentations, and publications related to the historical reconstruction of contaminated drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina—continued

Expert Peer Review Panel Meeting, Summary and Recommendations, March 28–29, 2005

6.0 Summary of Recommendations from Panel Members and ATSDR's Response

At the end of the meeting, the panel chair, the panel members, and ATSDR agreed that panel members would individually provide overall final comments, recommendations, and conclusions to ATSDR. Specific comments and recommendations from each panel member are provided in the verbatim transcript of the meeting (Volume II) on CD-ROM. The recommendations and ATSDR's responses are grouped into five generalized categories.

6.1 Data Discovery

Panel members recommended that ATSDR expend additional effort and resources in the area of conducting more rigorous data discovery activities. To the extent possible, the agency should augment, enhance, and refine data it is relying on to conduct water-modeling activities.

ATSDR agrees with the panel recommendation. The agency is planning to devote additional resources and work with its partners and contractors to implement data discovery activities.

6.2 Chronology of Events

Panel members recommended that ATSDR focus its next efforts on refining its understanding of chronological events. These need to include documenting periods of known contamination, times when water-distribution systems were interconnected, and the start of operations of the Holcomb Blvd. WTP.

ATSDR agrees with the panel recommendation. The agency is planning to devote additional resources and work with its partners and contractors to obtain updated information so that the water-modeling team can refine its understanding of the chronology of contamination events.

6.3 Groundwater Modeling, Tarawa Terrace Area

Panel members made several recommendations with respect to groundwater modeling and associated activities for the Tarawa Terrace area, including the following:

(1) conduct sensitivity and uncertainty analyses to refine initial estimates of model parameter values,
(2) determine sensitivity of model to grid/cell sizes and boundary conditions,
(3) refine on/off cycling patterns of water-supply wells, and
(4) conduct fate and dispersive transport analyses.

ATSDR agrees in principal with the panel recommendations. The water-modeling team is planning to devote significant effort in conducting sensitivity and uncertainty analyses and in developing a calibrated fate and dispersive transport model for the Tarawa Terrace area.

6.4 Data Analyses, Hadnot Point Area

Panel members recommended that ATSDR proceed with assessment of data to develop an understanding of geohydrologic and groundwater-contamination characteristics for the Hadnot Point area. These activities would be required before initiating additional modeling activities for the Hadnot Point area. Panel members also recommended that additional efforts be put into determining periods of interconnection between the Hadnot Point and Holcomb Blvd. water-distribution systems.

ATSDR agrees with the panel recommendation. The agency is planning to devote additional resources and work with its partners and contractors to implement the panel recommendations.

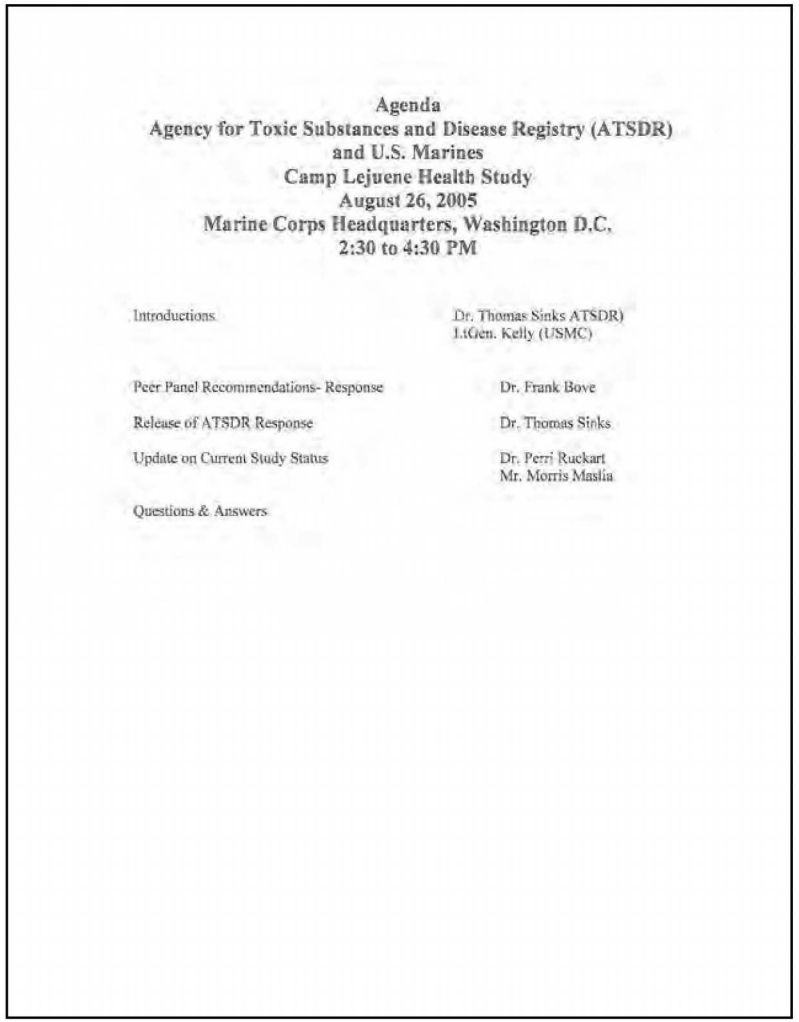
6.5 Water-Distribution System Analyses

Panel members commended ATSDR for the vigor and quality of its field investigation and current model simulations of the water-distribution systems. Because flowmeters are already installed, members recommended that ATSDR proceed with collecting data from the flowmeters, but not initiate any additional field-testing activities. Panel members recommended that the water-modeling team consider using more simplified mixing models to quantify historical exposures to drinking-water supplies. (More complex modeling might be warranted if data discovery shows that the water-distribution systems had a greater frequency of interconnectivity.)

ATSDR agrees with the panel recommendation. The agency has concluded its water-distribution system field-testing activities. Additionally, the water-modeling team will be using simplified mixing models as a first estimate of historical exposures to contaminated drinking-water supplies.

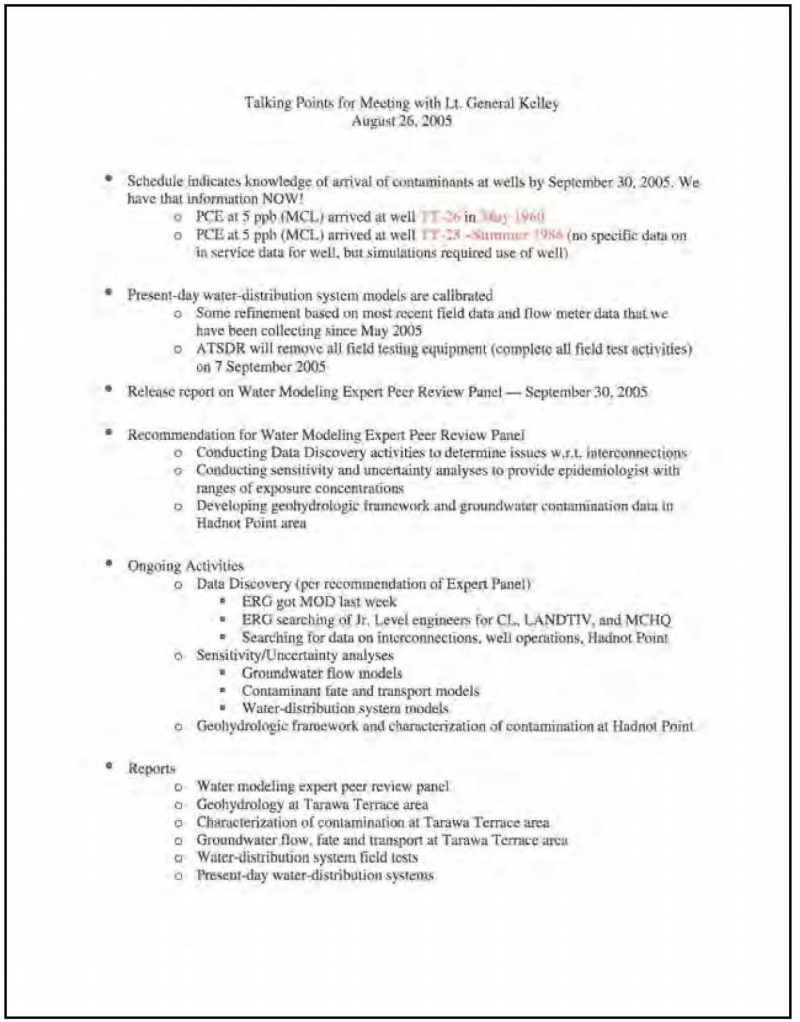
Attachment 2. Chronology of meetings, presentations, and publications related to the historical reconstruction of contaminated drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina—continued

Meeting with Lt. General Kelly and Staff, U.S. Marine Corps Headquarters, 26 August 2005



Agenda
Agency for Toxic Substances and Disease Registry (ATSDR)
and U.S. Marines
Camp Lejuene Health Study
August 26, 2005
Marine Corps Headquarters, Washington D.C.
2:30 to 4:30 PM

Introductions	Dr. Thomas Sinks ATSDR) LtGen. Kelly (USMC)
Peer Panel Recommendations- Response	Dr. Frank Bove
Release of ATSDR Response	Dr. Thomas Sinks
Update on Current Study Status	Dr. Perri Ruckart Mr. Morris Maslia
Questions & Answers	



Talking Points for Meeting with Lt. General Kelley
August 26, 2005

- Schedule indicates knowledge of arrival of contaminants at wells by September 30, 2005. We have that information NOW!
  - PCE at 5 ppb (MCL) arrived at well TT-26 in May 1960
  - PCE at 5 ppb (MCL) arrived at well TT-28 -Summer 1986 (no specific data on in service data for well, but simulations required use of well)
- Present-day water-distribution system models are calibrated
  - Some refinement based on most recent field data and flow meter data that we have been collecting since May 2005
  - ATSDR will remove all field testing equipment (complete all field test activities) on 7 September 2005
- Release report on Water Modeling Expert Peer Review Panel — September 30, 2005
- Recommendation for Water Modeling Expert Peer Review Panel
  - Conducting Data Discovery activities to determine issues w.r.t. interconnections
  - Conducting sensitivity and uncertainty analyses to provide epidemiologist with ranges of exposure concentrations
  - Developing geohydrologic framework and groundwater contamination data in Hadnot Point area
- Ongoing Activities
  - Data Discovery (per recommendation of Expert Panel)
    - ERG got MOD last week
    - ERG searching of Jr. Level engineers for CL, LANDTIV, and MCHQ
    - Searching for data on interconnections, well operations, Hadnot Point
  - Sensitivity/Uncertainty analyses
    - Groundwater flow models
    - Contaminant fate and transport models
    - Water-distribution system models
  - Geohydrologic framework and characterization of contamination at Hadnot Point
- Reports
  - Water modeling expert peer review panel
  - Geohydrology at Tarawa Terrace area
  - Characterization of contamination at Tarawa Terrace area
  - Groundwater flow, fate and transport at Tarawa Terrace area
  - Water-distribution system field tests
  - Present-day water-distribution systems

Attachment 2. Chronology of meetings, presentations, and publications related to the historical reconstruction of contaminated drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina—continued

Meeting with Lt. General Richard Kramlich and Staff, U.S. Marine Corps Headquarters, 18 May 2006

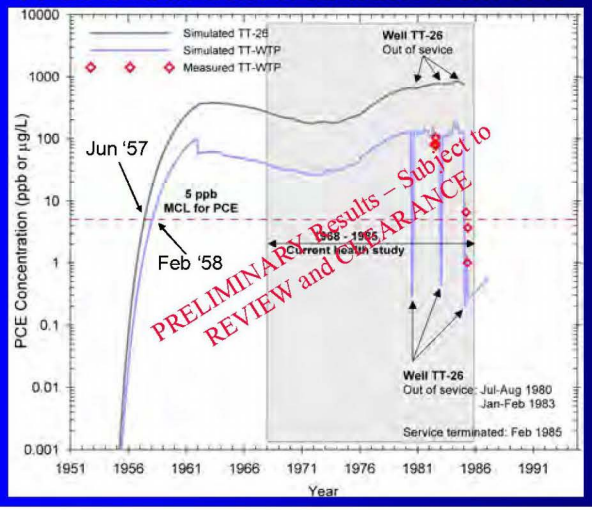
Summary of Water Modeling Activities Supporting the Current Health Study at U.S. Marine Corps Base Camp Lejeune

Morris L. Maslia
ATSDR Division of Health Assessment and Consultation

Presentation for Lieutenant General Richard S. Kramlich
U.S. Marine Corps Headquarters
May 18, 2006

18 MAY 06 — *PRELIMINARY Results -- Subject to REVIEW and CLEARANCE* — ATSDR

SIMULATED PCE concentration TT-26 and in delivered water from WTP



PRELIMINARY Results – Subject to REVIEW and CLEARANCE

18 MAY 06 — ATSDR

Planned reports for Tarawa Terrace water modeling activities

- **A**: Summary of findings
- **B**: Geohydrology
- **C**: Simulation of groundwater flow
- **D**: Properties of VOCs
- **E**: Occurrence of contaminants
- **F**: Simulation of fate and transport of PCE
- **G**: Simulation of degradation products
- **H**: Field tests and simulation of water-distribution systems
- **I**: Parameter sensitivity and uncertainty analyses
- **J**: Effects of pumping schedule variation

18 MAY 06 — *PRELIMINARY Results -- Subject to REVIEW and CLEARANCE* — ATSDR

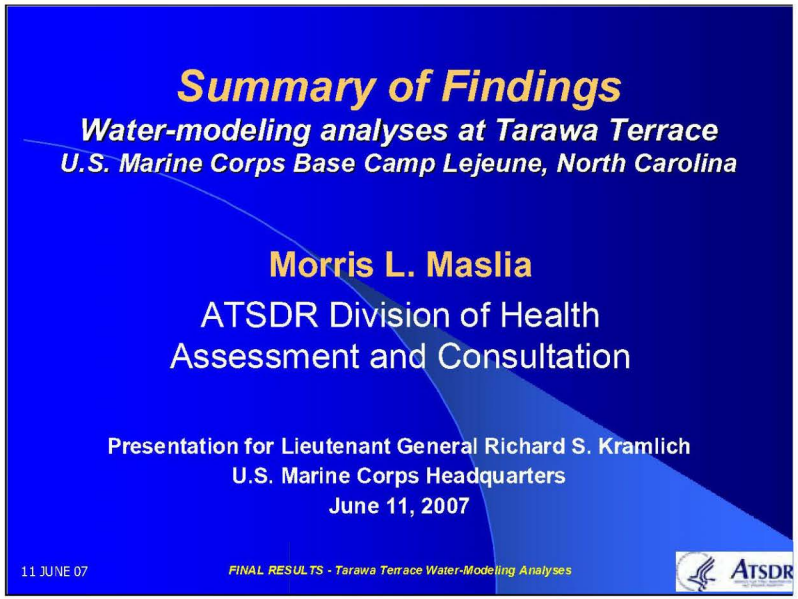
Process for public release of final water modeling results

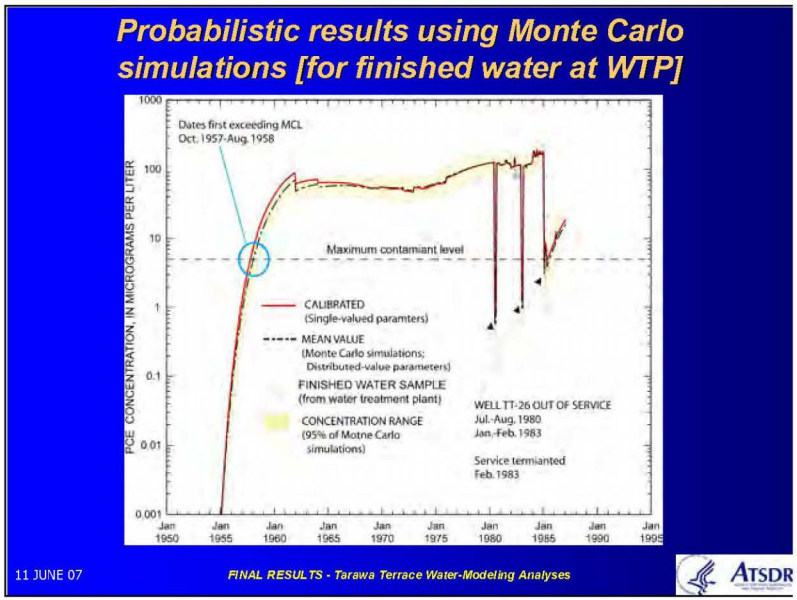
- Draft reports
- External peer review each report
- Reports sent through agency clearance
- Reports prepared for printing
- Reports prepared for web access
- Reports released to public

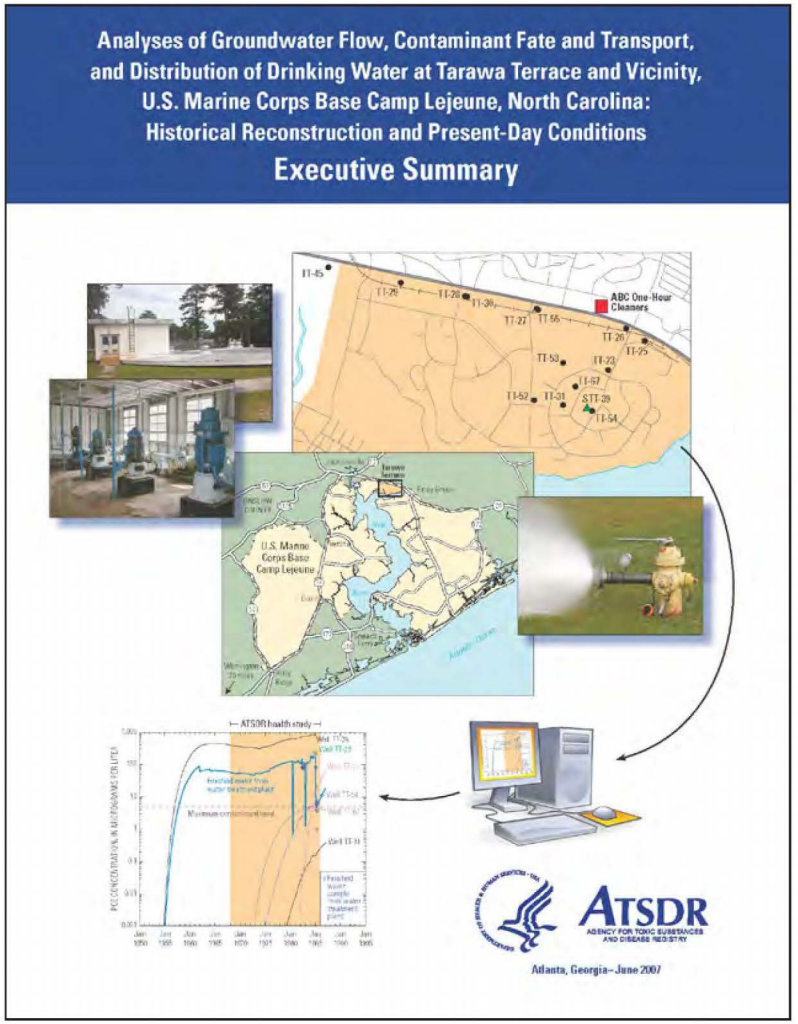
18 MAY 06 — *PRELIMINARY Results -- Subject to REVIEW and CLEARANCE* — ATSDR

Attachment 2. Chronology of meetings, presentations, and publications related to the historical reconstruction of contaminated drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina—continued

Meeting with Lt. General Richard Kramlich and Staff, U.S. Marine Corps Headquarters, 11 June 2007

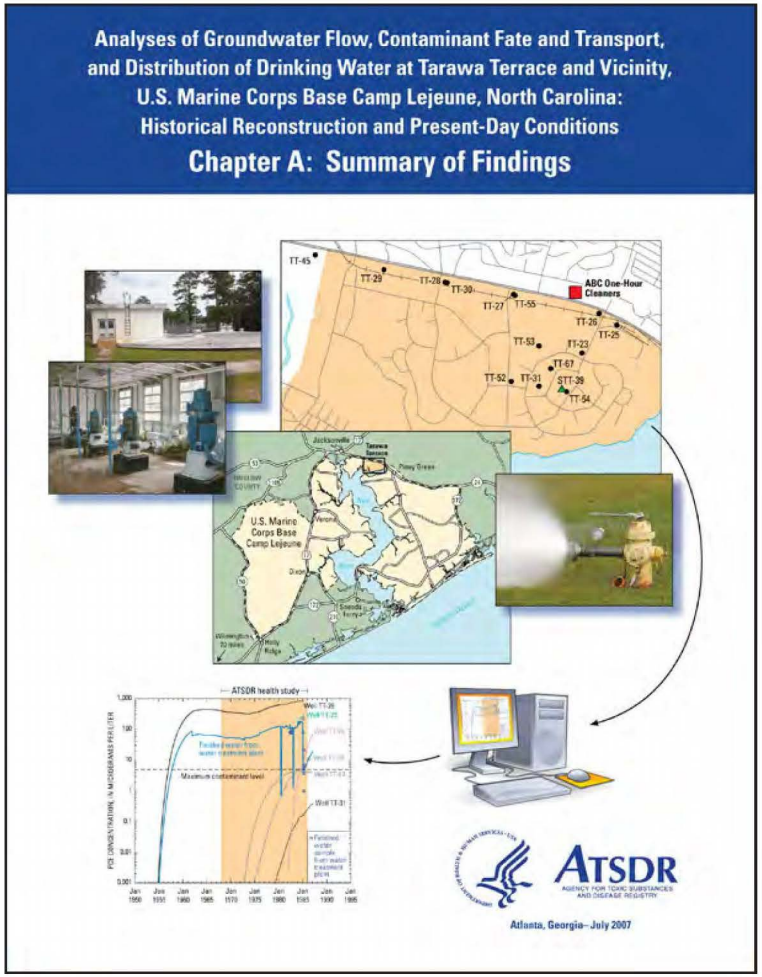




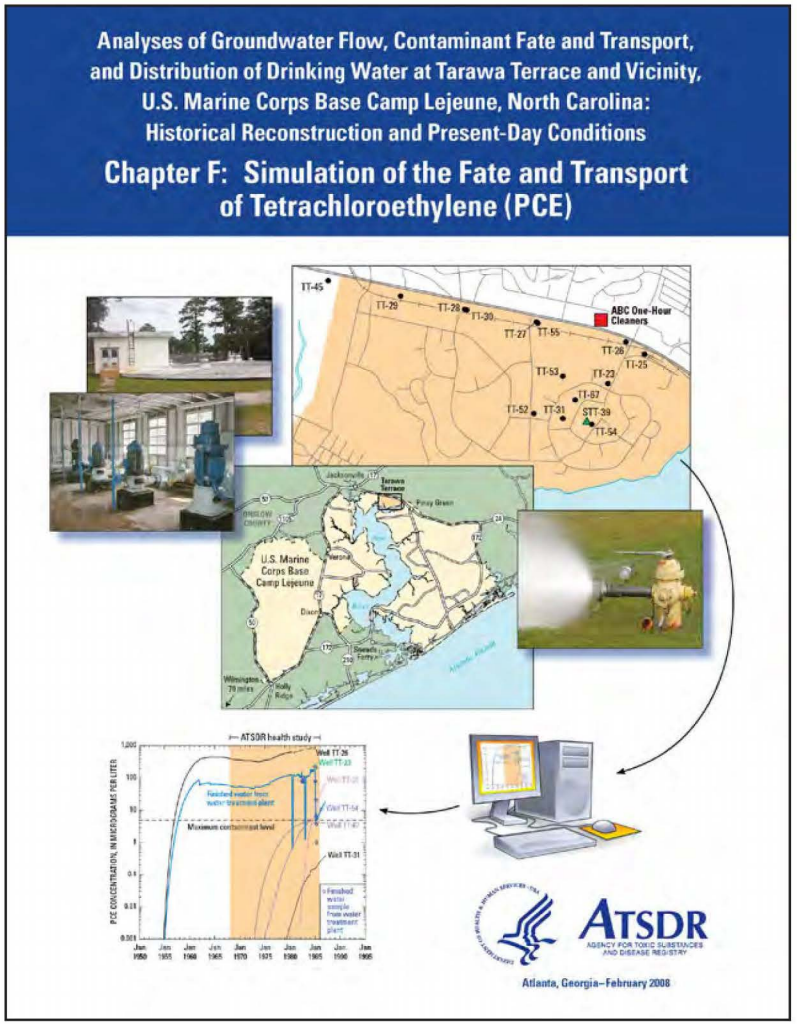


Attachment 2. Chronology of meetings, presentations, and publications related to the historical reconstruction of contaminated drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina—continued

Release of Tarawa Terrace Chapter A Report (Summary of Findings), July 2007

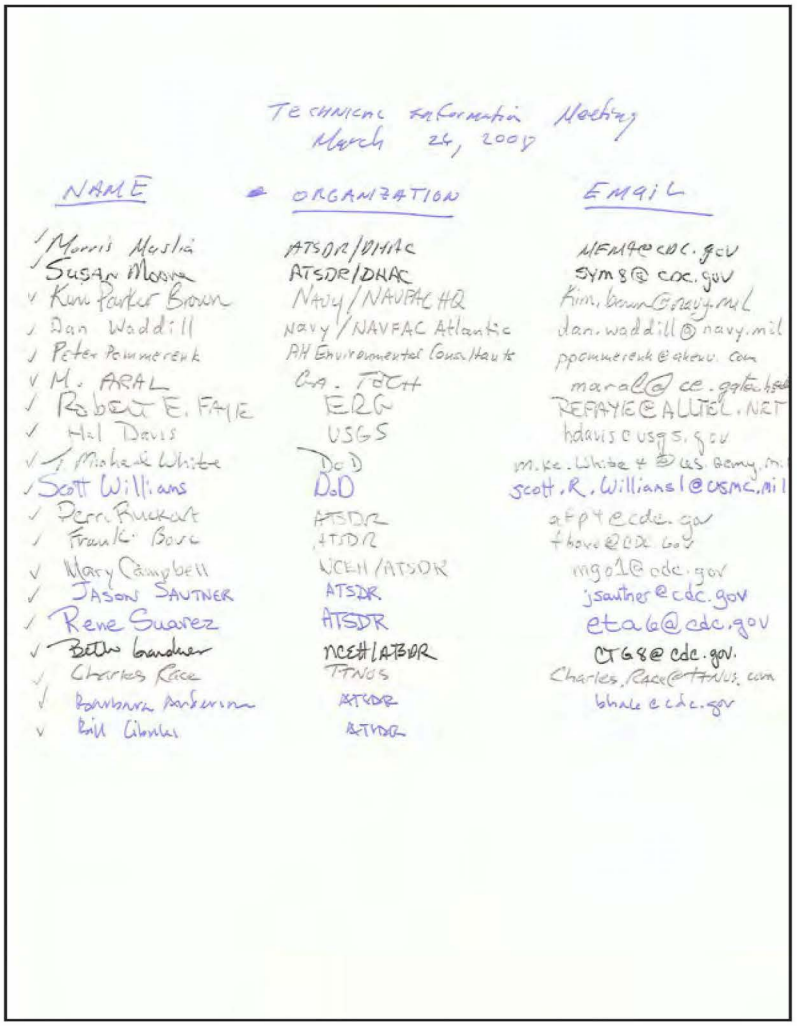


Release of Tarawa Terrace Chapter F Report (Fate and Transport), February 2008



Attachment 2. Chronology of meetings, presentations, and publications related to the historical reconstruction of contaminated drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina—continued

Technical Information Meeting with U.S. Navy and U.S. Marine Corps, 26 March 2008



Technical Information Meeting
March 26, 2008

NAME	ORGANIZATION	EMAIL
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Bill Cibulas	ATSDR	

D R A F T — Subject to Change

WORK PLAN II

Historical Reconstruction Analysis of
Volatile Organic Compound Contamination of Drinking Water Supplies
United States Marine Corps Base
Camp Lejeune, North Carolina

by Morris L. Maslia, MSCE, P.E.

Exposure Investigations and Site Assessment Branch
Division of Health Assessment and Consultation
Agency for Toxic Substances and Disease Registry

March 20, 2008

Camp Lejeune, NC, Health Study Page 1

Attachment 2. Chronology of meetings, presentations, and publications related to the historical reconstruction of contaminated drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina—continued

Technical Information Meeting with U.S. Navy and U.S. Marine Corps, 26 March 2008

Table 2. Schedule of proposed tasks, activities, and meetings, historical reconstruction analysis of contaminated drinking water, Hadnot Point and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

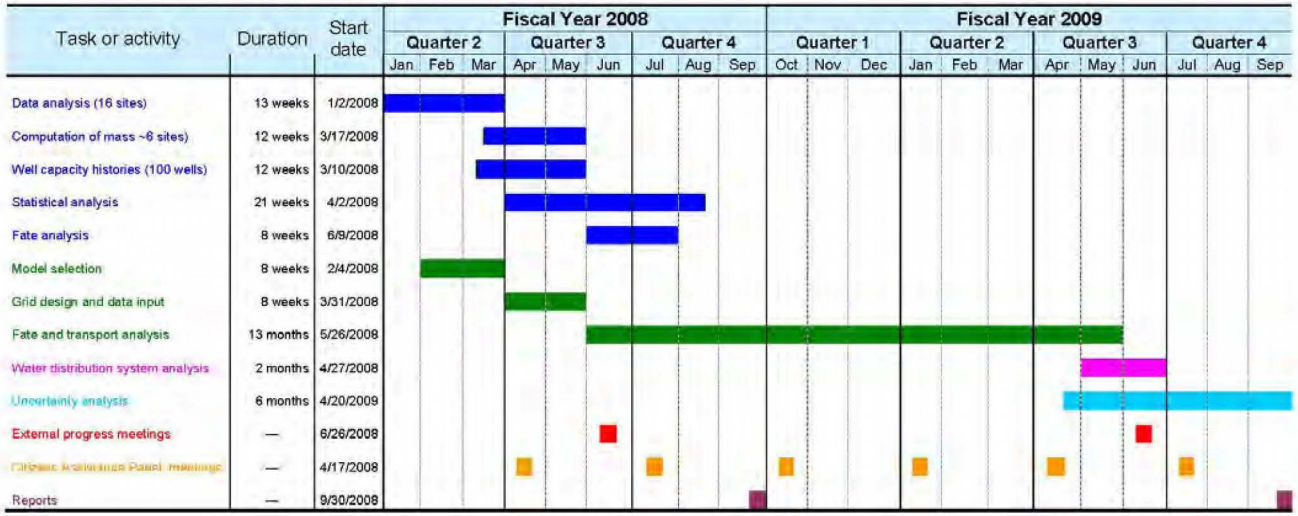


Table 3. Comparison of data and information availability for Hadnot Point and Tarawa Terrace areas.

Descriptive data and information	Hadnot Point and vicinity[1]	Tarawa Terrace and vicinity
Active model domain	40 mi^2	2.1 mi^2
Number of wells and boreholes (includes hydropunch)	720	185
Number of water-level measurements	4,700	820
Number of groundwater samples analyzed for chlorinated solvents	2,200	192
Number of groundwater samples analyzed for Benzene, Toluene, Ethylbenzene, and Xylenes (BTEX)	1,800	191

[1]Estimated values for Hadnot Point and vicinity

Response to the Department of the Navy's Letter on Assessment of ATSDR Water Modeling for Tarawa Terrace

Attachment 3: Comparison of contaminant fate and transport calibration statistics for the Naval Air Station, Jacksonville, Florida, and Tarawa Terrace, Camp Lejeune, North Carolina Sites

Attachment 3. Comparison of contaminant fate and transport analyses calibration statistics

Site[1]	Contaminant	Number of paired data points (excluding non-detects)[2]	Number of simulated data points within calibration target[3]	Number of simulated data points outside calibration target	Ratio (percentage) passing calibration target	Ratio (percentage) failing calibration target	Root-mean-square of concentration difference, in µg/L[4]
Naval Air Station, Jacksonville, FL	Trichloroethylene (TCE)	16	9	7	9/16 (56%)	7/16 (44%)	329
Tarawa Terrace, Camp Lejeune, NC	Tetrachloroethylene (PCE)	29	17	12	17/29 (59%)	12/29 (41%)	337

[1] Refer to the following references: **Jacksonville NAS**: Davis JH. Fate and Transport Modeling of Selected Chlorinated Organic Compounds at Hangar 1000, U.S. Naval Air Station, Jacksonville, Florida. Tallahassee, FL: U.S. Geological Survey Water-Resources Investigations Report 03-4089; 2003; **Tarawa Terrace, Camp Lejeune**: Maslia ML, Sautner JB, Faye RE, Suárez-Soto RJ, Aral MM, Grayman WM, Jang W, Wang J, Bove FJ, Ruckart PZ, Valenzuela C, Green JW Jr, and Krueger AL. 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. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2007.

[2] Paired data point, a location with observed data (concentration) that is associated with a model location for the purpose of comparing observed data with model results; for Davis (2003), see Figure 34 (page 37); for Maslia et al. (2007), see Tables A9 and A10 (pages A27 and A28).

[3] No calibration target was described in Davis (2003) for contaminant fate and transport modeling. Therefore, the calibration target described in Maslia et al. (2007, Table A8) of ±1/2-order of magnitude of observed data is used for comparison purposes.

[4] The root-mean-square or RMS is defined as: $$RMS = \left[\frac{\sum_{i=1}^{N_p} \left(C_i^{obs} - C_i^{sim} \right)^2}{N_p} \right]^{1/2}$$, where N_p is the number of paired data points, C_i^{obs} is the observed or measured concentration of the *i*th paired data point, and C_i^{sim} is the corresponding model simulated concentration of the *i*th paired data point.

Attachment 3. Comparison of contaminant fate and transport analyses calibration statistics—continued

Fate and transport of trichloroethylene (TCE), Hangar 1000, Naval Air Station, Jacksonville, Florida[1]					
Sample location[3]	Measured concentration, in µg/L	Calibration target[4, 5]		Simulated concentration, in µg/L	Pass or fail calibration target
		+1/2-order of magnitude	-1/2-order of magnitude		
H10-MW01	7.8	25	3	19.8	Pass
H10-MW02	1.0	3	0	0.0	Pass
H10-MW03	3.1	10	1	0.0	Fail
H10-MW05	18.5	59	6	0.0	Fail
H10-MW06	36.2	115	11	231.6	Fail
H10-MW07	4.2	13	1	25.3	Fail
H10-MW08	8,608.5	27,223	2,722	8,710.0	Pass
H10-MW10	1.0	3	0	0.0	Pass
H10-MW12	94.5	299	30	596.4	Fail
H10-MW14	266.0	841	84	652.6	Pass
H10-MW15	578.0	1,828	183	356.5	Pass
H10-MW16	48.1	152	15	47.2	Pass
H10-MW17	16.3	52	5	29.5	Pass
H10-MW18	0.8	3	0	8.6	Fail
H10-MW19	1,077.8	3,409	341	229.0	Fail
H10-MW22	1,610.0	5,091	509	2,396.0	Pass

[1]Sample data and simulation results from Davis (2003, Figure 34).
[2]Sample data and simulation results from Maslia et al. (2007, Tables A9 and A10).
[3]All samples measured on January 17, 2001 (Davis 2003, Figures 16 and 34).
[4]No calibration target was provided in Davis (2003) for contaminant fate and transport modeling; the calibration targets ±1/2-order of magnitude of measured data suggested by Maslia et al. (2007) are applied to the measured data of Davis (2003, Figure 16) for comparison purposes.
[5] Calibration targets are rounded to nearest integer.

Fate and transport of tetrachloroethylene (PCE), Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina[2]					
Sample location and date	Measured concentration, in µg/L	Calibration target[5]		Simulated concentration, in µg/L	Pass or fail calibration target
		+1/2 order of magnitude	-1/2 order of magnitude		
TT-23:					
1/16/1985	132	42	417	254	Pass
2/12/1985	37	12	117	253	Fail
2/19/1985	26.2	8	83	253	Fail
3/11/1985	14.9	5	47	265	Fail
3/11/1985	16.6	5	53	265	Fail
3/121985	40.6	13	128	265	Fail
3/12/1985	48.8	15	154	265	Fail
9/251985	4	1	13	279	Fail
TT-25:					
9/25/1985	0.43	0	1	18.1	Fail
7/11/1991	23	7	73	72.7	Pass
TT-26:					
1/16/1985	1,580.0	500	4,996	804	Pass
2/12/1985	3.8	1	12	804	Fail
2/19/1985	64.0	20	202	798	Fail
2/19/1985	55.2	18	175	798	Fail
4/9/1985	630	199	1,992	801	Pass
6/24/1985	1,160.0	367	3,668	799	Pass
9/25/1985	1,100.0	348	3,468	788	Pass
7/11/1991	350.0	111	1,107	670	Pass
RW2:					
7/12/1991	760	240	2,403	879	Pass
TT-WTP:					
5/27/1992	80	25	253	148	Pass
7/28/1982	104	33	329	112	Pass
7/28/1982	76	24	240	112	Pass
7/28/1982	82	26	259	112	Pass
2/5/1985	80	25	253	176	Pass
2/11/1985	215	68	680	176	Pass
3/12/1985	6.6	2	21	8.7	Pass
3/12/1985	21.3	7	67	8.7	Pass
4/22/1985	1	0	3	8.1	Fail
4/29/1985	3.7	1	12	8.1	Pass

Response to the Department of the Navy's Letter on Assessment of ATSDR Water Modeling for Tarawa Terrace

Attachment 4: Simulated concentrations of tetrachloroethylene in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina (From Maslia et al. 2008, Appendix I5)

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

Attachment 4: ATSDR Response to DON Letter of June 19, 2008

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

Attachment 4: ATSDR Response to DON Letter of June 19, 2008

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

Attachment 4: ATSDR Response to DON Letter of June 19, 2008

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

Attachment 4: ATSDR Response to DON Letter of June 19, 2008

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

Response to the Department of the Navy's Letter on Assessment of ATSDR Water Modeling for Tarawa Terrace

Attachment 5: A Practical Method to Evaluate Ground water Plume Stability (Ricker 2008)

Ground Water Monitoring&Remediation

A Practical Method to Evaluate Ground Water Contaminant Plume Stability

by Joseph A. Ricker

Abstract

Evaluating plume stability is important for the evaluation of natural attenuation of dissolved chemicals in ground water. When characterizing ground water contaminant plumes, there are numerous methods for evaluating concentration data. Typically, the data are tabulated and ground water concentrations presented on a site figure. Contaminant concentration isopleth maps are typically developed to evaluate temporal changes in the plume boundaries, and plume stability is often assessed by conducting trend analyses for individual monitoring wells. However, it is becoming more important to understand and effectively communicate the nature of the entire plume in terms of its stability (i.e., is the plume growing, shrinking, or stable?). This article presents a method for evaluating plume stability using innovative techniques to calculate and assess historical trends in various plume characteristics, including area, average concentration, contaminant mass, and center of mass. Contaminant distribution isopleths are developed for several sampling events, and the characteristics mentioned previously are calculated for each event using numerical methods and engineering principles. A statistical trend analysis is then performed on the calculated values to assess the plume stability. The methodology presented here has been used at various contaminated sites to effectively evaluate the stability of contaminant plumes comprising tetrachloroethene, carbon tetrachloride, pentachlorophenol, creosote, naphthalene, benzene, and chlordane. Although other methods for assessing contaminant plume stability exist, this method has been shown to be efficient, reliable, and applicable to any site with an established monitoring well network and multiple years of analytical data.

Introduction

Evaluating plume stability is important for the evaluation of natural attenuation of dissolved chemicals in ground water. U.S. EPA (1998) states that the primary line of evidence in evaluating natural attenuation is historical ground water chemistry data that demonstrate a clear and meaningful trend of decreasing contaminant mass and/or concentration over time at appropriate monitoring or sampling points. When characterizing ground water contaminant plumes, there are numerous methods for evaluating concentration data.

Wiedemeier et al. (2000) discussed common approaches for evaluating plume stability using both graphical and statistical techniques. Graphical methods include the following: (1) the preparation of contaminant concentration isopleth maps; (2) plotting concentration data vs. time for individual monitoring wells; and (3) plotting concentration data vs. distance downgradient for several monitoring wells. Common statistical methods for evaluation of temporal and spatial trends include regression analysis (U.S. EPA 2006), the Mann-Whitney *U*-test (Mann and Whitney 1947), and the Mann-Kendall test (U.S. EPA 2006; Gilbert 1987).

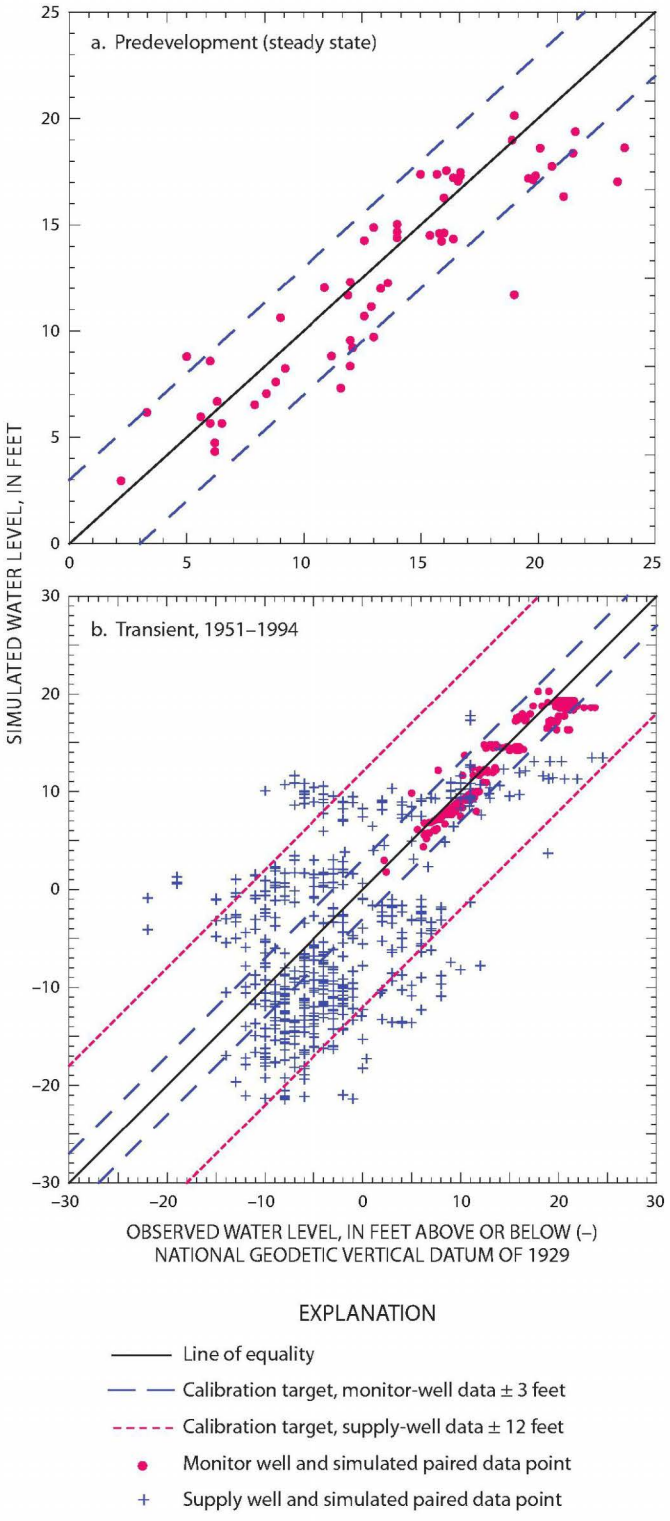
Graphical plume stability analysis by comparing isopleth maps over time can provide compelling visual evidence for natural attenuation. However, a comparison of apparent plume size over time does not always provide a complete analysis. Consider, for example, the case of a plume that discharges to a surface water body, or a plume geometry that is persistent over time. In this case, the plume area would remain relatively unchanged, whereas the overall plume average concentration and mass may be decreasing. The change in plume mass would not be necessarily reflected in the visual analysis of isopleth maps. However, a quantitative analysis of changes in overall plume concentration and mass would provide a better understanding of the plume stability.

A common approach for evaluating plume stability is the use of statistical analysis techniques for single-well data. However, chemical concentration trends at individual monitoring wells may show different trends. For example, at a given site, there may be wells exhibiting decreasing

Response to the Department of the Navy's Letter on Assessment of ATSDR Water Modeling for Tarawa Terrace

Attachment 6: Observed and simulated water levels, model layer 1, and calibration targets for (*A*) predevelopment (steady state) conditions and (*B*) transient conditions, 1951–1994, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina (from Maslia et al. 2007b, Figure A10)

Attachment 6: ATSDR response to DON letter of June 19, 2008



Response to the Department of the Navy's Letter on Assessment of ATSDR Water Modeling for Tarawa Terrace

Attachment 7: Summary of calibration targets and resulting calibration statistics for simulation models used to reconstruct historical contamination events at Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina (from Maslia et al. 2007b, Table A8)

Table A8. Summary of calibration targets and resulting calibration statistics for simulation models used to reconstruct historical contamination events at Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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: $\left|\overline{\Delta h}\right| = \frac{1}{N}\sum_{i=1}^{N}\left|\Delta h_i\right|$; 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

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Attachment 8: Stopping (convergence) criteria results for Monte Carlo simulations (scenario 1—pumping uncertainty excluded) shown as relative change in: (*a*) arithmetic mean of PCE concentration ($\overline{C}$), (*b*) standard deviation of PCE concentration (σC), and coefficient of variation of PCE concentration (C_v), Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina (from Maslia et al. 2008, Figure I26)

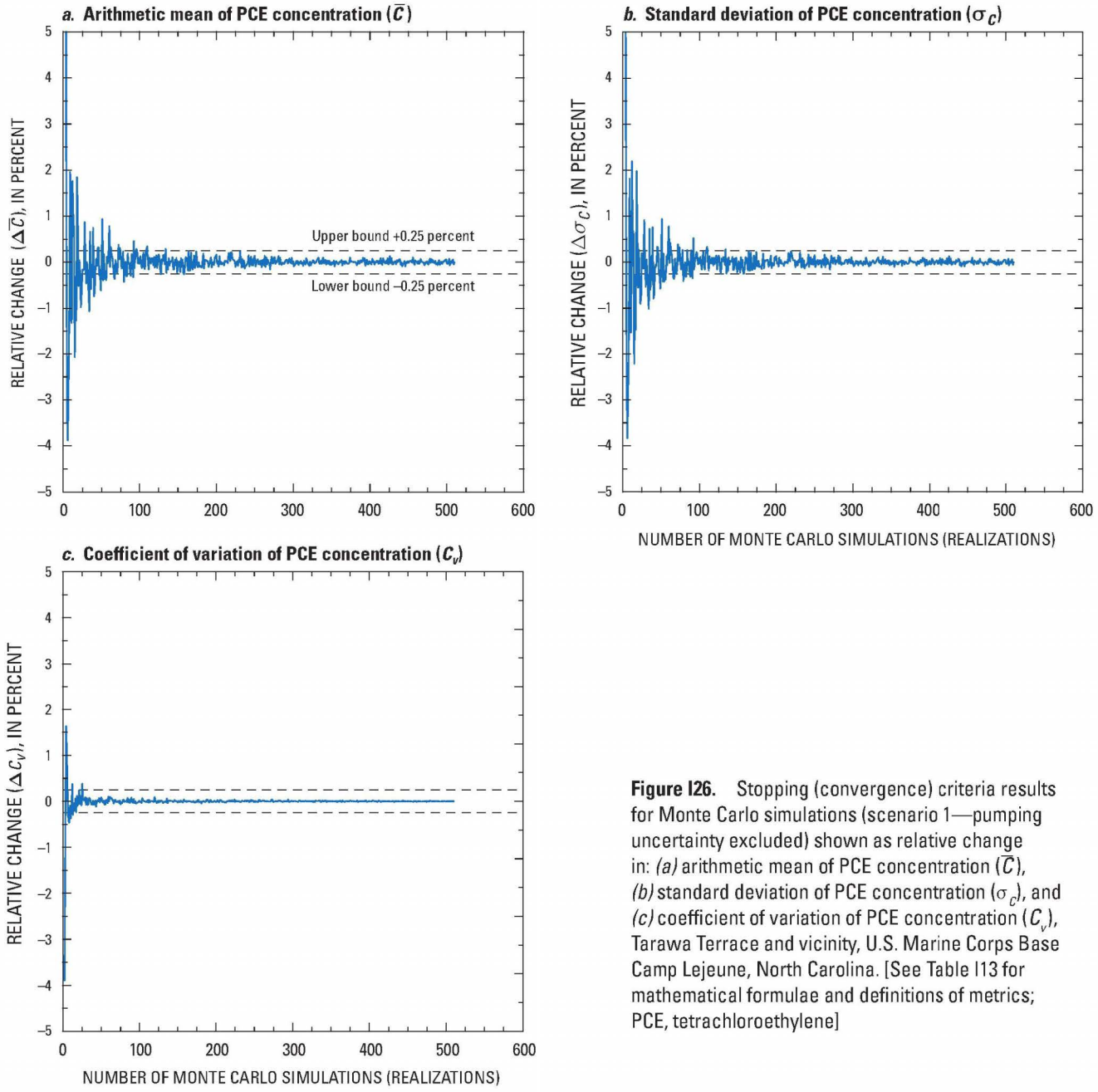

Figure I26. Stopping (convergence) criteria results for Monte Carlo simulations (scenario 1—pumping uncertainty excluded) shown as relative change in: *(a)* arithmetic mean of PCE concentration ($\overline{C}$), *(b)* standard deviation of PCE concentration (σ_c), and *(c)* coefficient of variation of PCE concentration (C_v), Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [See Table I13 for mathematical formulae and definitions of metrics; PCE, tetrachloroethylene]