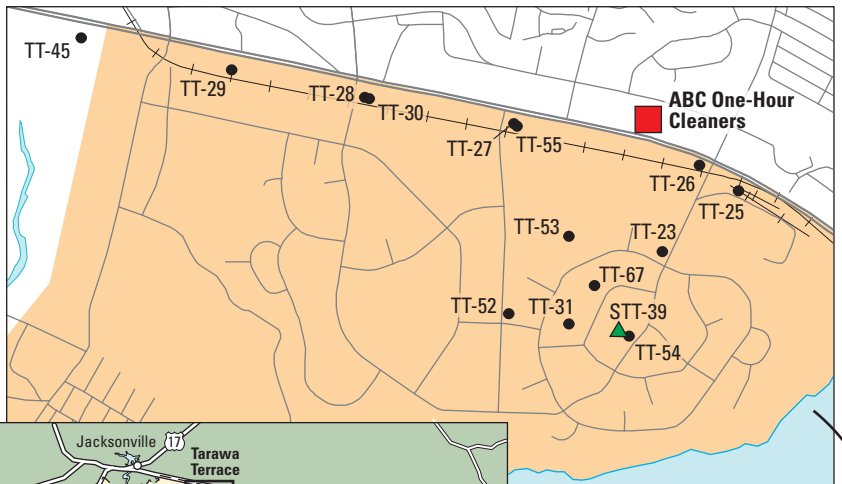
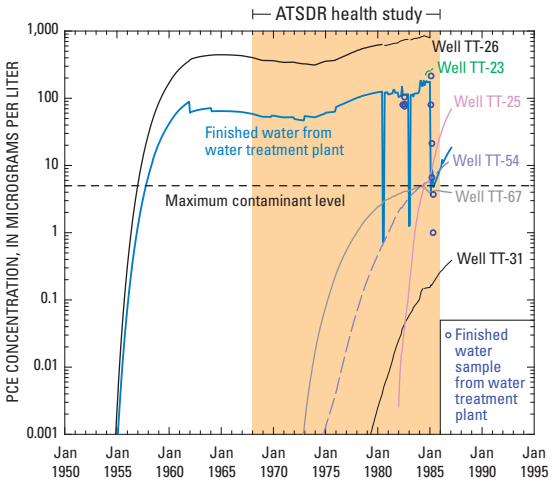
Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions

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

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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

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

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Authors

Morris L. Maslia, MSCE, PE, D.WRE, DEE
Research Environmental Engineer and Project Officer
Exposure-Dose Reconstruction Project
Agency for Toxic Substances and Disease Registry
Atlanta, Georgia

Jason B. Sautner, MSCE, EIT
Environmental Health Scientist
Division of Health Assessment and Consultation
Agency for Toxic Substances and Disease Registry
Atlanta, Georgia

Robert E. Faye, MSCE, PE
Hydrologist
Robert E. Faye and Associates
Consultant to Eastern Research Group, Inc.
Lexington, Massachusetts

René J. Suárez-Soto, MSCE, EIT
Environmental Health Scientist
Division of Health Assessment and Consultation
Agency for Toxic Substances and Disease Registry
Atlanta, Georgia

Mustafa M. Aral, PhD, PE, Phy
Director and Professor
Multimedia Environmental Simulations Laboratory
School of Civil and Environmental Engineering
Georgia Institute of Technology
Atlanta, Georgia

Walter M. Grayman, PhD, PE
Consulting Engineer
W.M. Grayman Consulting Engineer
Cincinnati, Ohio

Wonyong Jang, PhD
Post Doctoral Fellow
Multimedia Environmental Simulations Laboratory
School of Civil and Environmental Engineering
Georgia Institute of Technology
Atlanta, Georgia

Jinjun Wang, MSCE
Ph.D. Candidate
Multimedia Environmental Simulations Laboratory
School of Civil and Environmental Engineering
Georgia Institute of Technology
Atlanta, Georgia

Frank J. Bove, ScD
Senior Epidemiologist
Division of Health Studies
Agency for Toxic Substances and Disease Registry
Atlanta, Georgia

Perri Z. Ruckart, MPH
Epidemiologist and Principal Investigator
Division of Health Studies
Agency for Toxic Substances and Disease Registry
Atlanta, Georgia

Claudia Valenzuela, MSCE
Post Graduate Research Fellow
Oak Ridge Institute for Science and Education
Agency for Toxic Substances and Disease Registry
Atlanta, Georgia

Joseph W. Green, Jr., MA
Post Graduate Research Fellow
Oak Ridge Institute for Science and Education
Agency for Toxic Substances and Disease Registry
Atlanta, Georgia

Amy L. Krueger, MPH
Post Graduate Research Fellow
Oak Ridge Institute for Science and Education
Agency for Toxic Substances and Disease Registry
Atlanta, Georgia

For additional information write to:

Project Officer
Exposure-Dose Reconstruction Project
Division of Health Assessment and Consultation
Agency for Toxic Substances and Disease Registry
1600 Clifton Road, Mail Stop E-32
Atlanta, Georgia 30333

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Foreword

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

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

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

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

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.*

Contents

Figures

Tables

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

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

[1] Agency for Toxic Substances and Disease Registry, Atlanta, Georgia.
[2] Robert E. Faye and Associates, consultant to Eastern Research Group, Inc., Lexington, Massachusetts.
[3] School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, Georgia.
[4] W.M. Grayman Consulting Engineer, Cincinnati, Ohio.
[5] Oak Ridge Institute for Science and Education, Oak Ridge, Tennessee.

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.

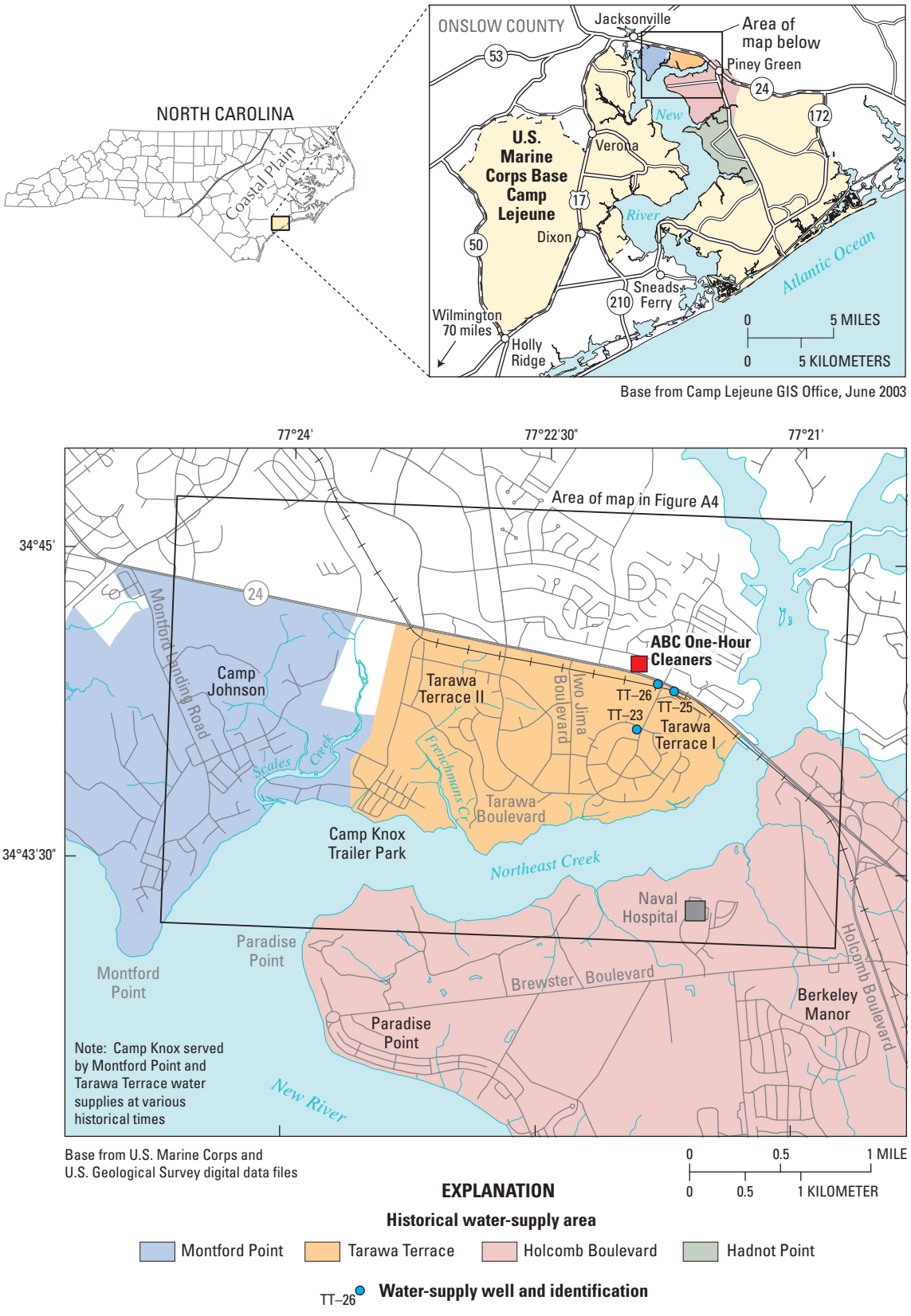


Figure A1. Selected base housing and historical water-supply areas, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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

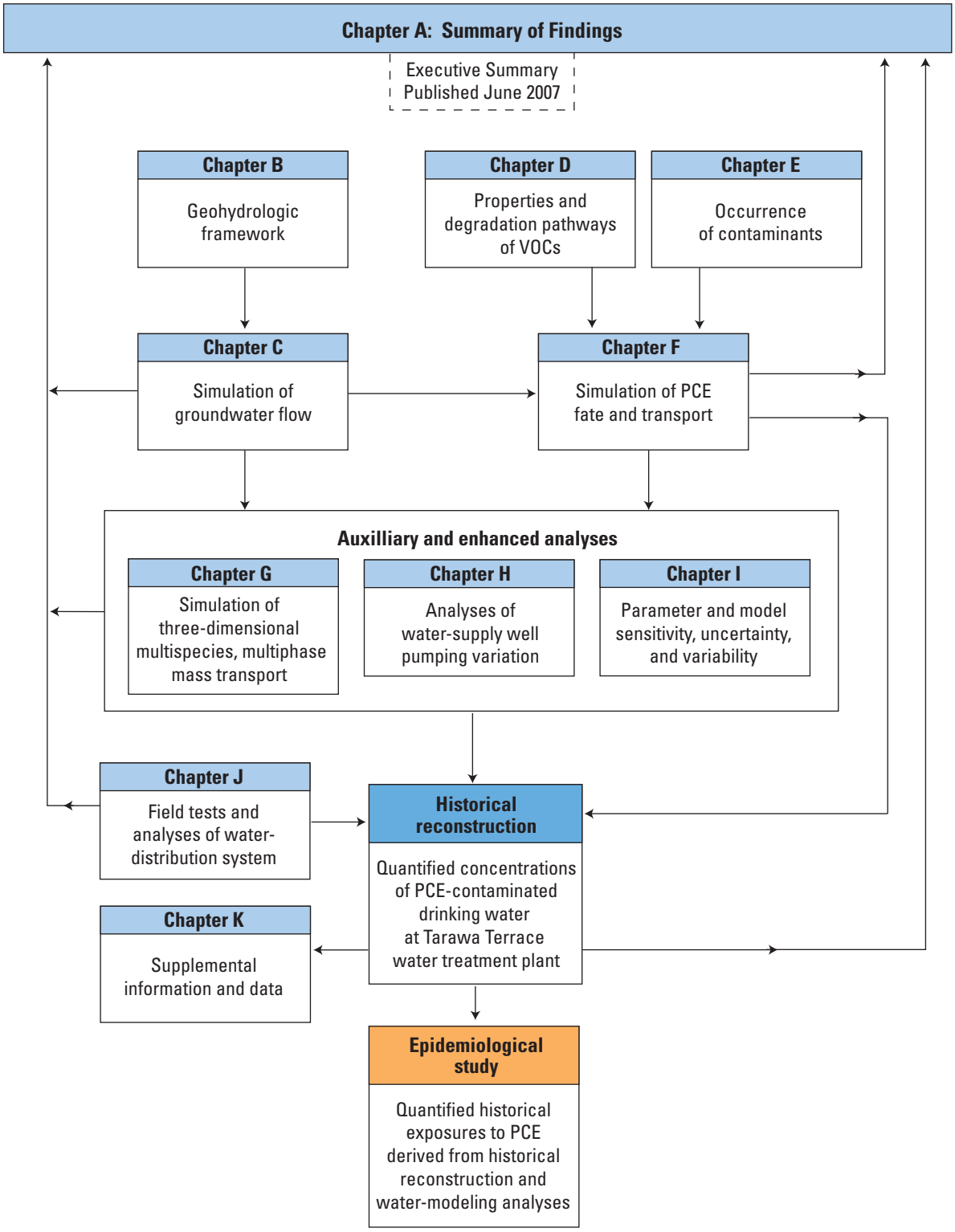


Figure A2. Relation among Chapter A report (Summary of Findings), Chapters B–K reports, historical reconstruction process, and the ATSDR epidemiological case-control study, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [VOCs, volatile organic compounds; PCE, tetrachloroethylene]

- *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.

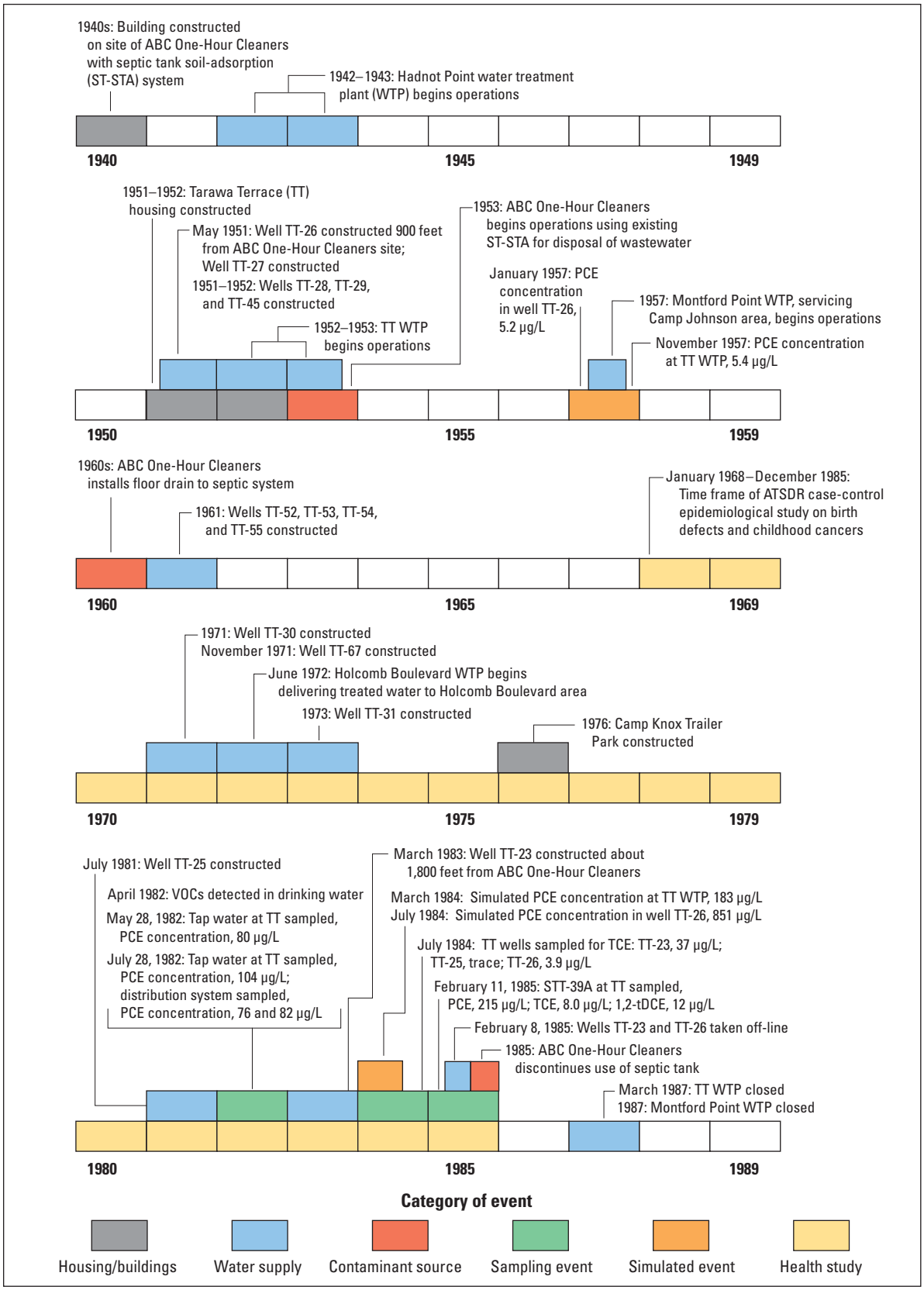


Figure A3. Chronology of events related to supply and contamination of drinking water, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. (STT-39A is the pump house associated with storage tank STT-39.) [ft, foot; µg/L, microgram per liter; VOC, volatile organic compound; 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.

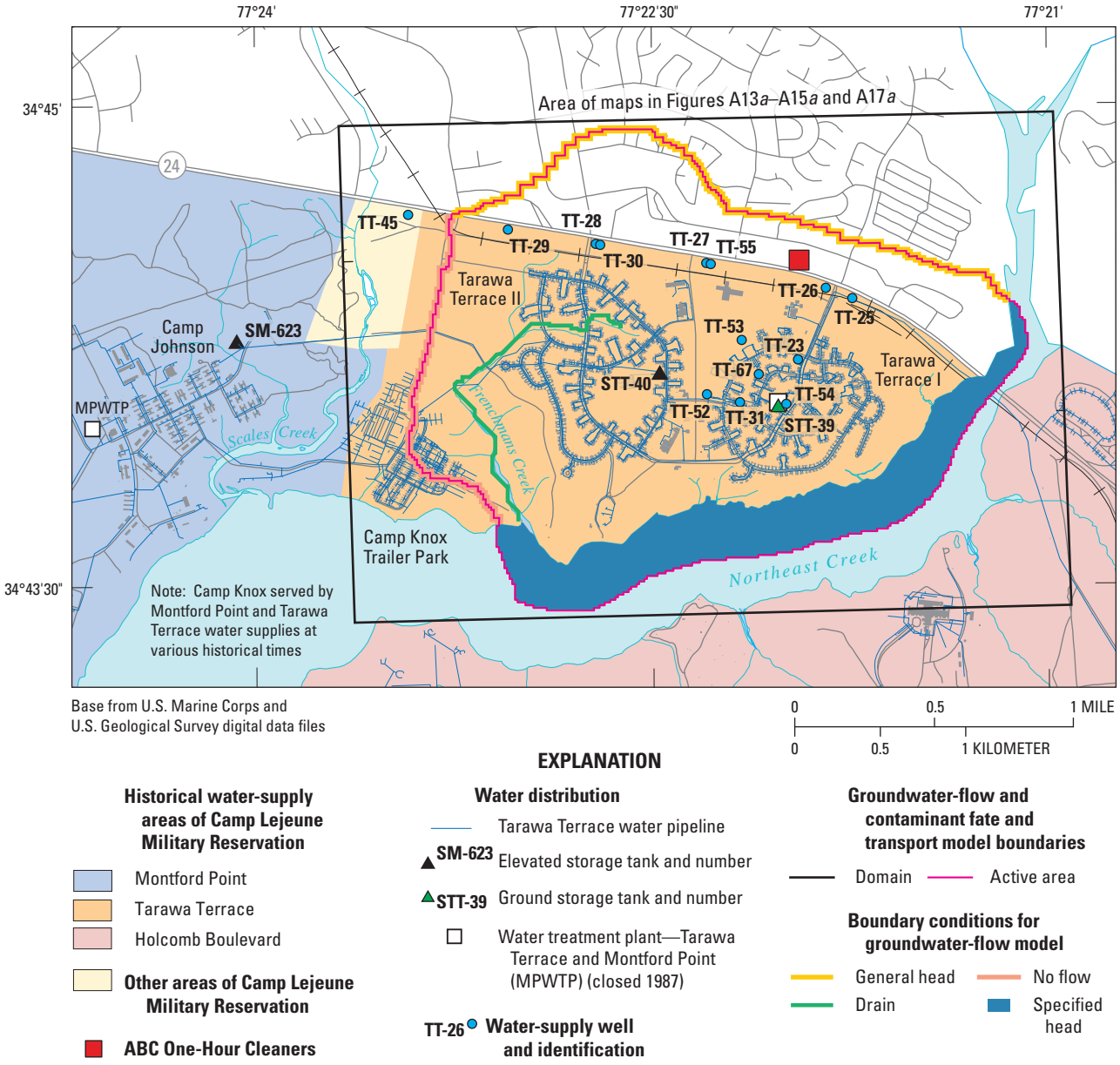


Figure A4. Location of groundwater-flow and contaminant fate and transport modeling areas and water-supply facilities used for historical reconstruction analyses, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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

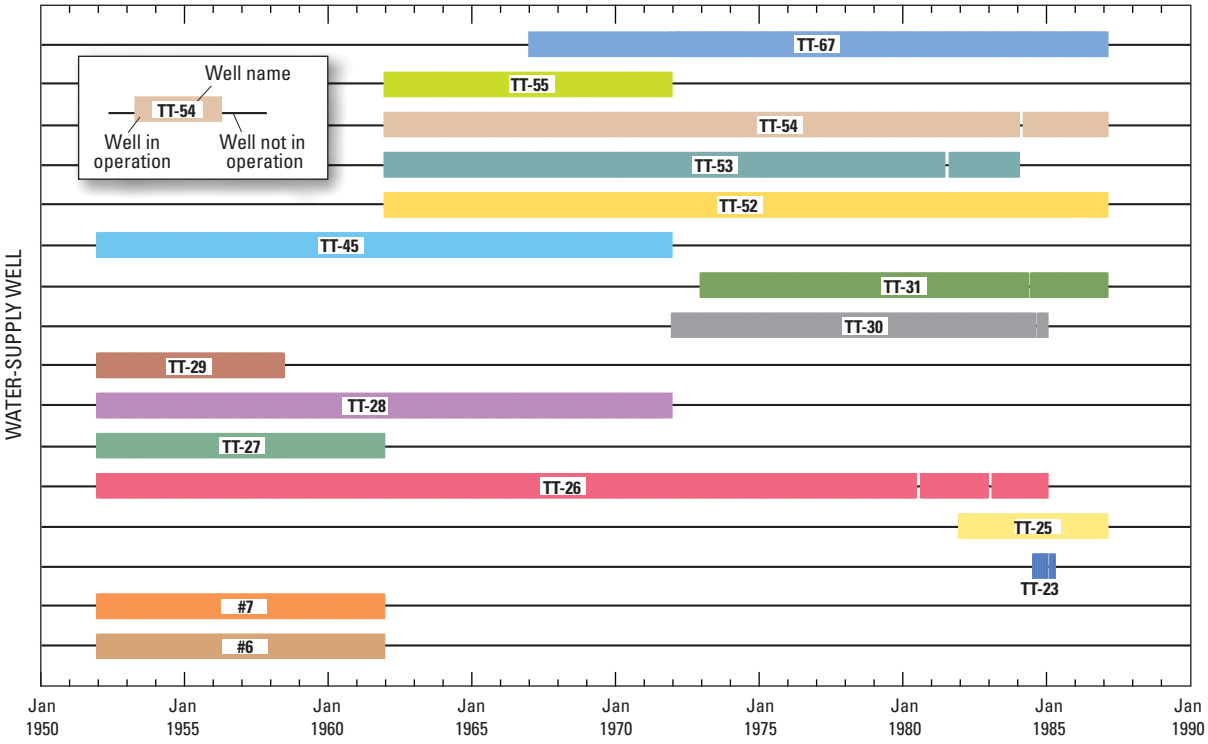


Figure A5. Historical operations of water-supply wells, 1952–87, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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).

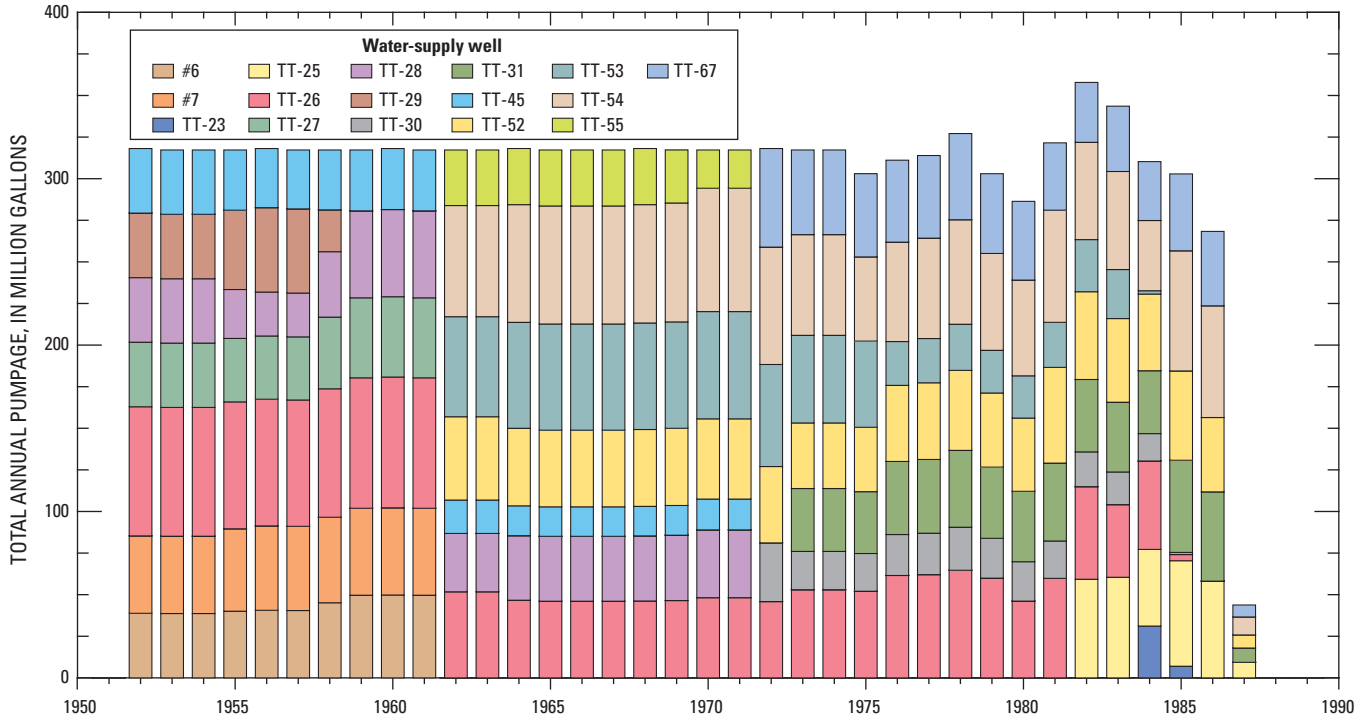


Figure A6. Total annual groundwater pumpage at water-supply wells, 1952–1987, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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)

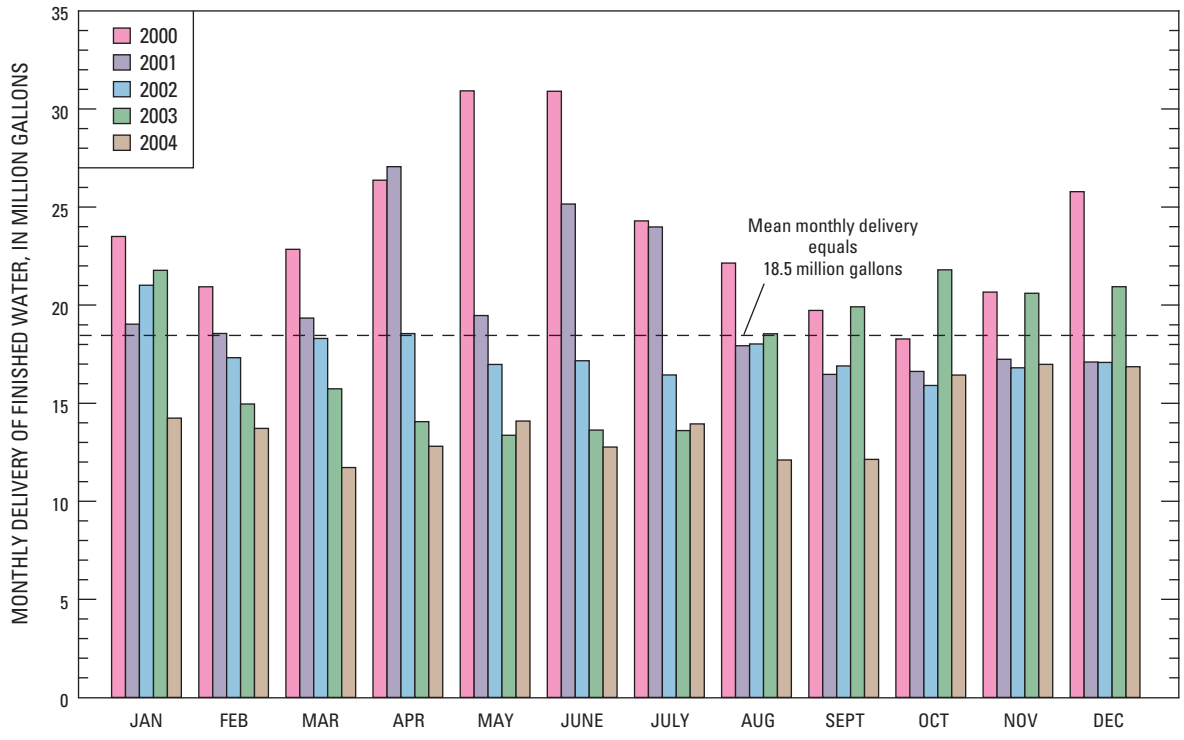


Figure A7. Estimated monthly delivery of finished water to the Tarawa Terrace water-distribution system, 2000–2004, U.S. Marine Corps Base Camp Lejeune, North Carolina. [Data from Joel Hartsoe, Camp Lejeune Public Works Department Utilities Section, December 6, 2006; flow data measured at venturi meter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

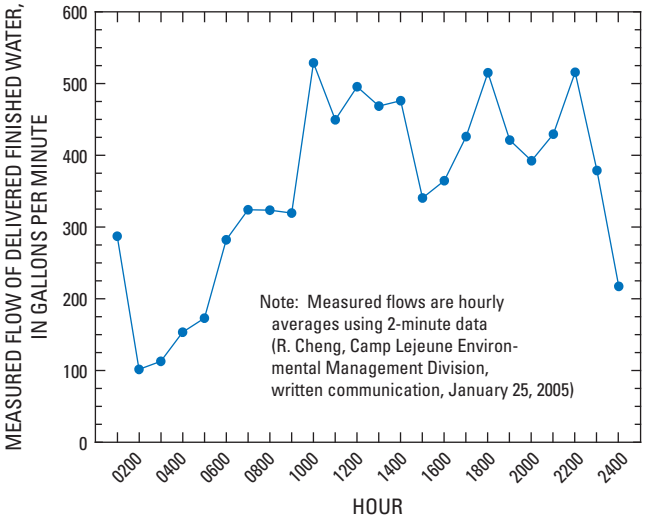


Figure A8. Measured diurnal pattern (24 hours) of delivered finished water during field test, September 22–October 12, 2004, Tarawa Terrace water-distribution system, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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

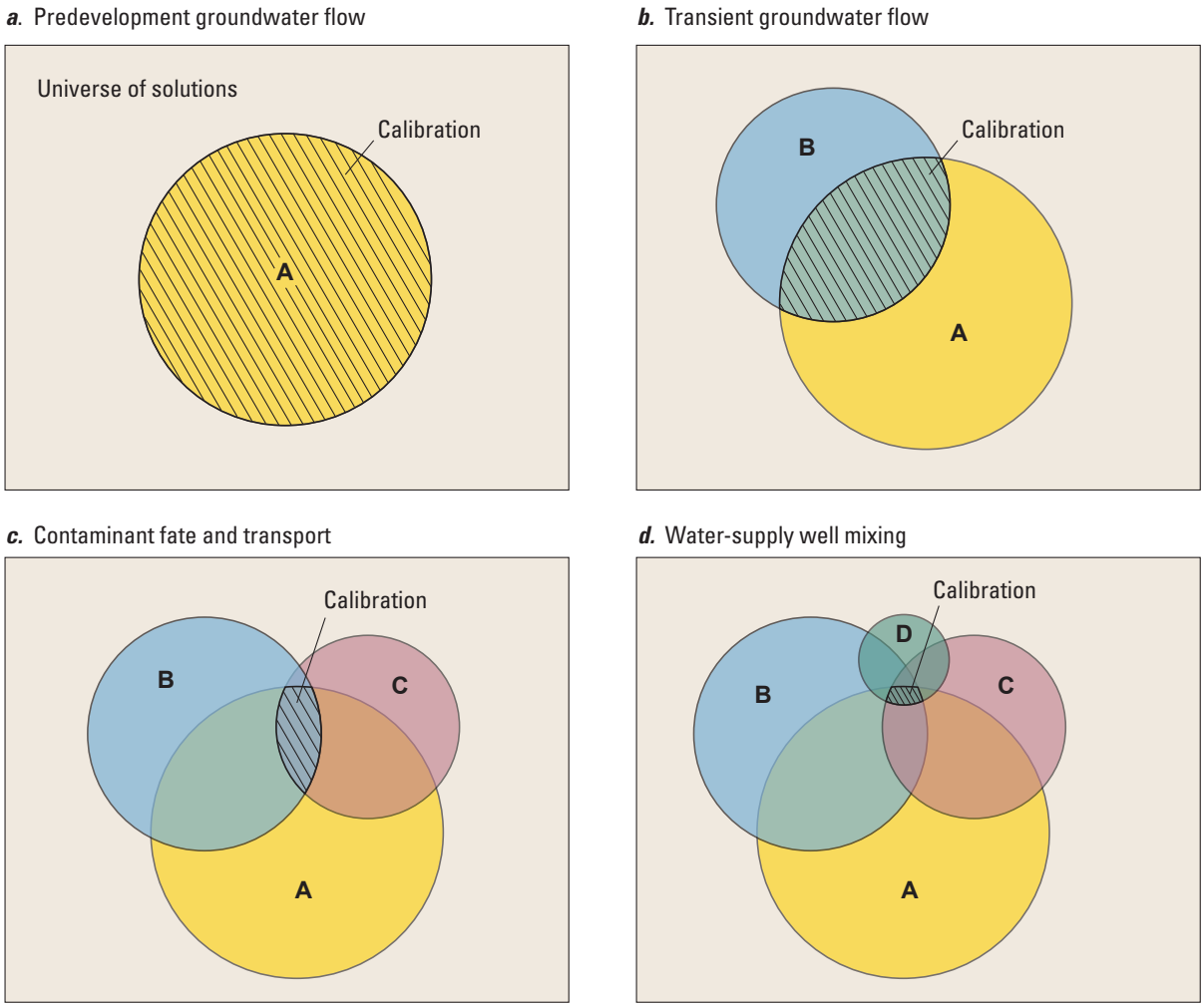


Figure A9. Venn diagrams showing hierarchical approach of model calibration used to estimate concentration of finished water: *(a)* predevelopment groundwater flow, *(b)* transient groundwater flow, *(c)* contaminant fate and transport, and *(d)* water-supply well mixing, Tarawa Terrace and vicinity,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

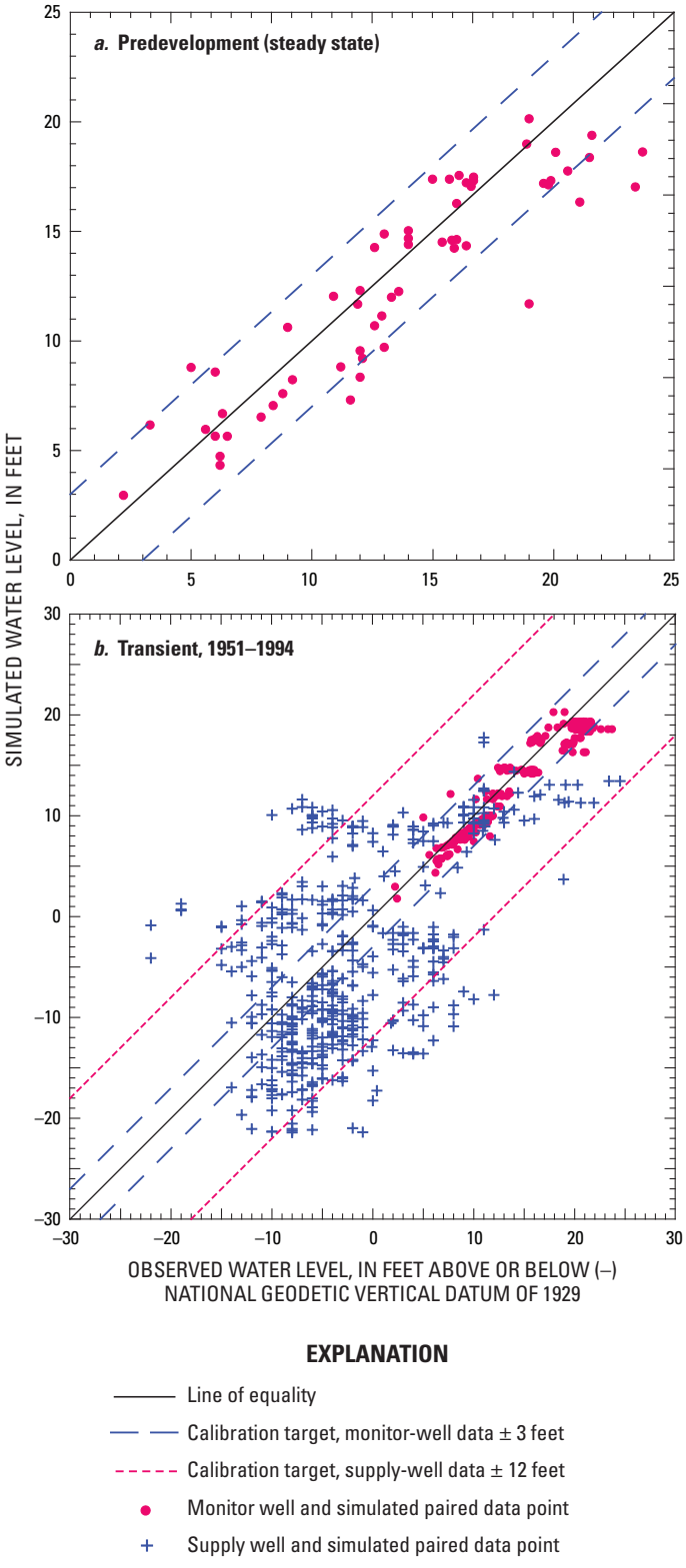


Figure A10. Observed and simulated water levels, model layer 1, and calibration targets for *(a)* predevelopment (steady-state) conditions and *(b)* transient conditions, 1951–1994, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

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

Model parameter[1]	Model layer number[2]						
	1	2	3	4	5	6	7
Predevelopment groundwater-flow model (conditions prior to 1951)							
Horizontal hydraulic conductivity, K_H (ft/d)	12.2–53.4	1.0	4.3–20.0	1.0	6.4–9.0	1.0	5.0
Ratio of vertical to horizontal hydraulic conductivity, K_v/K_H[3]	1:7.3	1:10	1:8.3	1:10	1:10	1:10	1:10
Infiltration (recharge), I_R (inches per year)	13.2	—	—	—	—	—	—
Transient groundwater-flow model, January 1951–December 1994							
Specific yield, S_y	0.05	—	—	—	—	—	—
Storage coefficient, S	—	4.0×10^{-4}	4.0×10^{-4}	4.0×10^{-4}	4.0×10^{-4}	4.0×10^{-4}	4.0×10^{-4}
Infiltration (recharge), I_R (inches per year)	6.6–19.3	—	—	—	—	—	—
Pumpage, Q_k (ft^3/d)	See footnote[4]	—	See footnote[4]	—	0	—	0
Fate and transport of tetrachloroethylene (PCE) model, January 1951–December 1994							
Distribution coefficient, K_d (ft^3/g)	5.0×10^{-6}	5.0×10^{-6}	5.0×10^{-6}	5.0×10^{-6}	5.0×10^{-6}	5.0×10^{-6}	5.0×10^{-6}
Bulk density, ρ_b (g/ft^3)	77,112	77,112	77,112	77,112	77,112	77,112	77,112
Effective porosity, n_E	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Reaction rate, r (d^{-1})	5.0×10^{-4}	5.0×10^{-4}	5.0×10^{-4}	5.0×10^{-4}	5.0×10^{-4}	5.0×10^{-4}	5.0×10^{-4}
Mass-loading rate[5], $q_S C_S$ (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* (ft^2/d)	8.5×10^{-4}	8.5×10^{-4}	8.5×10^{-4}	8.5×10^{-4}	8.5×10^{-4}	8.5×10^{-4}	8.5×10^{-4}

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

[2] Refer to Chapter B (Faye 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

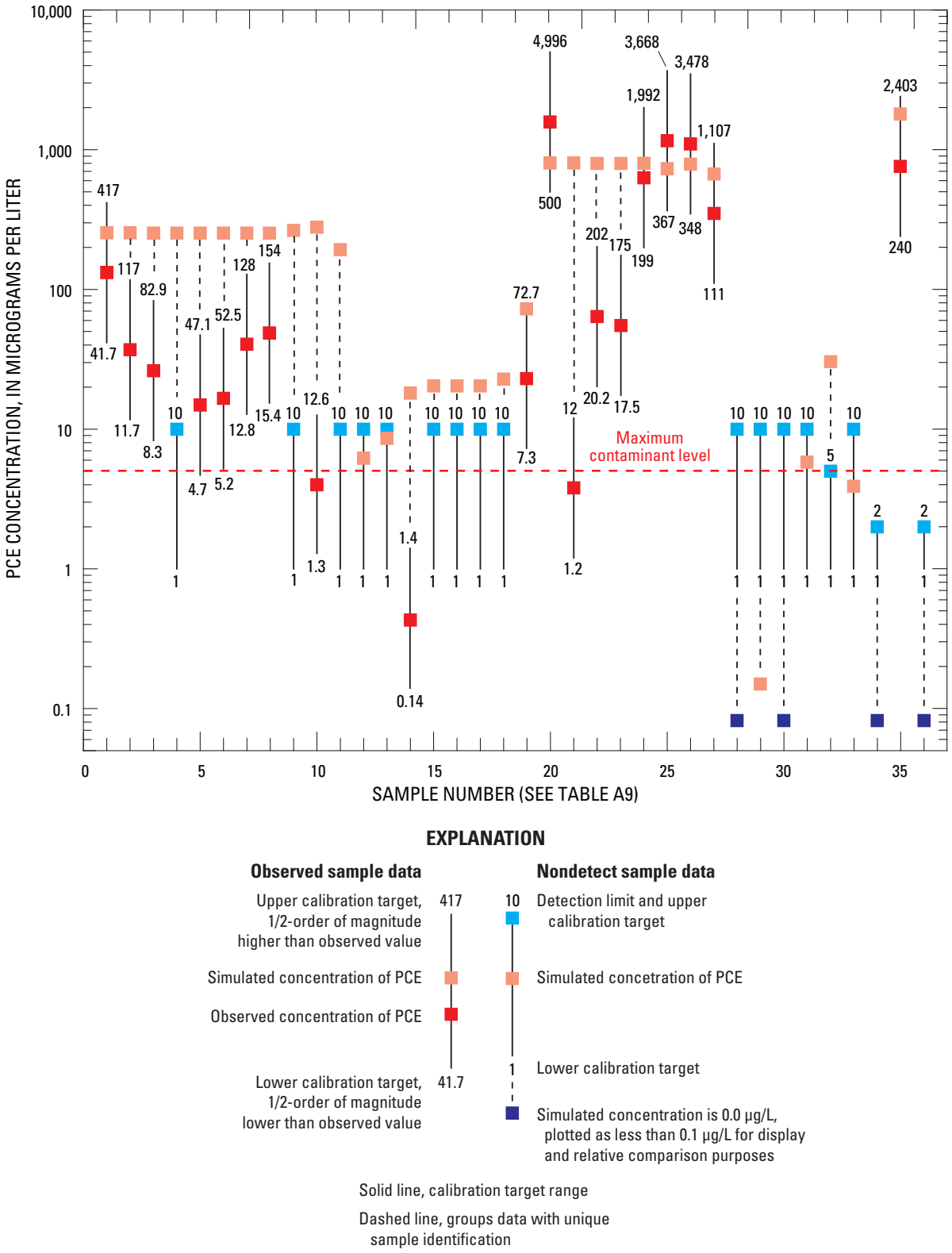


Figure A11. Comparison of observed and nondetect tetrachloroethylene sample data with calibration targets and simulated concentrations at water-supply wells, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [PCE, tetrachloroethylene; µg/L, microgram per liter]

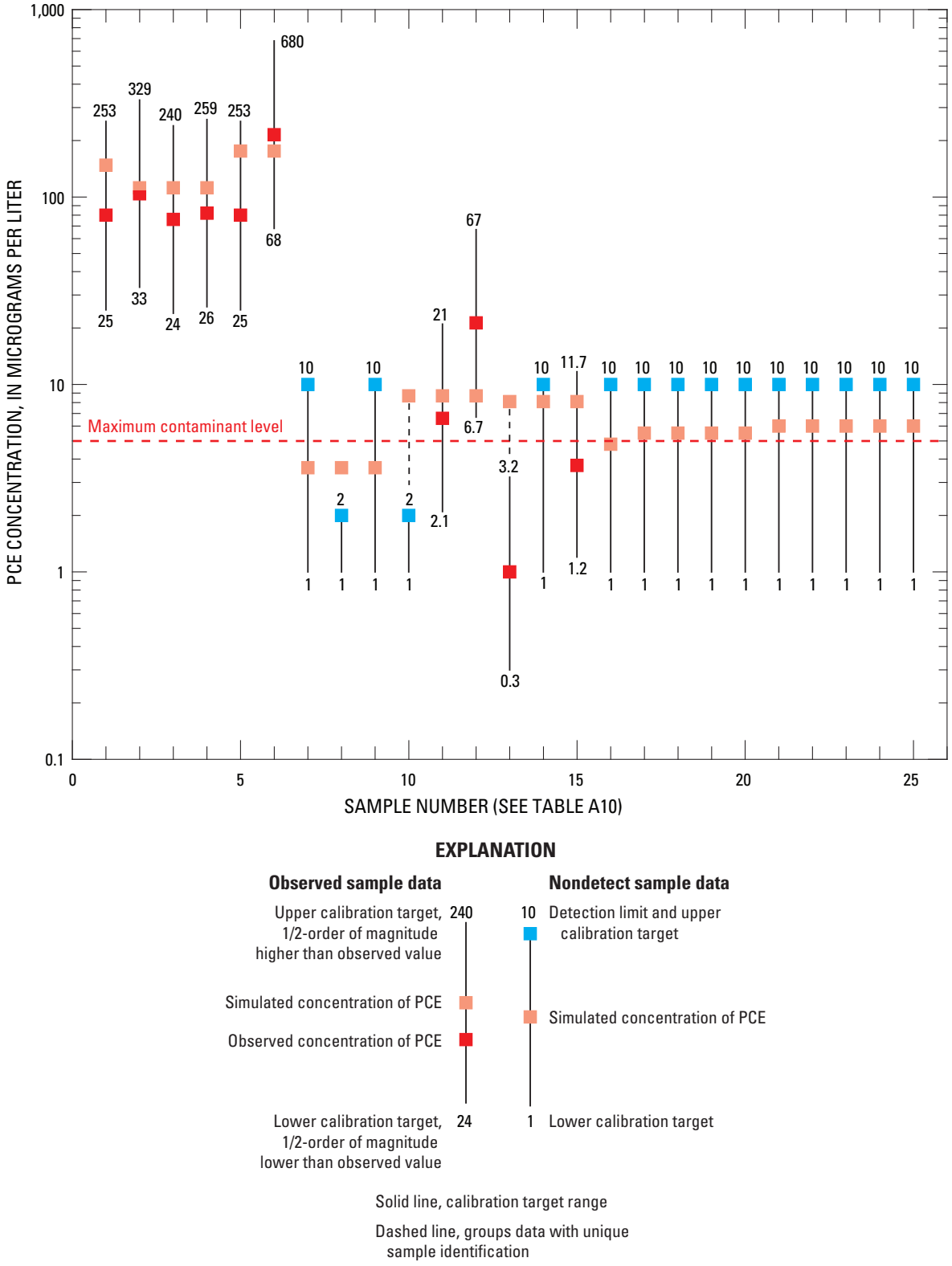


Figure A12. Comparison of observed and nondetect tetrachloroethylene sample data with calibration targets and simulated concentrations at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [PCE, tetrachloroethylene]

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.

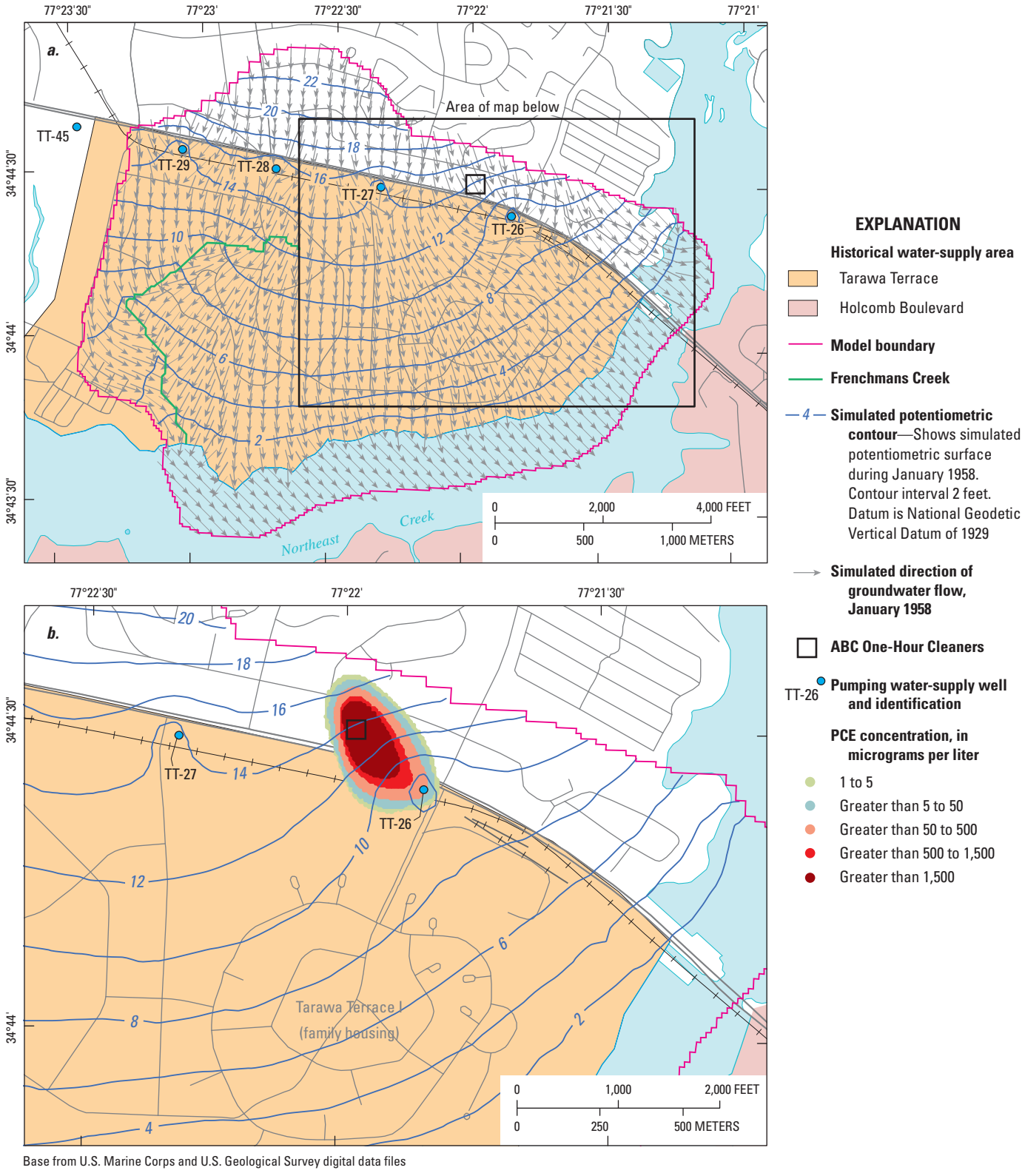
December 1984

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).

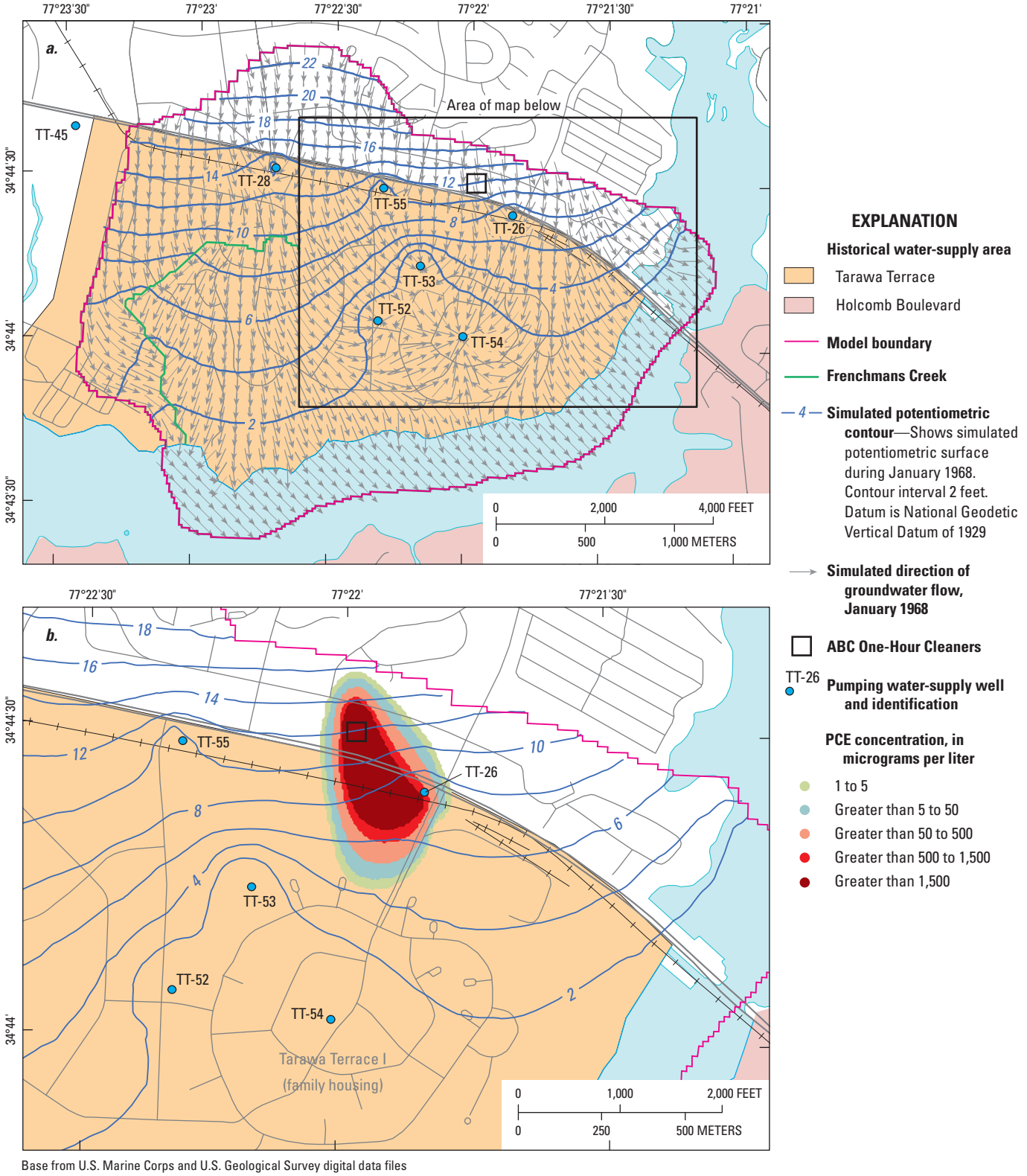
[25] Refer to report Chapter C (Faye and Valenzuela In press 2007) and Chapter F (Faye In press 2007b) reports for details specific to the computational grid and model boundaries used to simulate groundwater flow and contaminant fate and transport.

[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.



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

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]

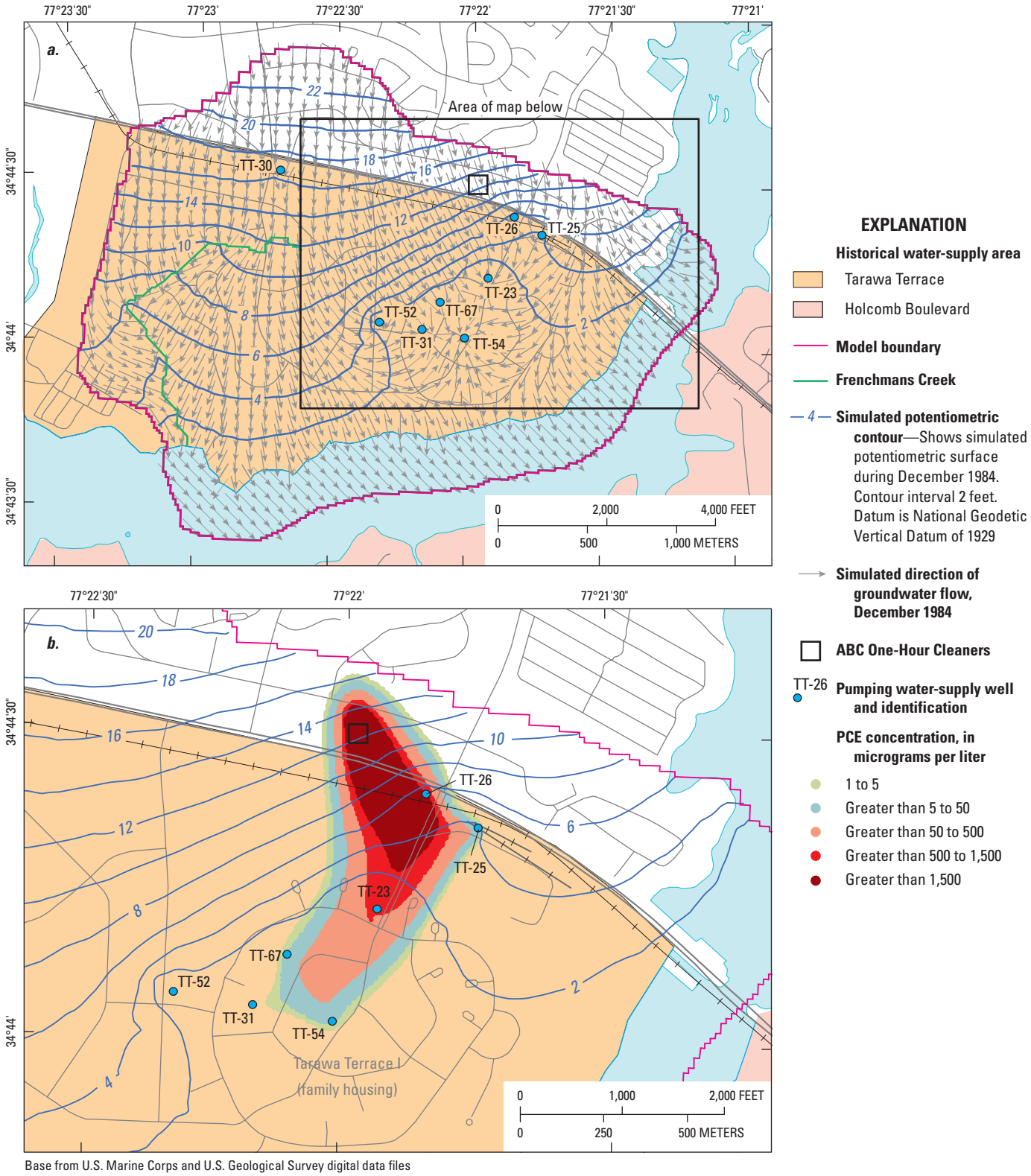


Figure A15. Simulated *(a)* water level and direction of groundwater flow and *(b)* distribution of tetrachloroethylene, model layer 1, December 1984, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [PCE, tetrachloroethylene]

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).

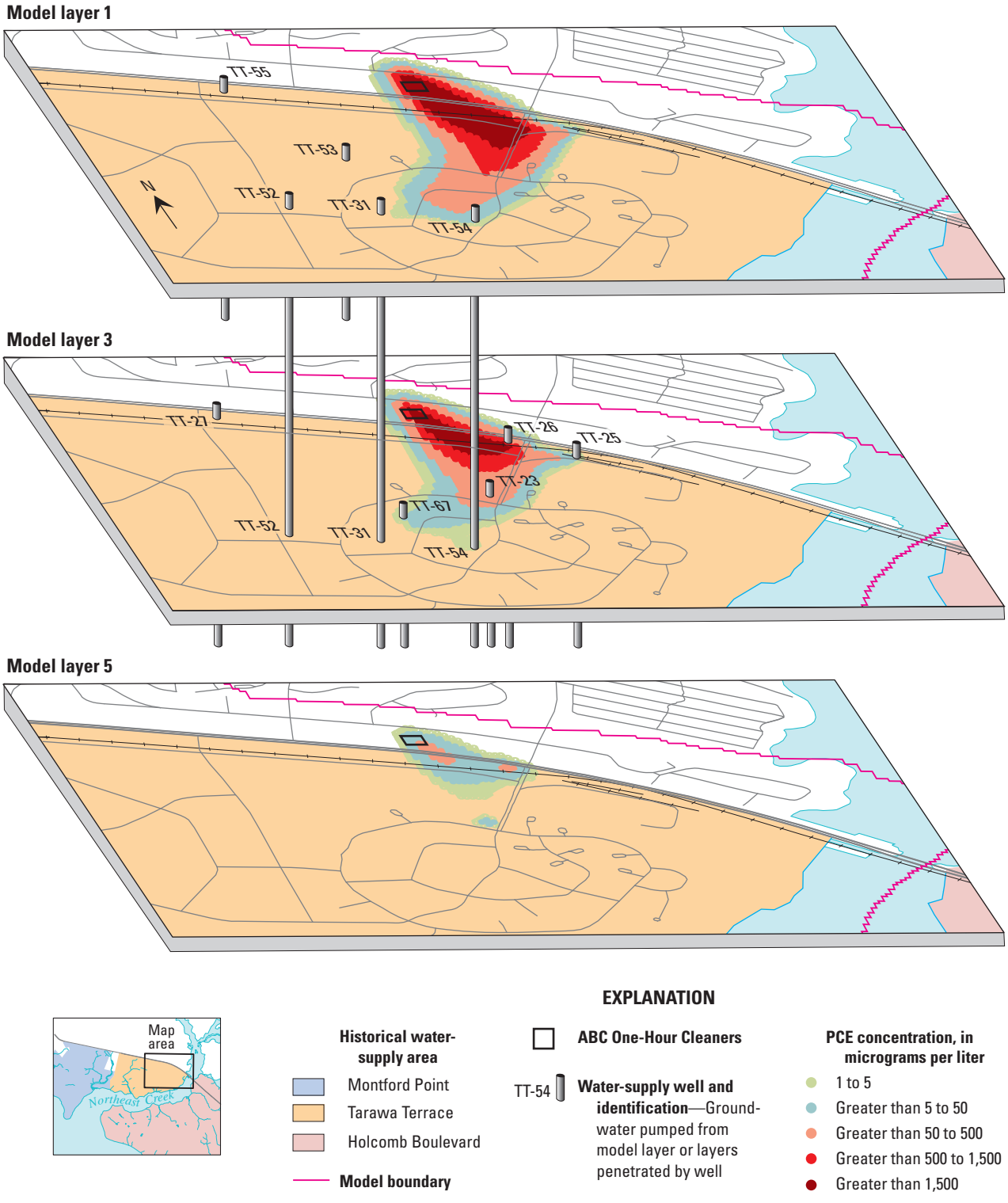
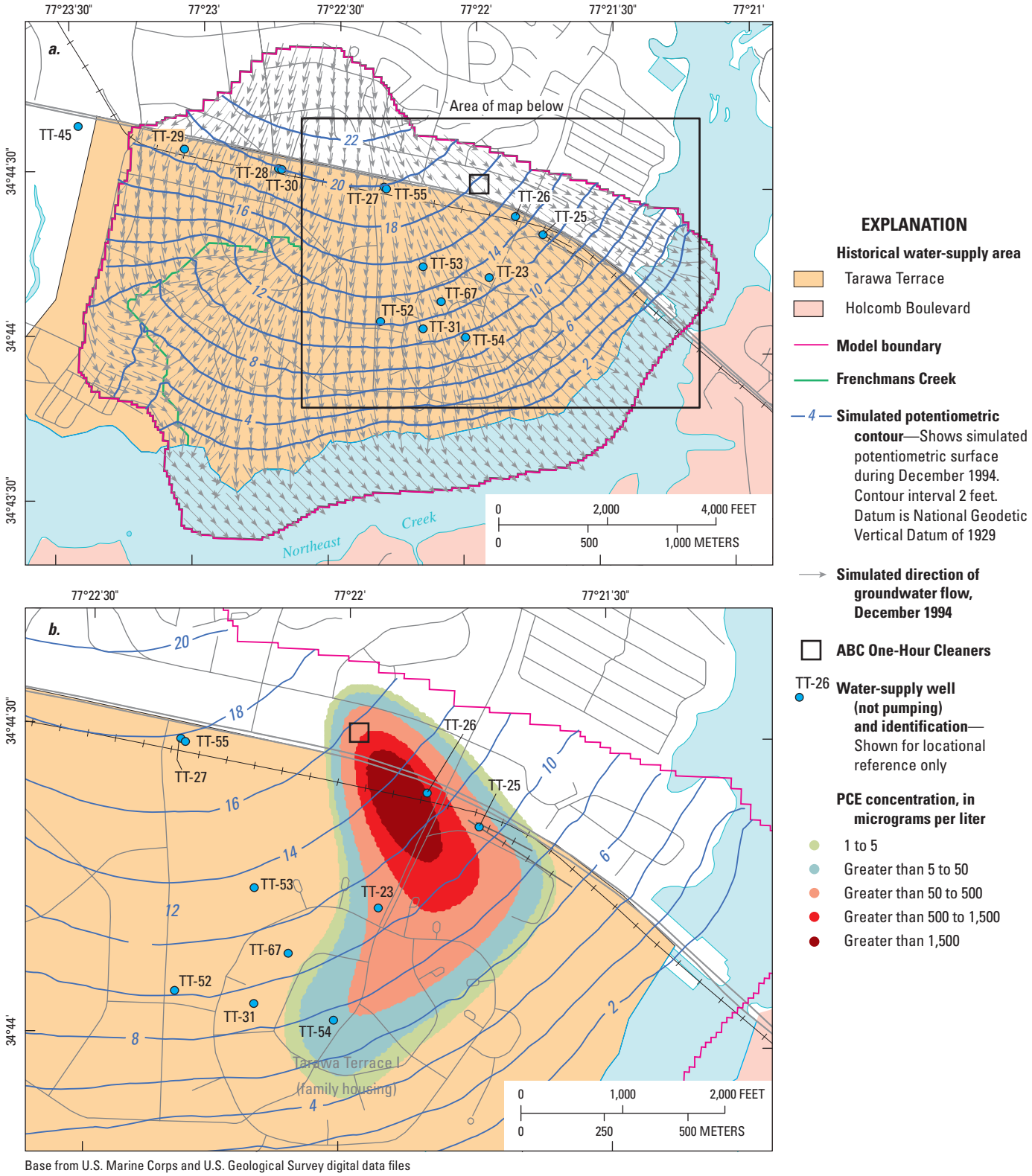


Figure A16. Diagram showing perspective views of the simulated distribution of tetrachloroethylene, model layers 1, 3, and 5, December 1984, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [PCE, tetrachloroethylene; thickness and vertical separation of layers not to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



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

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]

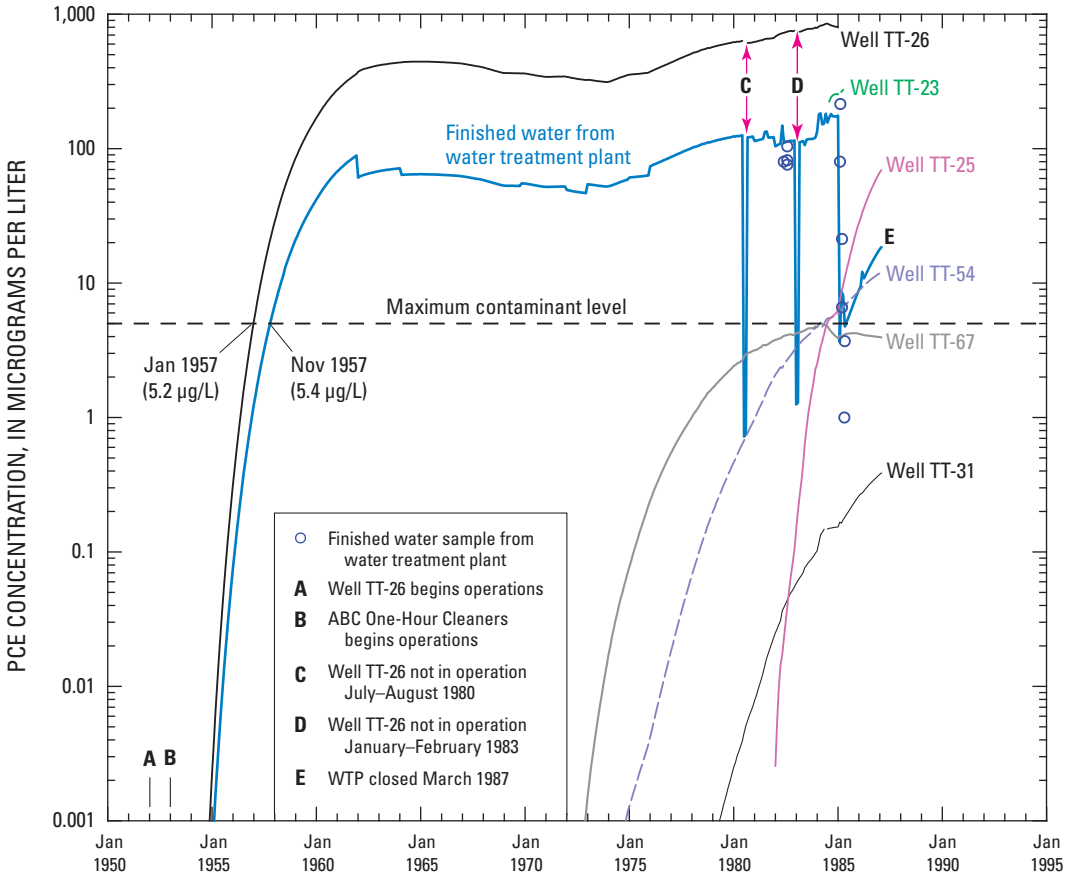


Figure A18. Concentration of tetrachloroethylene: simulated at selected water-supply wells and in finished water at the water treatment plant, and measured in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [PCE, tetrachloroethylene; µg/L,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

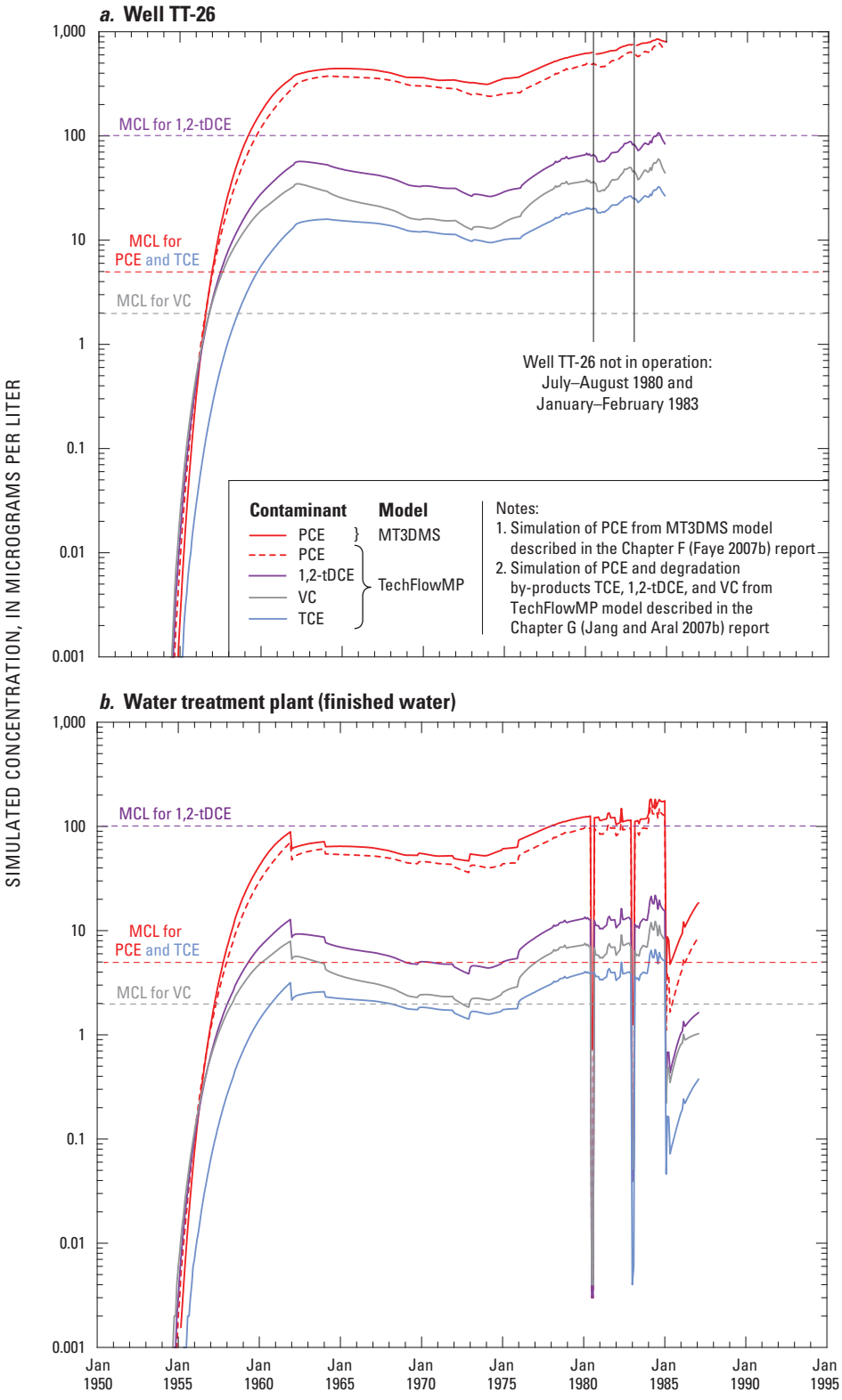


Figure A19. Simulated concentration of tetrachloroethylene (PCE) and degradation by-products trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) *(a)* at water-supply well TT-26 and *(b)* in finished water from water treatment plant, Tarawa Terrace, U.S. Marine Corps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

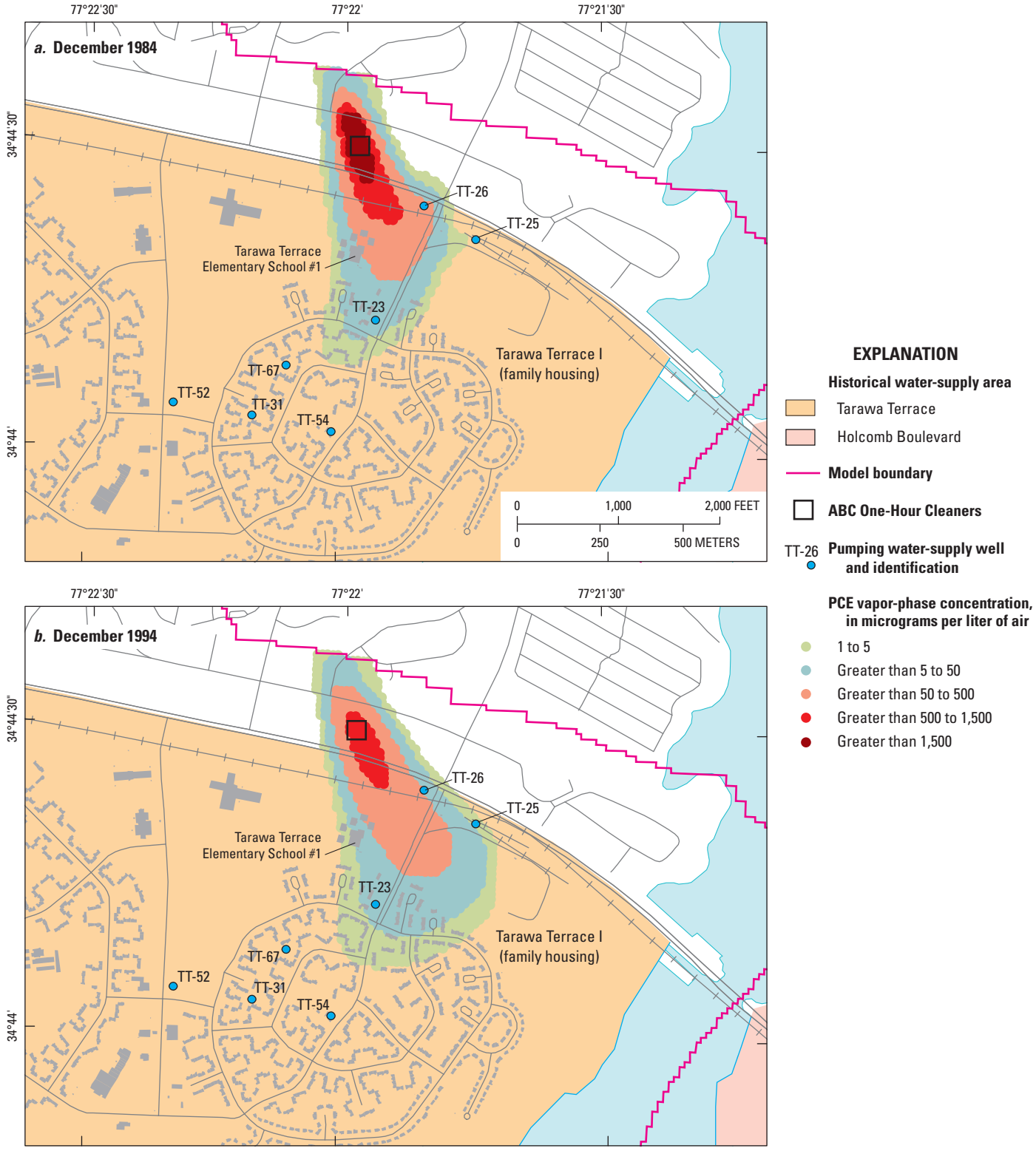
[5]Water-supply well TT-26 was not operating July–August 1980 and January–February 1983

[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.



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

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.

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]).

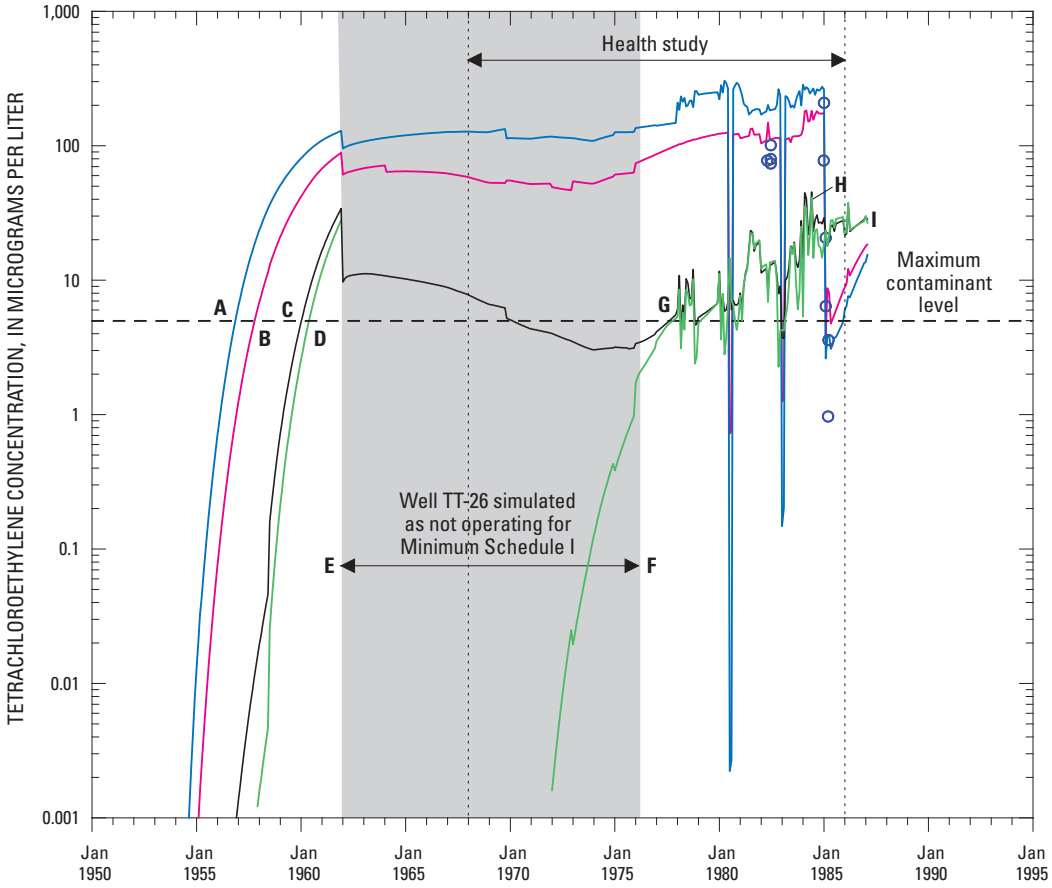
Results of analyses using the PSOpS simulation tool to assess the effects of water-supply well pumping variation are presented graphically as a series of curves of simulated PCE concentration in finished water at the Tarawa Terrace WTP versus time (Figure A21).[35] The calibration curve in Figure A21 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

[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).

[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; ft^3/g, cubic foot per gram; g/ft^3, grams per cubic foot; d^{-1}, 1/day; g/d, grams per day; ft^2/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 (ft^3/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/ft^3)	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* (ft^2/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).

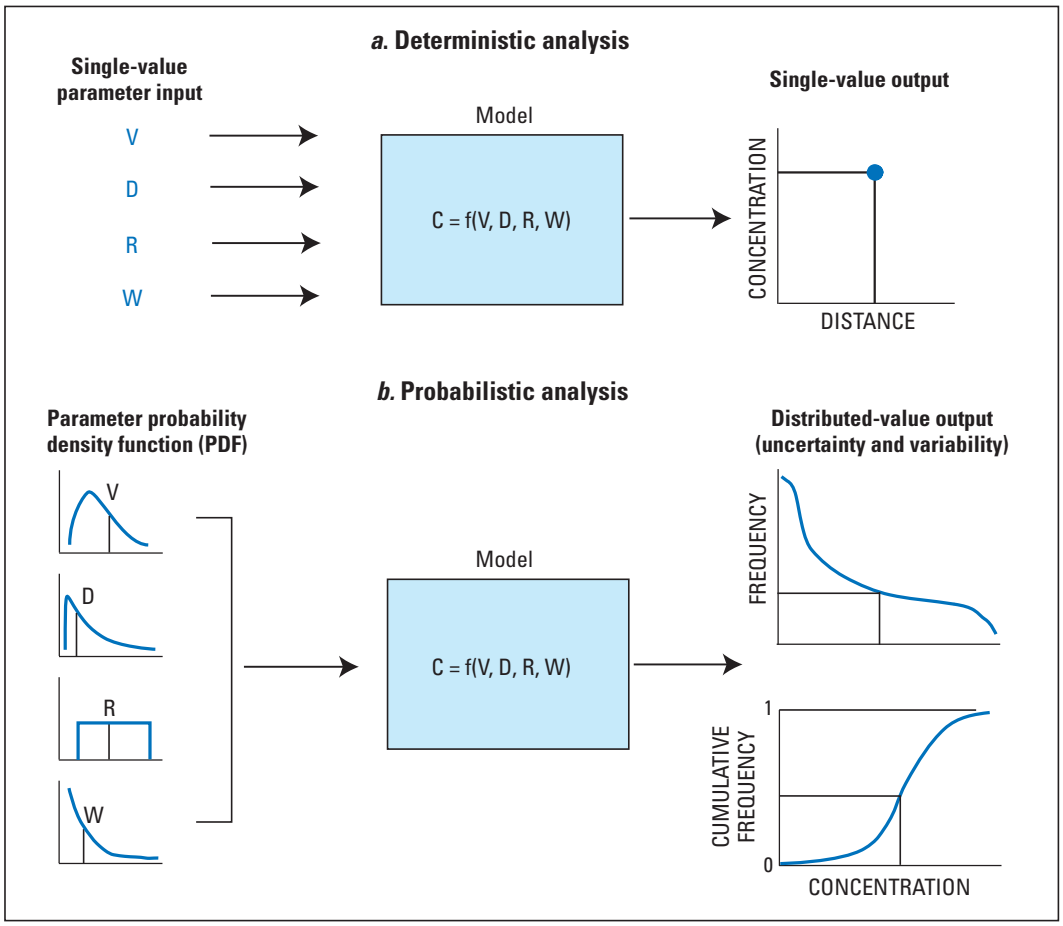


Figure A22. Conceptual framework for *(a)* a deterministic analysis and *(b)* a probabilistic analysis (from Maslia and Aral 2004).

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})	$5.0x10^{-4}$	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

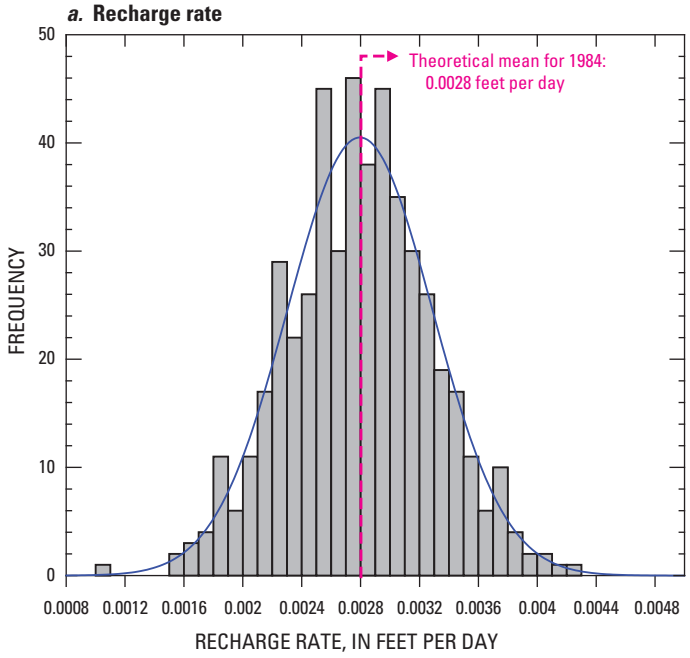
[2] Symbolic notation used to describe model parameters obtained from Chiang and Kinzelbach (2001)

[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

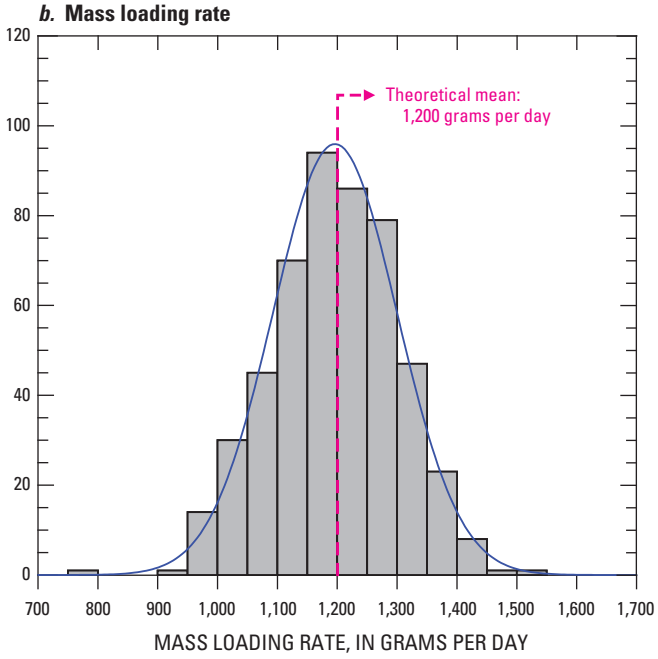
[5] The mean value derived from ln (25); standard deviation derived from ln (5)/2, where ln ( ) is the Naperian logarithm

a. **Recharge rate**



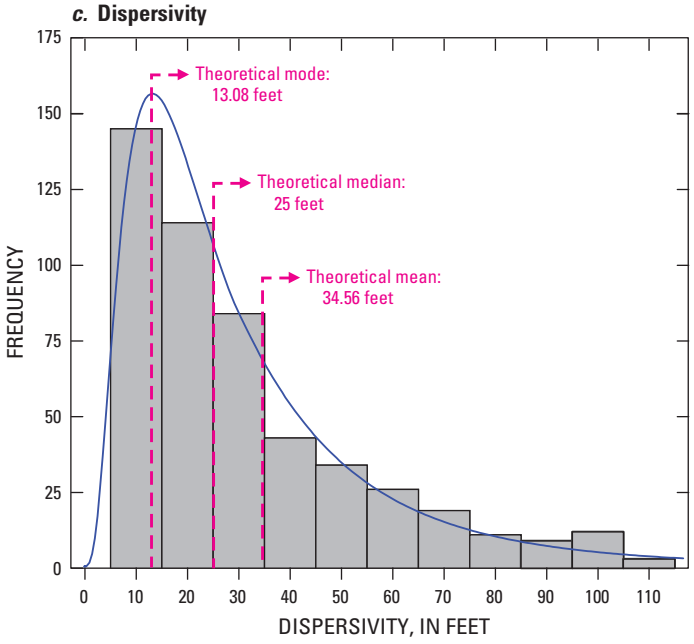
STATISTICS		
	Theoretical	**Monte Carlo simulation**
Distribution	Normal	Normal
Number of realizations	Not applicable	500
Minimum	– Infinity	0.001
Maximum	+ Infinity	0.005
Mean	0.00280	0.00280
Mode	0.00280	0.00260
Median	0.00280	0.00279
Standard deviation	0.00050	0.00049

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.

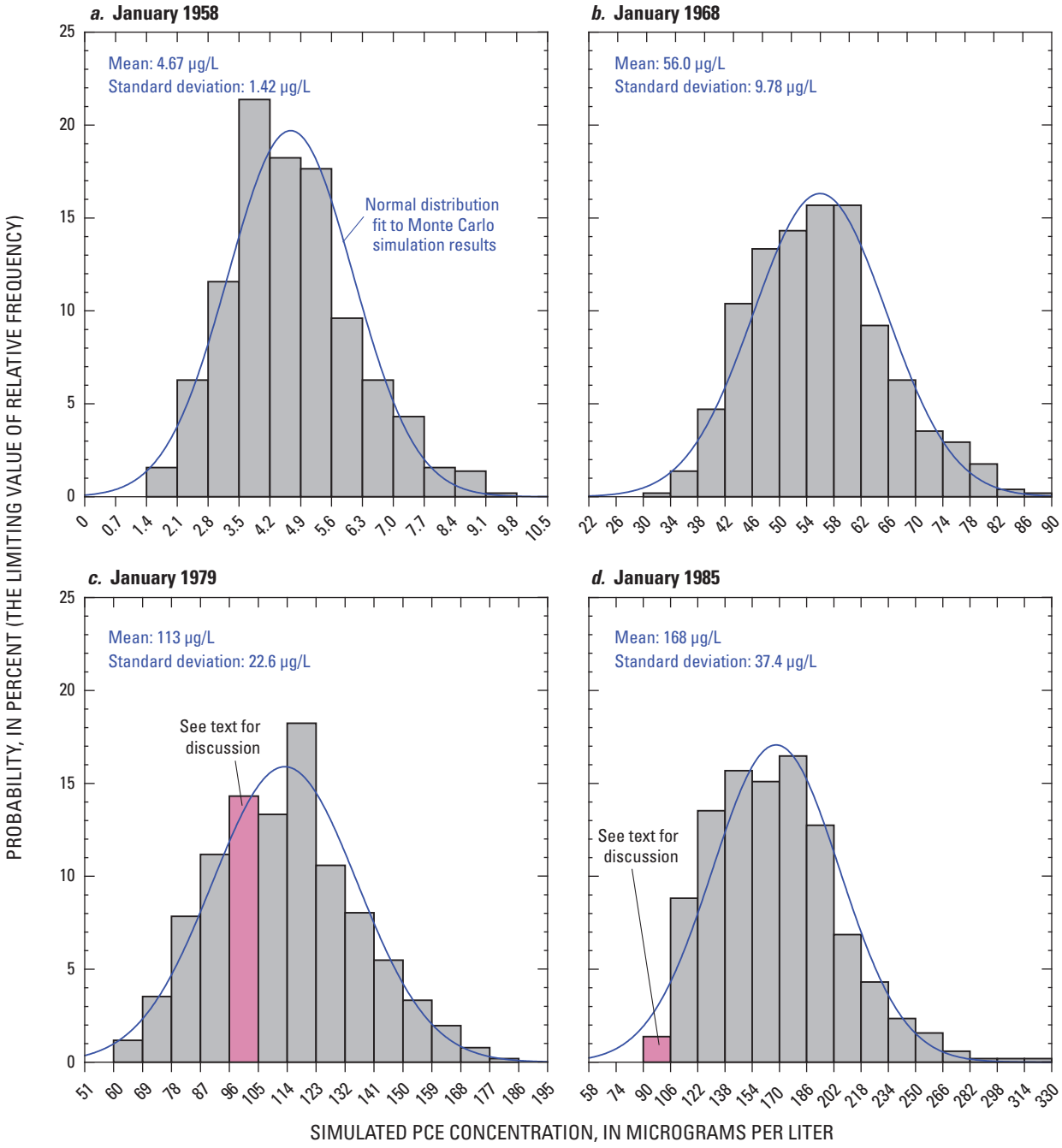


Figure A24. Probability of occurrence of tetrachloroethylene contamination in finished water at the water treatment plant derived from probabilistic analysis using Monte Carlo simulation for *(a)* January 1958, *(b)* January 1968, *(c)* January 1979, and *(d)* January 1985, Tarawa Terrace, U.S. Marine 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%.

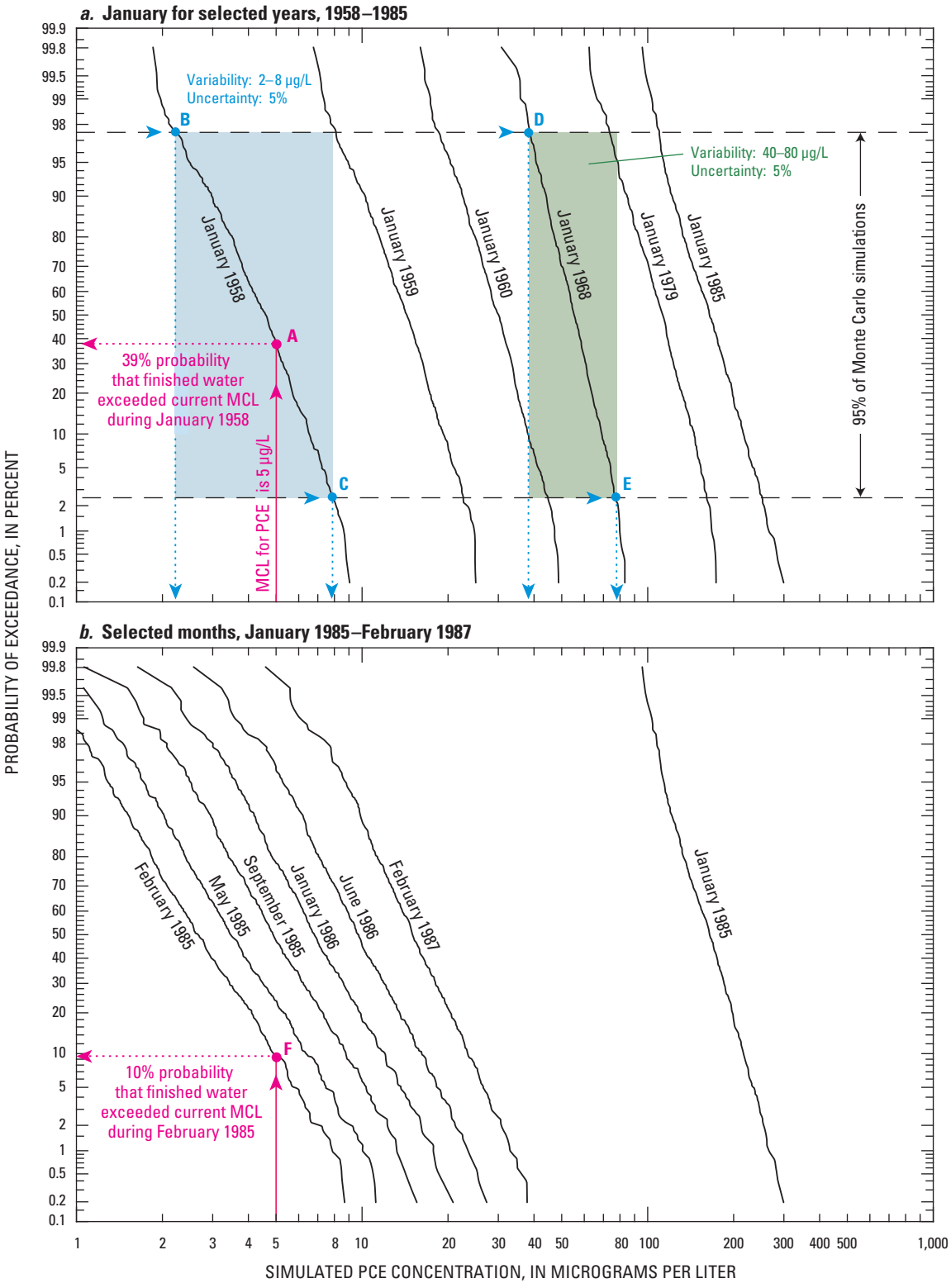


Figure A25. Probabilities of exceeding tetrachloroethylene concentrations in finished water at the water treatment plant derived from probabilistic analysis using Monte Carlo simulation for *(a)* selected years, 1958–1985, and *(b)* selected months, January 1985–February 1987, Tarawa Terrace, U.S. Marine 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.

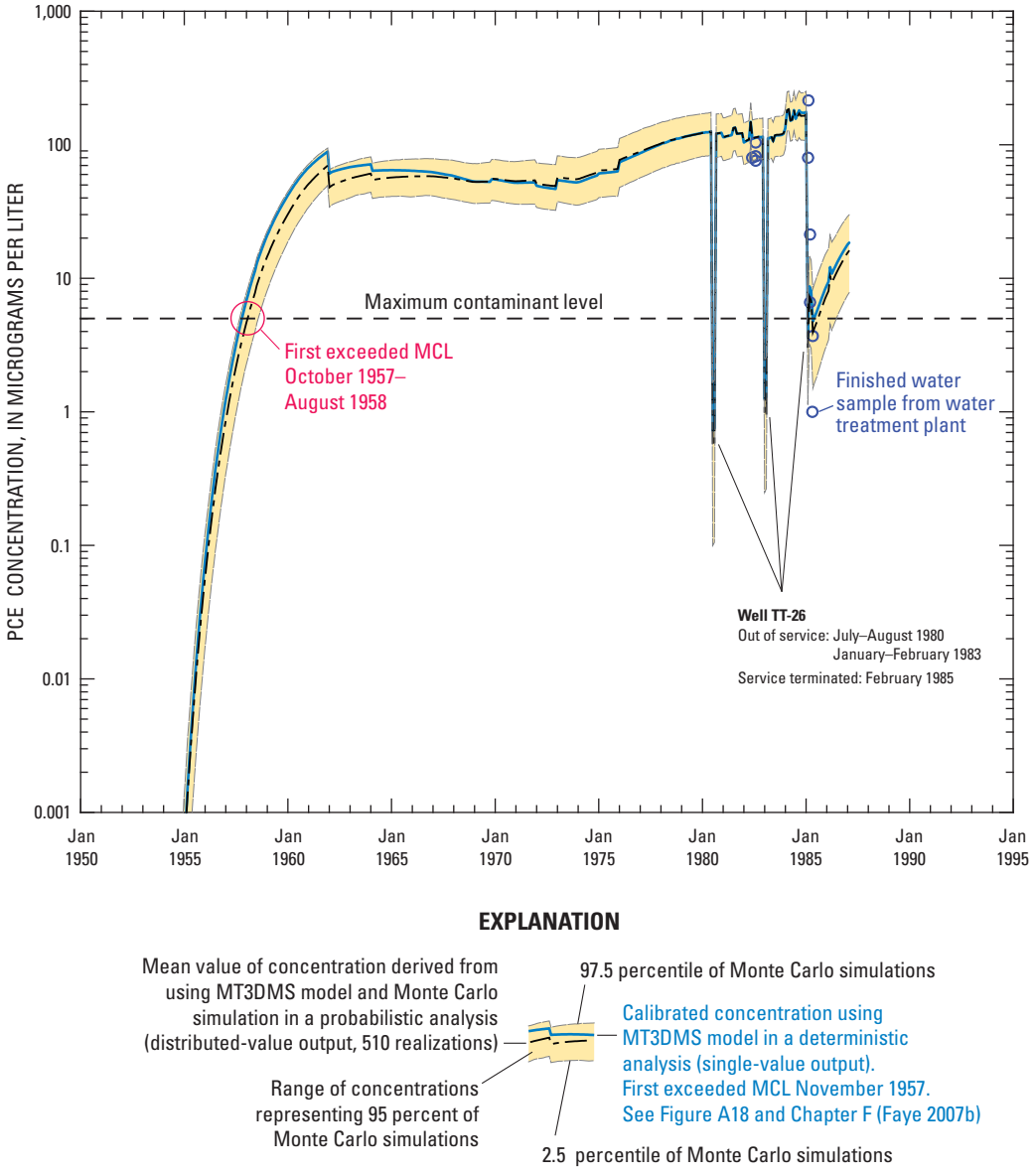


Figure A26. Concentrations of tetrachloroethylene in finished water at the water treatment plant derived from probabilistic analysis using Monte Carlo simulation, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [PCE, tetrachloroethylene; MCL, maximum contaminant level]

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:

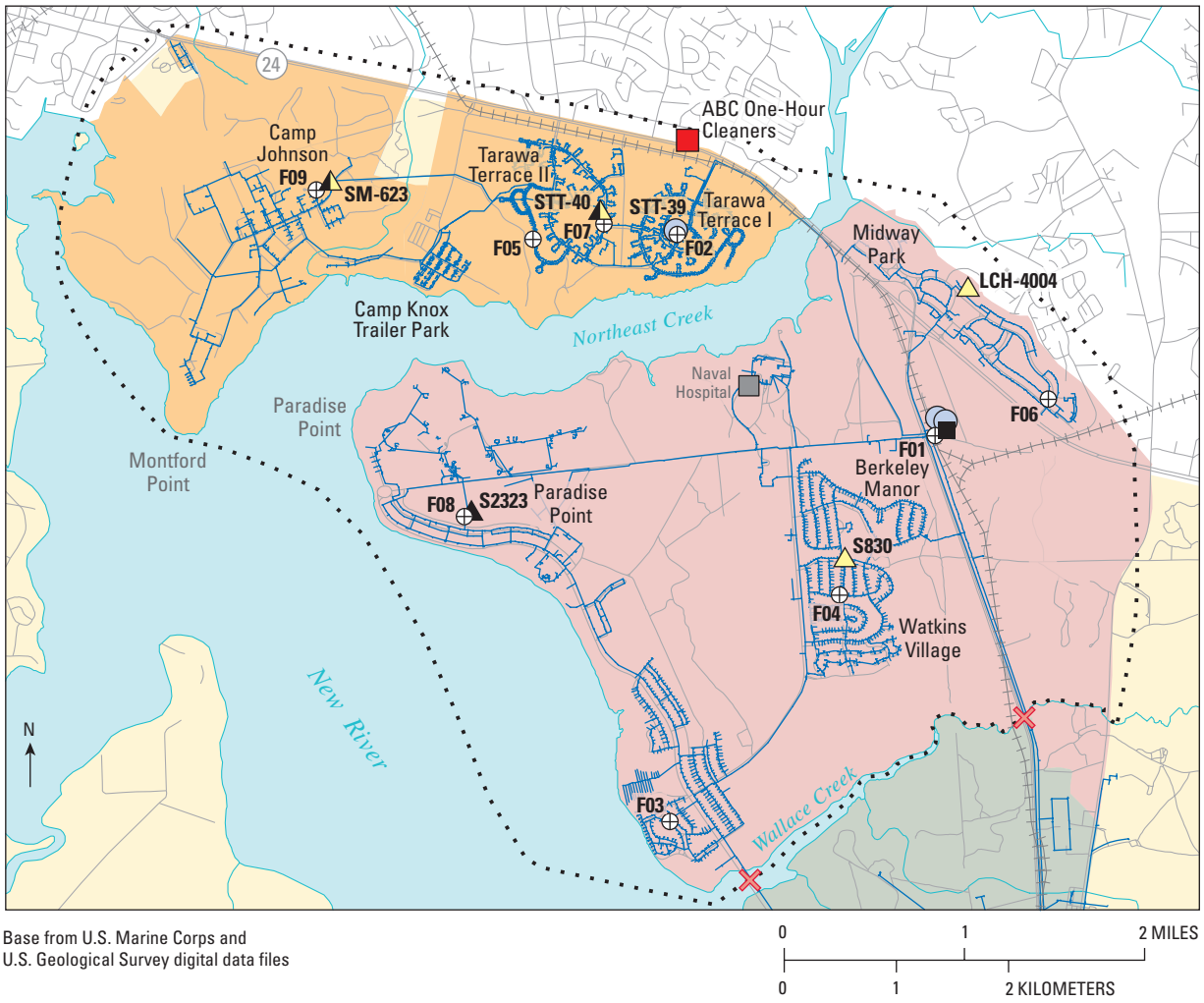
1. The Holcomb Boulevard WTP came online during June 1972 (Figure A3); prior to that date, the Holcomb Boulevard area received finished water from the Hadnot Point WTP (Plate 1);

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.



EXPLANATION

Present-day (2004) water-distribution system on Camp Lejeune Military Reservation

- Tarawa Terrace
- Holcomb Boulevard
- Hadnot Point

Other areas of Camp Lejeune Military Reservation

Holcomb Boulevard Water Treatment Plant Service Area—March 1987 to present

Holcomb Boulevard Water Treatment Plant

Water pipeline—2004

Shut-off valve

F03 **Fluoride logger and number**—CRWQME

Storage tank

S2323 Elevated—Controlling

S830 Elevated—Noncontrolling

SM-623 Elevated—Intermittently controlling and noncontrolling depending on demand conditions

STT-39 Ground—Finished water

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).

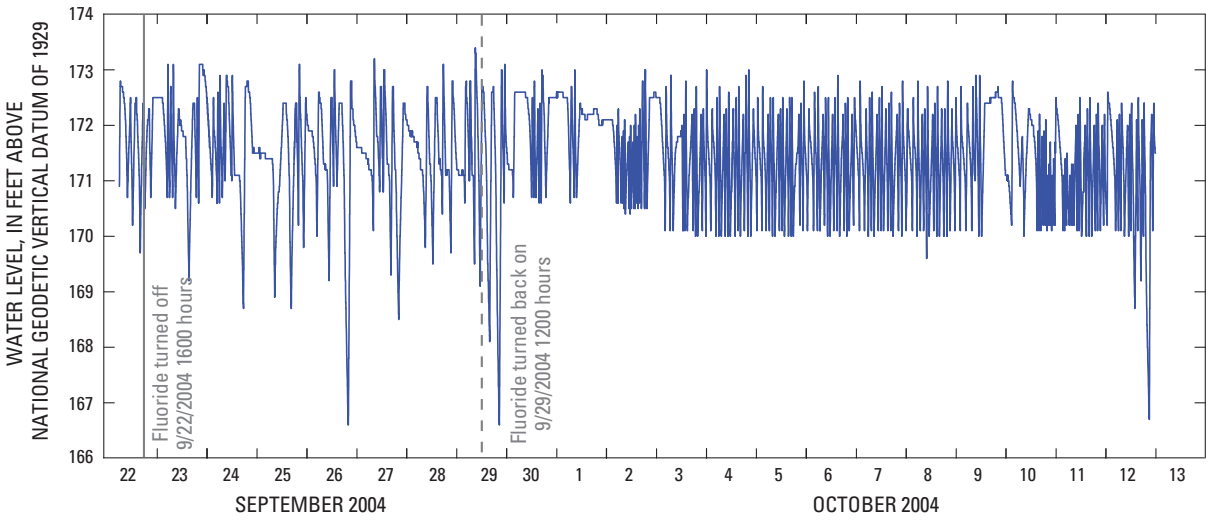


Figure A28. Measured water-level data from the Camp Lejeune SCADA system for controlling elevated storage tank STT-40, September 22–October 12, 2004, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SCADA, supervisory control and data acquisition]

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.

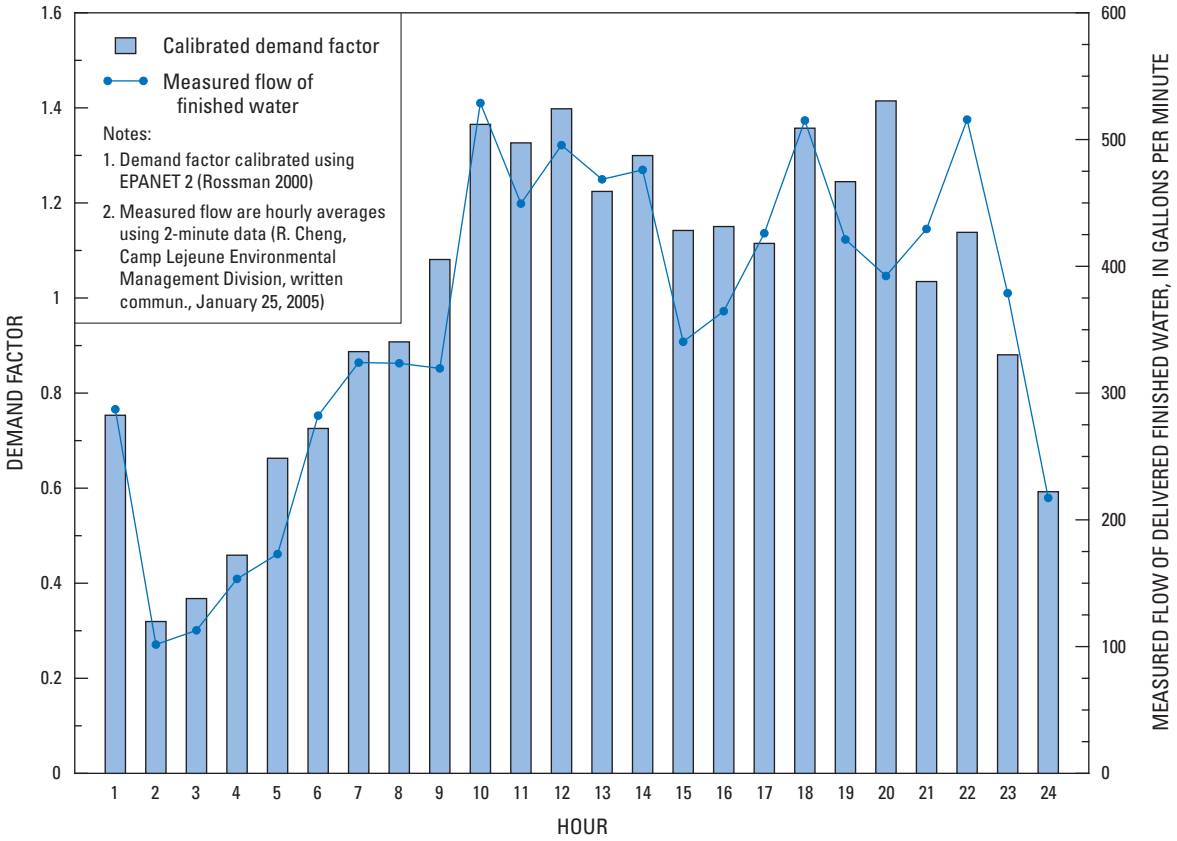


Figure A29. Calibrated and measured diurnal pattern (24 hours) of delivered finished water during field test, September 22–October 12, 2004, Tarawa Terrace water-distribution system, U.S. Marine Corps Base Camp Lejeune, North Carolina. [Flow data measured at venturi meter located in building STT-39A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

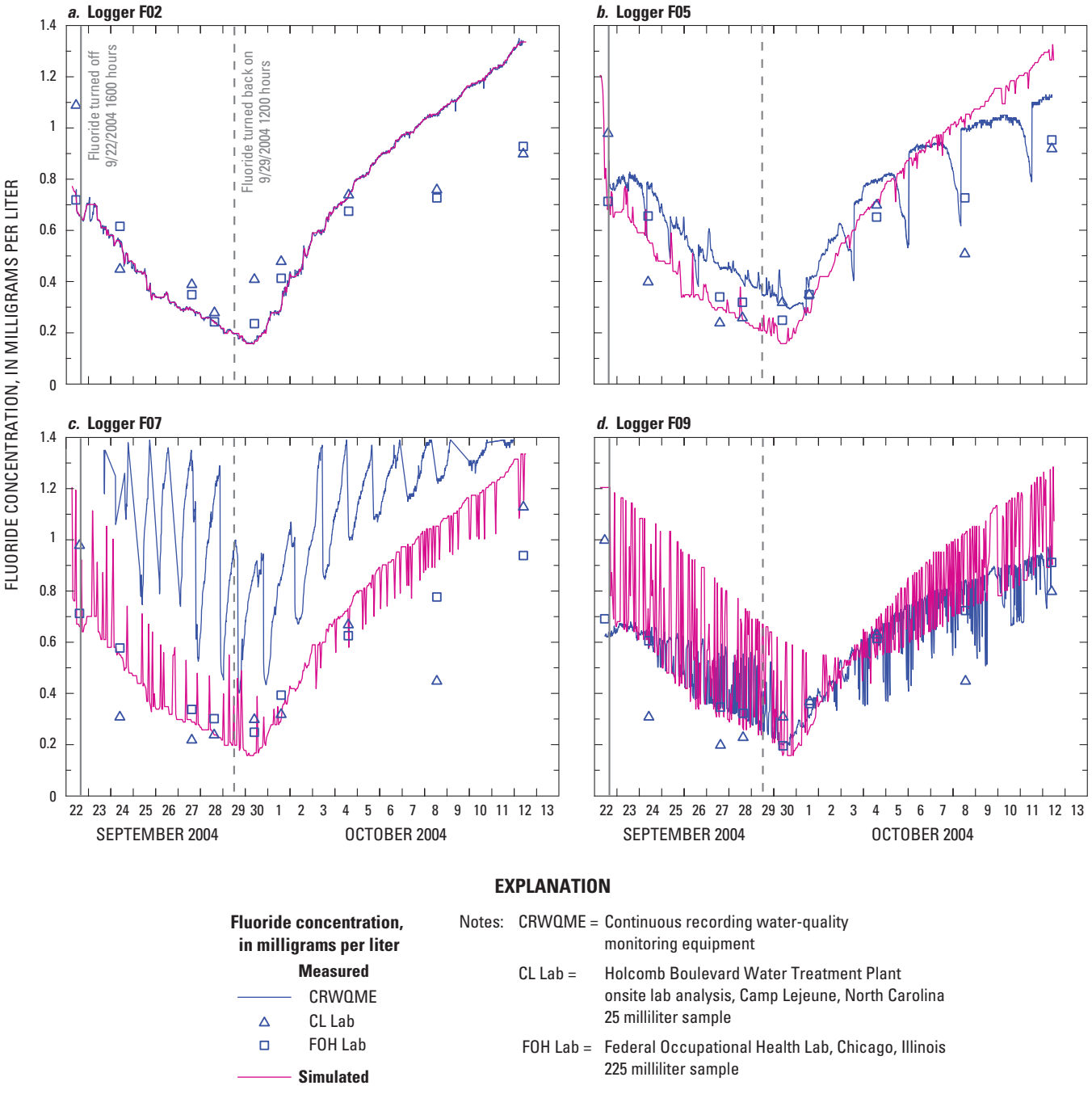


Figure A30. Measured and simulated fluoride concentrations at four monitoring locations *(a)* F02, *(b)* F05, *(c)* F07, and *(d)* F09 in the Tarawa Terrace water-distribution system, September 22–October 12, 2004, U.S. Marine Corps Base Camp Lejeune, North Carolina. (See Figure A27 for monitoring locations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

Morris L. Maslia, MSCE, PE, D.WRE, DEE
Exposure-Dose Reconstruction Project
Division of Health Assessment and Consultation
Agency for Toxic Substances and Disease Registry
1600 Clifton Road, Mail Stop E-32
Atlanta, Georgia 30333
Telephone: (404) 498-0415
Fax: (404) 498-0069
E-mail: mmaslia@cdc.gov

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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.

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Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—Chapter A: Summary of Findings