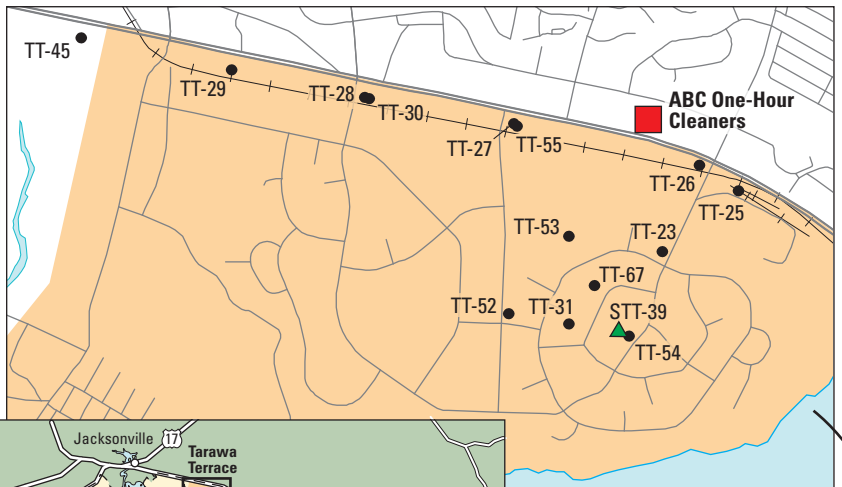
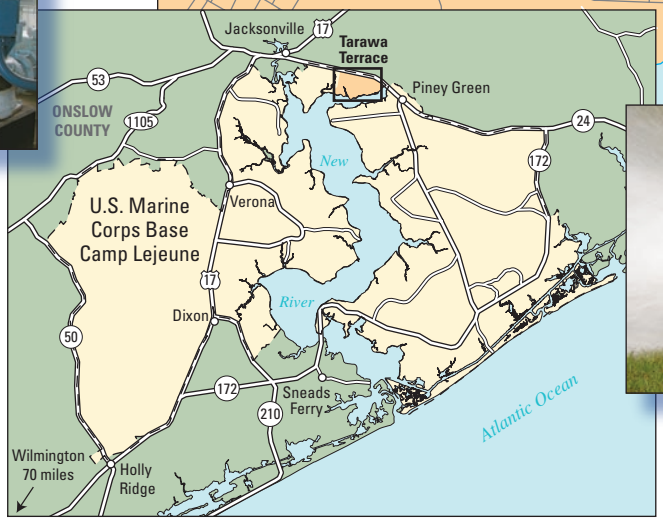
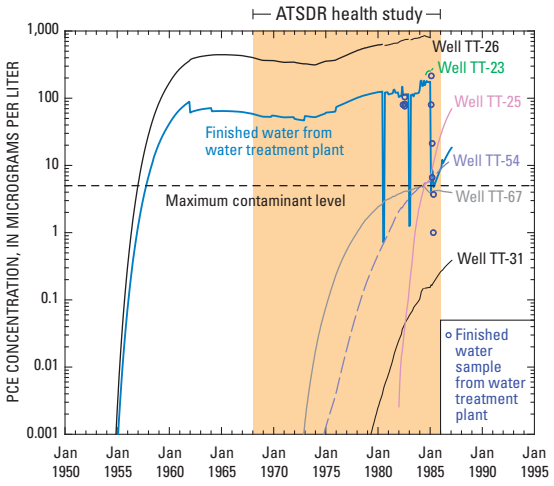
Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions

Executive Summary







DEPARTMENT OF HEALTH & HUMAN SERVICES • USA

ATSDR
AGENCY FOR TOXIC SUBSTANCES AND DISEASE REGISTRY

Atlanta, Georgia–June 2007

Foreword

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

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

Final interpretive results for Tarawa Terrace and vicinity—based on information gathering, data interpretations, and water-modeling analyses—are presented as a series of ATSDR reports. These reports provide comprehensive descriptions of information, data analyses and interpretations, and modeling results used to reconstruct historical contaminant exposure 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 at right:

- **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*.

Suggested citation:
Maslia ML, Sautner JB, Faye RE, Suárez-Soto RJ, Aral MM, Grayman WM, Jang W, Wang J, Bove FJ, Ruckart PZ, Valenzuela C, Green JW Jr, and Krueger AL. Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—Executive Summary. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2007.

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Introduction

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 (Figure ES1). Two of the water-distribution systems were contaminated with volatile organic compounds (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—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 Executive Summary 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.

Historical Background

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 VOCs 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 pregnant women who resided in family housing at the base. Because limited measurements of contaminant and exposure data are available to support the epidemiological study, ATSDR is using water-modeling techniques to provide the epidemiological study with quantitative estimates of monthly contaminant levels in the drinking water. 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).

Camp Lejeune is located in the Coastal Plain of North Carolina, in Onslow County, southeast of the City of Jacksonville and about 70 miles northwest of the City of Wilmington, North Carolina (Figure ES1). Operations began at the base 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. The base consists of 15 different housing areas; families live in base housing for an average of 2 years. During the 1970s and

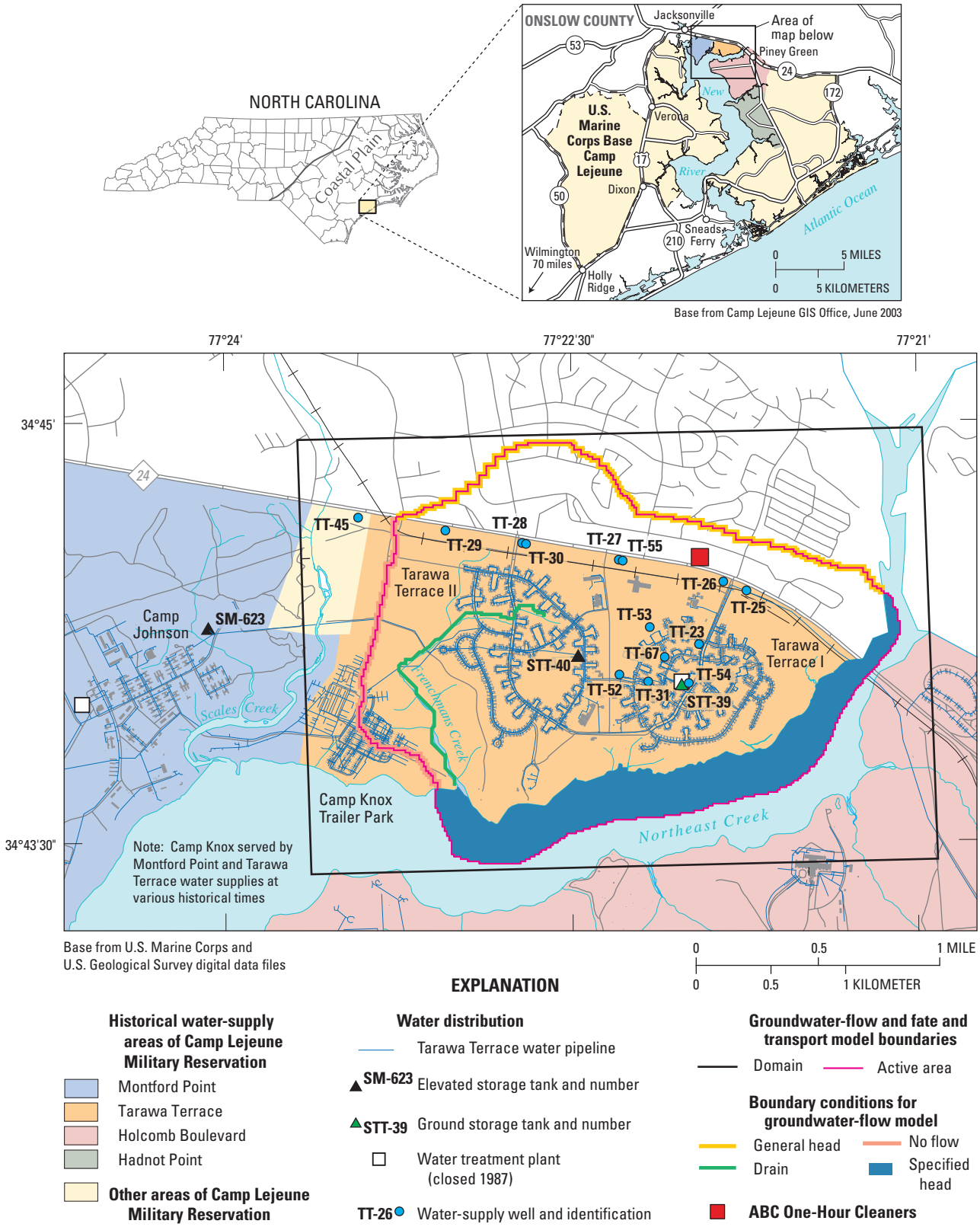

Figure ES1. Historical water-supply areas, groundwater-flow modeling area, and water-supply facilities used for historical reconstruction analyses, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

1980s, family housing areas were served by three water-distribution systems—Hadnot Point, Tarawa Terrace, and Holcomb Boulevard (starting June 1972). Hadnot Point was the original water-distribution system serving the entire base with drinking water during the 1940s.

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, began operations during 1952 (Figure ES1). 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 during 1953.

During 1989, the U.S. Environmental Protection Agency (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 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), *trans*-1,2-dichloroethylene (1,2-tDCE), 1,1-dichloroethylene (DCE), vinyl chloride (VC), benzene, and toluene (ATSDR 1990).

During 1997, ATSDR completed a PHA for the base, 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 from in utero exposure to chlorinated solvents (for example, PCE and TCE) contained in on-base drinking water (ATSDR 1997).

Following this recommendation, ATSDR published a study of adverse birth outcomes during 1998 (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, through 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 this study used incorrect information on the start-up date for the Holcomb Boulevard water treatment plant, errors were made in assigning exposures to the mothers. This study is being re-analyzed using the results from the historical reconstruction water modeling.

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 in 1968. The last year of the study, 1985, was chosen because contaminated Tarawa Terrace water-supply wells were removed from regular service that year (February 1985). The study is evaluating the central nervous system defects known as neural tube defects (i.e., 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.

Tarawa Terrace Reports

Owing to the complexity, uniqueness, and the number of topical subjects included in the historical reconstruction process, a number of reports are being prepared that provide comprehensive descriptions of information, data, and methods used to conduct historical and present-day (2004) analyses at Tarawa Terrace and vicinity. Table ES1 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 ES1 are listings of the authors and a topical summary of each chapter report. The Chapter A report—Summary of Findings—provides a 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 at Tarawa Terrace and vicinity. Also contained in Chapter A are brief summaries of all of the other chapter reports and a searchable electronic database—on digital video disc (DVD) format—of information and data sources used to conduct the historical reconstruction analysis.

Information and data used for the water-modeling analyses were obtained from a variety of sources, such as 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. Readers interested in details for a specific analysis (for example, numerical model development, model calibration procedures, synoptic maps showing groundwater migration of PCE at Tarawa Terrace, or uncertainty analysis) should consult the appropriate chapter report listed in Table ES1. Electronic versions of each chapter report described above and supporting information and data will be made available at the ATSDR Camp Lejeune Web site at *http://www.atsdr.cdc.gov/sites/lejeune/index.html*.

Water-Distribution Investigation

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 will have 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 ES2. One of the purposes of Figure ES2 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 during March 1987. Thus, care has been taken to assure that chronological event information and data required for modeling analyses and the historical reconstruction process are consistent and in agreement for all of the Tarawa Terrace reports and reflect the most up-to-date information.

Occurrence of Contaminants in Groundwater

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. 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. This volume represents an average minimum loss rate of PCE to the subsurface at ABC One-Hour Cleaners of about 13 gallons per year during the period 1953–1985.

Table ES1. 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. (In press 2007a)	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 and 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 the 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 2007c)	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 the study

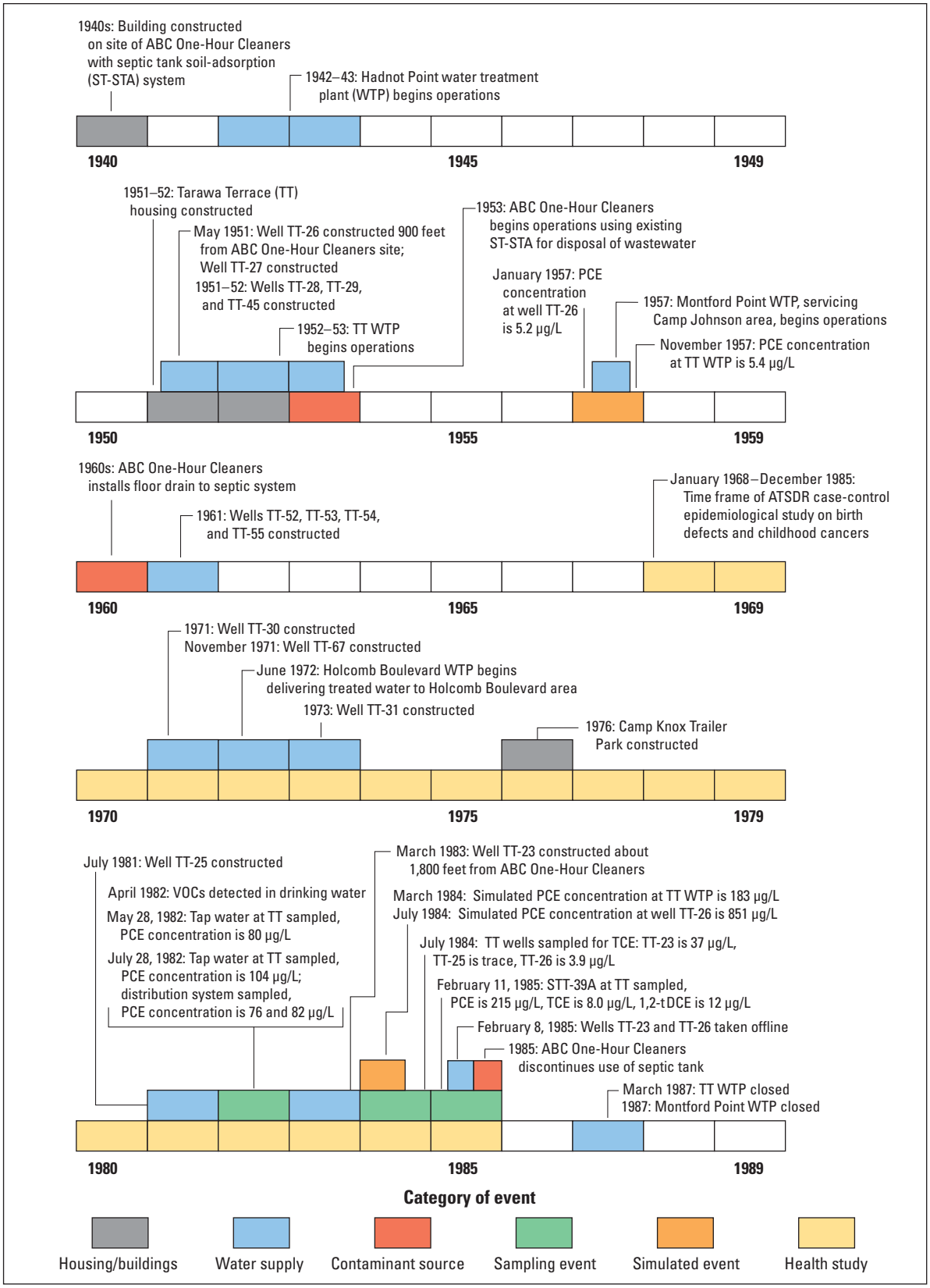

Figure ES2. Chronology of events related to supply and contamination of drinking water at Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. (STT-39A is the pump house associated with storage tank STT-39.) [ft, foot; µg/L, microgram per liter; PCE, tetrachloroethylene; TCE, trichloroethylene; 1,2-tDCE, *trans*-1,2-dichloroethylene; maximum contaminant levels: PCE 5 µg/L, TCE 5 µg/L, 1,2-tDCE 100 µg/L]

Approach for Reconstructing Historical Concentrations

A simulation or modeling approach was used to reconstruct and estimate (quantify) historical concentrations of PCE in finished water[1] that was 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—reproduces the behavior of real-world systems (for example, migration of PCE) as closely as possible. Calibration of models used for the Tarawa Terrace analyses was accomplished in a 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 satisfactorily conformed to preselected calibration targets or measures. The step-wise order of model calibration levels consisted of simulating (1) predevelopment (steady or nonpumping) groundwater-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, 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 base housing.

To understand the calibration process from a non-technical point of view, it is useful to view the step-wise approach used to estimate the concentration of PCE in finished water from the Tarawa Terrace WTP in terms of venn or set diagrams (Borowski and Borwein 1991). These diagrams are useful for showing logical relations between sets or groups of like items and are shown in Figure ES3 for each calibration level. At level 1 (Figure ES3*a*), there may be a large number of combinations of model parameters that yield solutions to predevelopment (steady, nonpumping) groundwater-flow conditions. However, only a smaller set—the subset of solutions indicated by circle "A" in Figure ES3*a*—yields acceptable combinations of parameters for a calibrated predevelopment groundwater flow model. For transient (time-varying and pumping) groundwater-flow conditions, feasible solutions are indicated by circle "B" (Figure ES3*b*). However, only those solutions that satisfy both predevelopment and transient groundwater flow can be accepted and classified as resulting in calibrated transient and predevelopment groundwater-flow models. These select and fewer solutions are indicated by the intersection of circles "A" and "B." The transient groundwater-flow simulations provide velocity information (rate of groundwater flow or discharge) required to conduct a fate and transport simulation. Feasible solutions for the fate and transport analysis are indicated by circle "C" (Figure ES3*c*). Only those solutions that satisfy: (a) predevelopment flow, (b) transient groundwater flow, and (c) contaminant fate and transport 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 level used to determine historical

[1]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

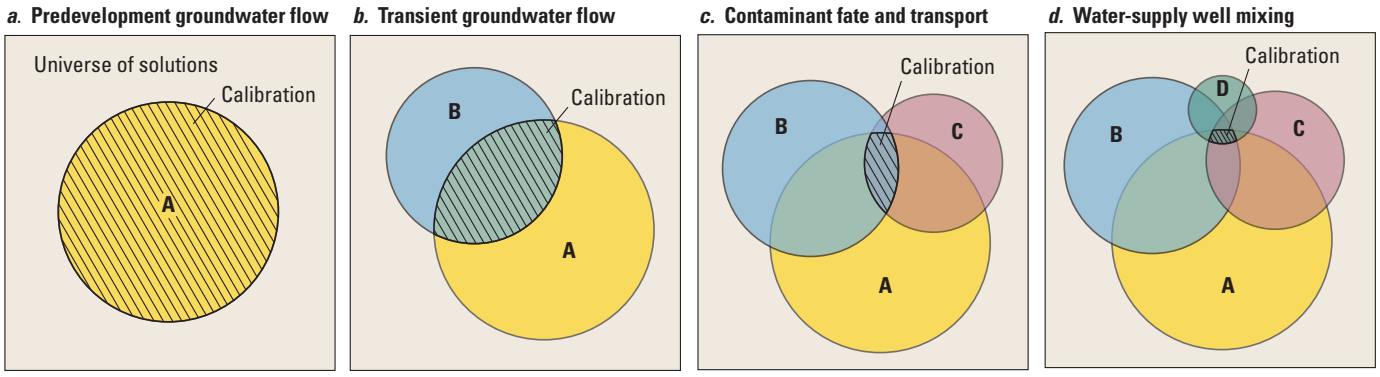

Figure ES3. Venn diagrams showing step-wise approach of model calibration used to estimate concentration of finished water: *(a)* predevelopment groundwater flow, *(b)* transient groundwater flow, *(c)* contaminant fate and transport, and *(d)* water-supply well mixing, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

concentrations of finished water was to develop a calibrated mixing model for uncontaminated and PCE-contaminated groundwater from water-supply wells. Feasible solutions depend on calibrated solutions for the previous three levels of model calibration, thereby resulting in even fewer calibrated solutions to the mixing model—circle "D" in Figure ES3*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 WTP that was distributed through the network of storage tanks and pipelines to residents of Tarawa Terrace and vicinity.

Results of Water-Modeling Analyses

The fate and transport (migration) of a contaminant in groundwater (level 3 of the step-wise calibration process described previously) is a complex physical phenomenon. There can be a variety of mathematical and modeling approaches used to address this process depending on the complexities being investigated. Modeling approaches can range from highly complex to very simple.

Two types of models were used to reconstruct the migration of PCE from its source to the Tarawa Terrace water-supply wells. The first model, MODFLOW-96/MT3DMS (Harbaugh and McDonald 1996; Zheng and Wang 1999), simulated transient groundwater flow and PCE as a single contaminant dissolved in groundwater. The second model, TechFlowMP (Jang and Aral 2007) considered PCE and its degradation by-products of TCE, 1,2-tDCE, and VC in both the dissolved phase (in groundwater) and the vapor phase (i.e., in the unsaturated zone above the water table). Both approaches yielded similar results for the concentrations of PCE at water-supply wells (Figure ES4*a*). Once the concentrations of PCE and PCE degradation by-products were simulated at water-supply wells, a mixing model based on the principles of continuity and conservation of mass (Masters 1998) was used to determine the concentration of PCE and degradation by-products in finished water delivered to residents of Tarawa Terrace from the WTP (Figure ES4*b*). Results obtained using the historical reconstruction process and modeling analyses indicate that contamination of water-supply well TT-26 at a concentration exceeding the maximum contaminant level (MCL) for PCE of 5 micrograms per liter (µg/L) occurred during January 1957. Finished water delivered from the Tarawa Terrace WTP exceeded the MCL for PCE during November 1957. Simulation of PCE degradation by-products showed that the concentration of TCE in finished water delivered from the WTP ranged from about 1–10 µg/L and was generally below the MCL for TCE of 5 µg/L (Figure ES4*b*).

The models and model results described above are based on limited field data and literature-derived values. Therefore, the models and results are characterized by uncertainty (lack of knowledge about specific factors) and variability (observed differences that can be attributed to differences in model parameters). This gives rise to the question, what confidence does ATSDR have in the historically reconstructed estimates of concentration such as results shown in Figure ES4? To answer this question and address issues of uncertainty and variability, ATSDR and its partners conducted exhaustive sets of additional simulations to estimate (quantify) confidence in models and their results.

One approach used to conduct these additional simulations and estimate confidence in model results is referred to as a probabilistic analysis. This method uses a procedure called Monte Carlo analysis (also referred to as Monte Carlo simulation). This is 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). Applying a probabilistic analysis to the groundwater flow and fate and transport models (MODFLOW-96 and MT3DMS, respectively) described previously allowed water modelers to express results for PCE concentration in finished water in terms of a range of results and the confidence one has in those results.

An example of probabilistic results derived by using Monte Carlo analysis is shown in Figure ES5. In this illustration, the concentration of PCE in finished water is shown as a range of most likely values for each month that the Tarawa Terrace WTP was in operation—January 1953–February 1987. As can be seen, the probabilistic results form a very narrow range or band around simulated concentration values obtained from running the groundwater-flow and fate and transport models without considering uncertainty and variability (referred to as the deterministic or single-value output approach). The range of PCE concentrations in finished water for each month of WTP operations represents 95 percent of

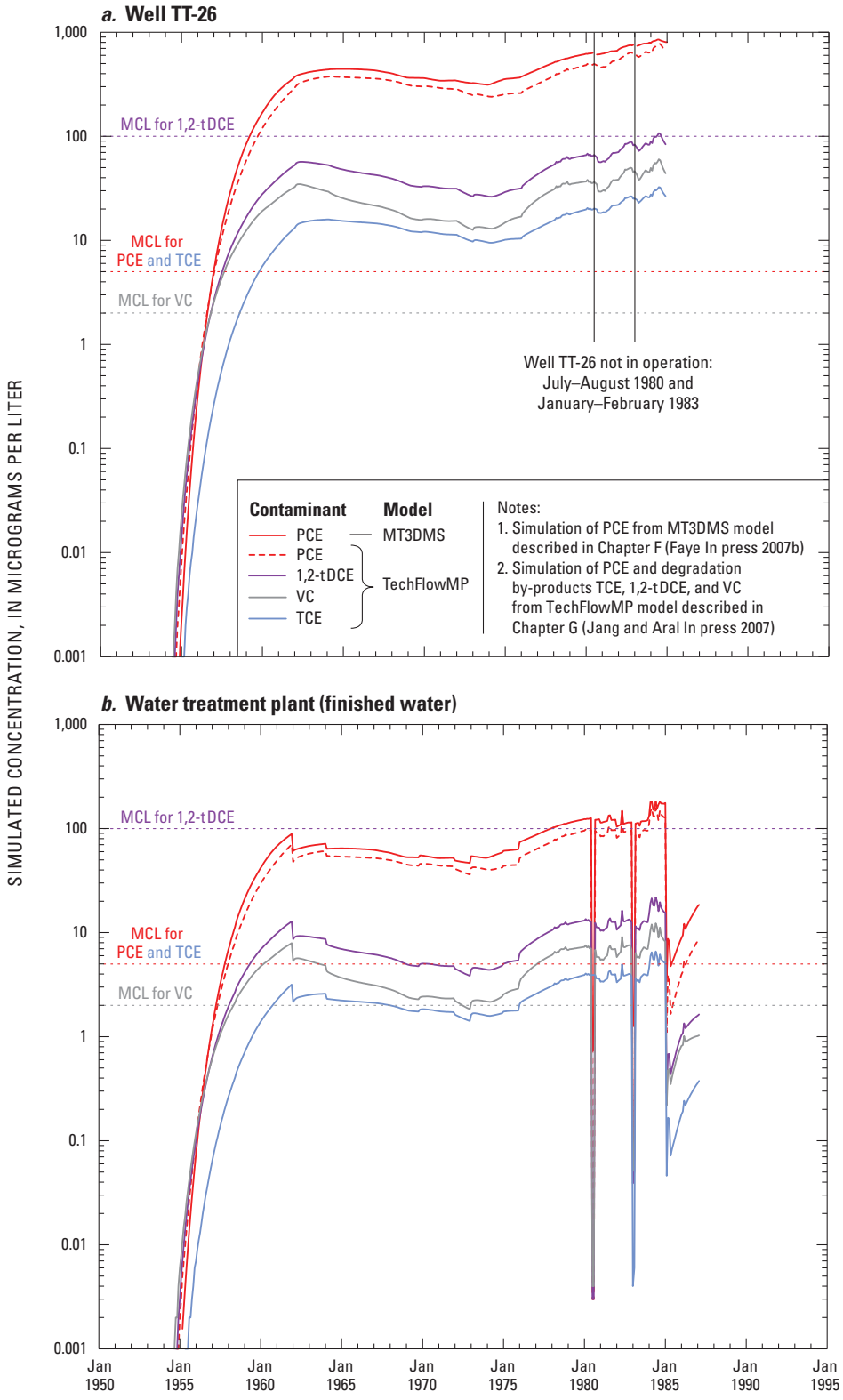

Figure ES4. Simulated concentration of tetrachloroethylene (PCE) and degradation by-products trichloroethylene (TCE), trans-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at *(a)* water-supply well TT-26 and *(b)* water treatment plant (finished water), Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [MCL, maximum contaminant level—effective dates for MCLs are as follows: VC and TCE, January 9, 1989; PCE and 1,2-tDCE, July 6, 1992 (40 CFR, Section 141.60, Effective Dates, July 1, 2002, ed.)]

Monte Carlo simulations (yellow band in Figure ES5). That is, there is a 95 percent probability that PCE concentrations in finished water delivered to residents of Tarawa Terrace from the WTP were within the band or range of values shown in Figure ES5 for each month that the WTP was operating.

Two specific results shown in Figure ES5 are worthy of further explanation. First, PCE concentrations in WTP finished water most likely exceeded the MCL for PCE of 5 µg/L for the first time during October 1957–August 1958 (95 percent probability). This range includes the date of November 1957 derived without considering uncertainty and variability. Second, the PCE concentration in 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 calibrated value of 176 µg/L (derived without considering uncertainty and variability) and the maximum measured value of 215 µg/L. 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.

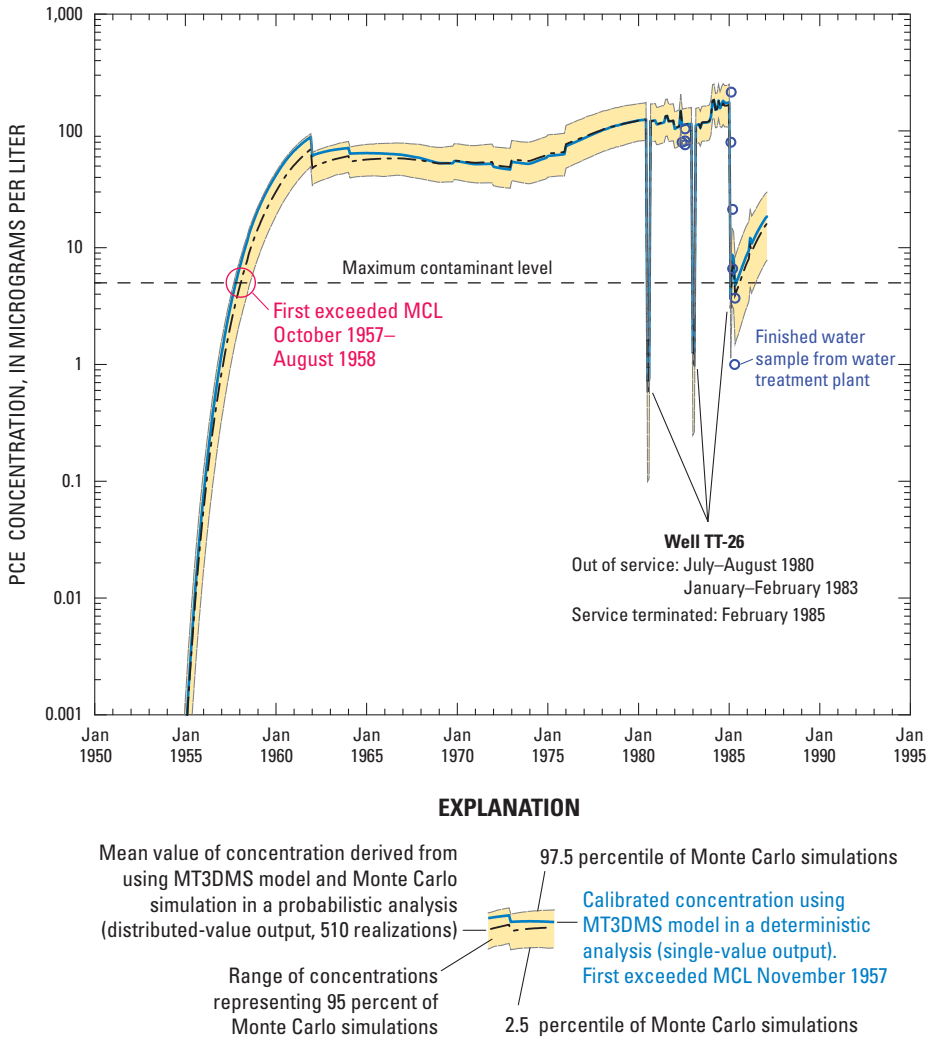

Figure ES5. Concentrations of tetrachloroethylene (PCE) in finished water at the water treatment plant derived from probabilistic analysis using Monte Carlo simulation, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [MCL, maximum contaminant level]

Conclusions

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

1. PCE concentrations exceeded the MCL of 5 µg/L at water-supply well TT-26 for 333 months—January 1957–January 1985;
2. The maximum simulated PCE concentration of well TT-26 exceeded 850 µg/L;
3. PCE concentrations exceeded the MCL of 5 µg/L in finished water at the Tarawa Terrace WTP for 346 months—November 1957–February 1987;
4. The maximum simulated PCE concentration in finished water from the Tarawa Terrace WTP exceeded 180 µg/L;
5. PCE concentrations in finished water exceeding the MCL of 5 µg/L at the Tarawa Terrace WTP could have been delivered as early as December 1956. Based on probabilistic analyses, the most likely dates that finished water first exceeded the MCL ranged from October 1957 to August 1958 (95 percent probability), with an average first exceedance date of November 1957; and
6. Exposure to PCE-contaminated drinking water ceased after February 1987.

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 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.

How certain is ATSDR that finished water exceeding the 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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Glossary and Abbreviations

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

ATSDR—Agency for Toxic Substances and Disease Registry

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)

DCE—1,1-dichloroethylene

1,2-t DCE—*trans*-1,2-dichloroethylene or *trans*-1,2-dichloroethene

degradation by-product—see biodegradation

DVD—digital video disc

epidemiological study—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

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

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

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

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

MODFLOW-96—three-dimensional groundwater-flow model, 1996 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—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

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

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

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

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

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

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

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

uncertainty—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

USEPA—U.S. Environmental Protection Agency

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

VC—vinyl chloride or chlorethene

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

VOC—volatile organic compound; an organic chemical compound 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

water-distribution system—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

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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