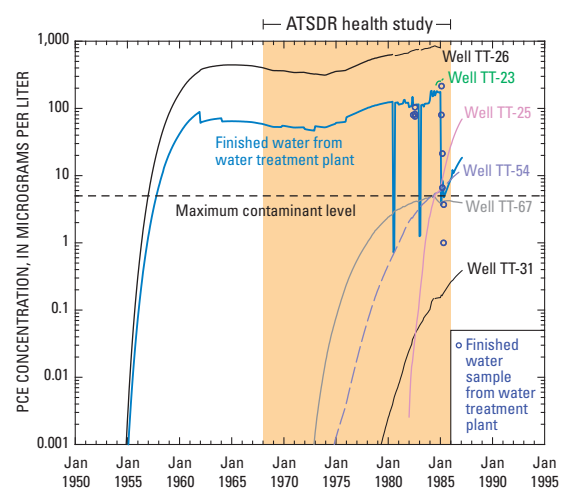
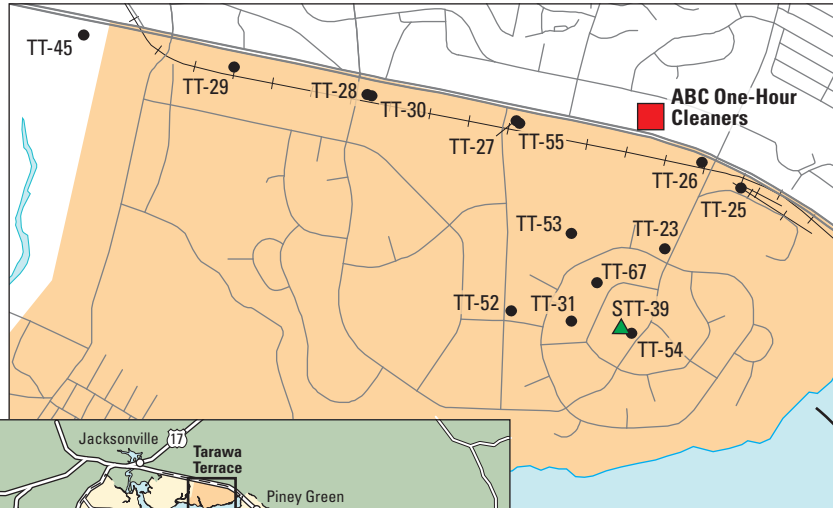


Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions

Chapter G: Simulation of Three-Dimensional Multispecies, Multiphase Mass Transport of Tetrachloroethylene (PCE) and Associated Degradation By-Products



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

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

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

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

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

**Analyses of Groundwater Flow, Contaminant Fate and Transport,
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Historical Reconstruction and Present-Day Conditions**

**Chapter G: Simulation of Three-Dimensional Multispecies,
Multiphase Mass Transport of Tetrachloroethylene (PCE) and
Associated Degradation By-Products**

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Foreword

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

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

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

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

An electronic version of this report, *Chapter G: Simulation of Three-Dimensional Multispecies, Multiphase Mass Transport of Tetrachloroethylene (PCE) and Associated Degradation By-Products*, will be made available on the ATSDR Camp Lejeune Web site at <http://www.atsdr.cdc.gov/sites/lejeune/index.html>. Readers interested solely in a summary of this report or any of the other reports should refer to *Chapter A: Summary of Findings* that also is available at the ATSDR Web site.

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Conversion Factors

Multiply	By	To obtain
Length		
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
Density		
kilogram per cubic meter (kg/m ³)	0.06242	pound per cubic foot (lb/ft ³)

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.

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

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

Glossary and Abbreviations

ATSDR	Agency for Toxic Substances and Disease Registry	
DCE	1,1-DCE	1,1-dichloroethylene or 1,1-dichloroethene
	1,2-DCE	1,2-dichloroethylene or 1,2-dichloroethene
	1,2-cDCE	<i>cis</i> -1,2-dichloroethylene or <i>cis</i> -1,2-dichloroethene
	1,2-tDCE	<i>trans</i> -1,2-dichloroethylene or <i>trans</i> -1,2-dichloroethene
GSBC	ground-surface boundary coefficient	
MCL	maximum contaminant level	
MESL	Multimedia Environmental Simulations Laboratory	
MODFLOW-96	A three-dimensional groundwater-flow model, 1996 version, developed by the U.S. Geological Survey	
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	
PCE	tetrachloroethene, tetrachloroethylene, 1,1,2,2-tetrachloroethylene, or perchloroethylene; also known as PERC® or PERK®	
PS-A	Pumping Schedule A	
PS-B	Pumping Schedule B	
PS-0	Original Pumping Schedule	
TechFlow MP	A three-dimensional multispecies, multiphase mass transport model developed by the Multimedia Environmental Simulations Laboratory at the Georgia Institute of Technology, Atlanta, Georgia	
TCE	1,1,2-trichloroethene, 1,1,2-trichloroethylene, or trichloroethylene	
USEPA	U.S. Environmental Protection Agency	
VC	vinyl chloride	
VOCs	volatile organic compounds	
WTP	water treatment plant	

Note: The maximum contaminant level (MCL) is 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.).

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

Chapter G: Simulation of Three-Dimensional Multispecies, Multiphase Mass Transport of Tetrachloroethylene (PCE) and Associated Degradation By-Products

By Wonyong Jang¹ and Mustafa M. Aral¹

Abstract

Two of three water-distribution systems that have historically supplied drinking water to family housing at U.S. Marine Corps Base Camp Lejeune, North Carolina, were contaminated with volatile organic compounds (VOCs). Tarawa Terrace was contaminated mostly with tetrachloroethylene (PCE), and Hadnot Point was contaminated mostly with trichloroethylene (TCE). Because scientific data relating to the harmful effects of VOCs on a child or fetus are limited, the Agency for Toxic Substances and Disease Registry (ATSDR), an agency of the U.S. Department of Health and Human Services, is conducting an epidemiological study to evaluate potential associations between in utero and infant (up to 1 year of age) exposures to VOCs in contaminated drinking water at Camp Lejeune and specific birth defects and childhood cancers. The study includes births occurring during the period 1968–1985 to women who were pregnant while they resided in family housing at Camp Lejeune. Because limited measurements of contaminant and exposure data are available to support the epidemiological study, ATSDR is using modeling techniques to reconstruct historical conditions of groundwater flow, contaminant fate and transport, and the distribution of drinking water contaminated with VOCs delivered to family housing areas. This report, Chapter G, describes the three-dimensional simulation of the fate, degradation, and advective dispersive transport of PCE and associated degradation by-products—TCE, *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC)—within the Tarawa Terrace aquifer and Castle Hayne aquifer system at Tarawa Terrace and vicinity. The analyses and results presented in this chapter refer solely to Tarawa Terrace and vicinity. Future analyses and reports will present information and data about contamination of the Hadnot Point water-distribution system.

Migration of PCE and three associated VOCs—TCE, 1,2-tDCE, and VC—from the vicinity of ABC One-Hour

Cleaners to Tarawa Terrace water-supply wells was simulated using the model TechFlowMP. This model uses hydrogeologic data and calibrated model parameter values derived from the application of the MODFLOW-96 groundwater-flow model at Tarawa Terrace and vicinity described in Faye and Valenzuela (2007). Simulated contaminant mass loading at the ABC One-Hour Cleaners site occurred at a constant rate of 1,200 grams per day using monthly stress periods representing the period January 1953–December 1984. Mass loading occurred at a depth from 0 to 4 meters (from 0 to 13 feet) below ground surface at the approximate location of ABC One-Hour Cleaners. The duration of the simulation covers the period January 1951–December 1994. Until 1984, the bulk of simulated PCE-contaminated groundwater supplied to the Tarawa Terrace water treatment plant (WTP) was contributed by water-supply well TT-26.

The calibrated pumping rate schedule of Faye and Valenzuela (2007) is identified as the “Original Pumping Schedule” (PS-O) in this chapter report. Flow-weighted average concentrations of PCE and associated degradation by-products (TCE, 1,2-tDCE, and VC) assigned to finished drinking water at the Tarawa Terrace WTP were computed using a materials mass balance model (simple mixing). Based on using the pumping rates of PS-O for the TechFlowMP model simulations and the materials mass balance model for finished drinking water concentrations at the Tarawa Terrace WTP, the following conclusions are made:

- The breakthrough of PCE at well TT-26—the nearest water-supply well to ABC One-Hour Cleaners—occurred during February 1957 at the current maximum contaminant level (MCL) concentration for PCE of 5 micrograms per liter ($\mu\text{g/L}$); simulated average and maximum PCE concentrations at well TT-26 were 332 and 775 $\mu\text{g/L}$, respectively.
- Contaminant breakthrough at the future location of water-supply well TT-23 occurred during January 1978, although well TT-23 was not operational until August 1984, based on PS-O operations.

¹ Multimedia Environmental Simulations Laboratory, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, Georgia.

- Computed maximum PCE concentration in finished drinking water at the Tarawa Terrace WTP was 158 µg/L during June 1984; the maximum measured PCE concentration was 215 µg/L during February 1985. The average PCE concentration in finished water that exceeded the current MCL for PCE of 5 µg/L was 57 µg/L during the period January 1958–February 1985.
- Simulation of PCE degradation by-products indicated that maximum concentrations of TCE, 1,2-tDCE, and VC were 33, 107, and 60 µg/L, respectively, 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.
- Simulation of PCE degradation by-products in finished drinking water at the Tarawa Terrace WTP indicated that maximum concentrations of TCE, 1,2-tDCE, and VC were 7, 22, and 12 µg/L, respectively; measured concentrations of TCE and 1,2-tDCE on February 11, 1985, were 8 and 12 µg/L, respectively.

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, 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 (Maslia et al. 2007). ATSDR is using water-modeling techniques to provide the epidemiological study with quantitative estimates of monthly contaminant concentrations in finished drinking water² 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).

This report (Chapter G of the Tarawa Terrace report series) describes the three-dimensional simulation of the fate, degradation, and advective-dispersive transport of tetrachloroethylene (PCE) and associated VOC degradation by-products—trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC). Simulations

² 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 concentration 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 2008). Herein, the term *finished water* will be used.

were conducted using the TechFlowMP model code (Jang and Aral 2005b).³ Results are reported for the Tarawa Terrace aquifer (for the most part, containing the unsaturated zone) and the Castle Hayne aquifer system, at and in the vicinity of Tarawa Terrace, as part of the overall historical reconstruction process.

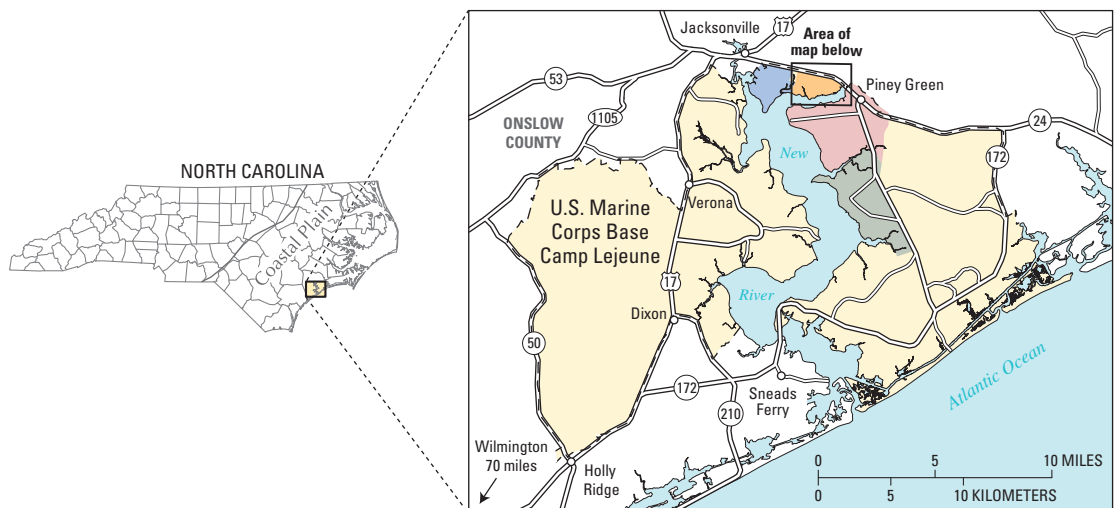
Background

U.S. Marine Corps Base Camp Lejeune is located in the Coastal Plain of North Carolina, in Onslow County, south of the City of Jacksonville and about 70 miles northeast of the City of Wilmington, North Carolina (Figure G1). Operations began at Camp Lejeune during the 1940s. The Tarawa Terrace housing area was constructed during 1951 and was subdivided into housing areas I and II. The general area of Tarawa Terrace is bordered on the east by Northeast Creek, to the south by New River and Northeast Creek, and generally to the west and north by drainage boundaries of these streams.

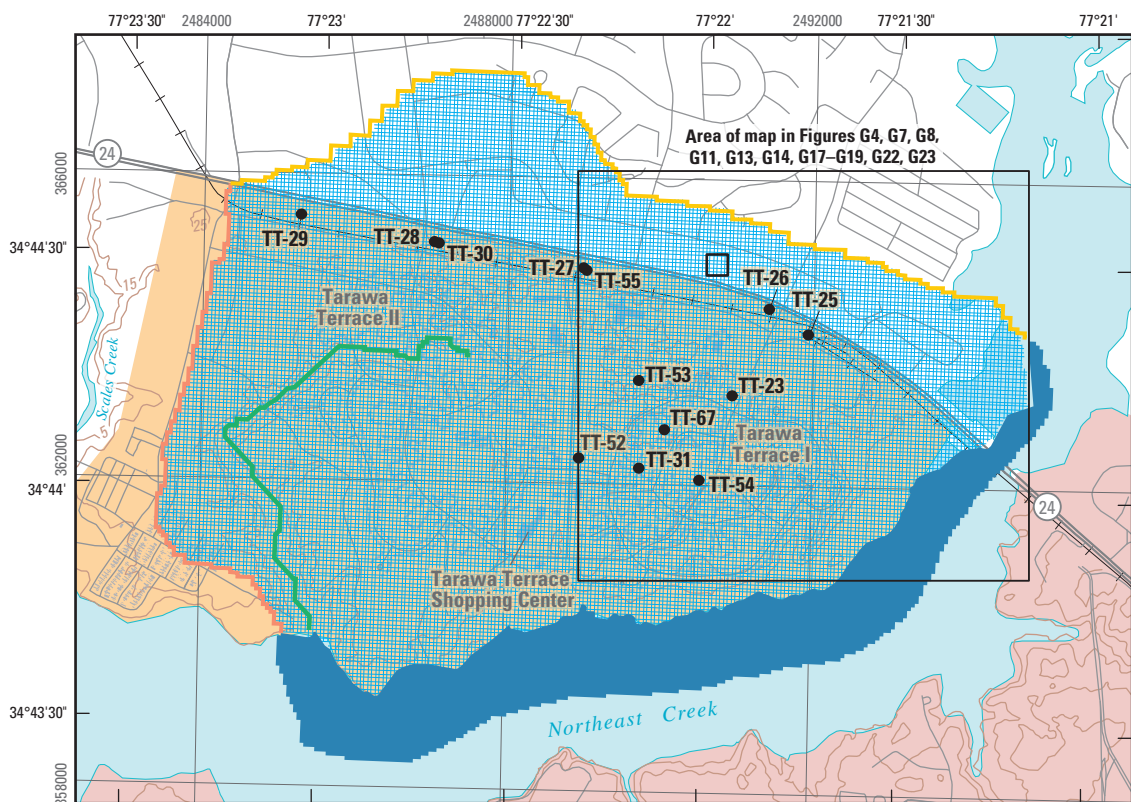
Contamination of groundwater by PCE, at and in the vicinity of Tarawa Terrace, has been linked to the release of PCE from ABC One-Hour Cleaners (Shiver 1985; Bozzini et al. 2007; Faye and Green 2007; Maslia et al. 2007). PCE is one of the most frequently detected organic compounds in contaminated groundwater, and can be biologically transformed through complicated dechlorination processes (Lorah et al. 1997; Lawrence 2007). Under anaerobic conditions in the subsurface system, PCE can be transformed to TCE, to dichloroethylenes (DCEs), to VC, and to ethylene. Biological transformation of PCE is of concern due to the toxicity of the by-products of PCE. Under the U.S. Environmental Protection Agency's (USEPA 1996, 1999) proposed cancer guidelines, TCE can be characterized as "highly likely to produce cancer in humans" (USEPA 2001). DCEs have adverse effects on health (ATSDR 1995, 1997), and VC is known as a human carcinogen (Montgomery 2000; ATSDR 2006). The field data collection efforts and the analysis of contaminated groundwater samples indicate that TCE and DCEs were present in water samples collected from water-supply wells TT-23 and TT-26 (Faye and Green 2007).⁴ The studies on biological transformation of PCE and its associated compounds are important to exposure and epidemiological studies conducted by ATSDR. To investigate the effect of biological processes on contaminant transport and groundwater contamination, the analyses described herein take into account the sequential dehalogenation of PCE—for example, PCE→TCE→1,2-tDCE→VC—under anaerobic conditions within the water phase in the unsaturated and saturated zones.

³ A copy of the report describing the development of the TechFlowMP model (Jang and Aral 2005b), prepared in Adobe® Portable Document Format (PDF) is contained on the computer disc—read only memory (CD-ROM) media accompanying this report.

⁴ TCE also is used in some dry-cleaning processes. Based on the legal deposition from the owner of ABC One-Hour Cleaners (Melts 2001), however, only PCE was used at ABC One-Hour Cleaners. Therefore, any TCE detected at Tarawa Terrace water-supply wells or in Tarawa Terrace WTP finished water occurred because of the degradation of PCE.



Base from Camp Lejeune GIS Office, June 2003



Base from U.S. Marine Corps and U.S. Geological Survey digital data files
Map coordinates are North Carolina State Plane coordinates
North American Datum of 1983

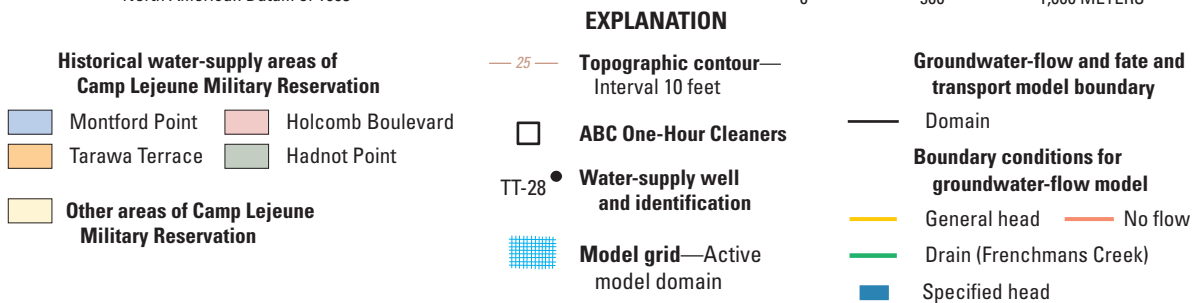


Figure G1. U.S. Marine Corps Base Camp Lejeune, water-supply wells, Tarawa Terrace Shopping Center, ABC One-Hour Cleaners, and groundwater-flow model grid and model boundaries, Onslow County, North Carolina.

Purpose of Study

The purpose of this study is to investigate the fate, degradation, and transport of PCE and associated VOC degradation by-products—TCE, 1,2-tDCE, and VC—within the Tarawa Terrace aquifer and Castle Hayne aquifer system at and in the vicinity of Tarawa Terrace. The study applies the numerical model TechFlowMP (Jang and Aral 2005b) to the Tarawa Terrace area. Calibration of the fate and transport model is based on the spatial and temporal distributions of contaminants PCE, TCE, and 1,2-tDCE at selected water-supply well locations within the Castle Hayne aquifer system. Thus, the application of the TechFlowMP model was used 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 and saturated zones.

Biological Transformation

Chlorinated VOCs such as PCE and TCE in a ground-water system may be in contact with indigenous microorganisms, which can biologically transform compounds (Vogel et al. 1987; Lawrence 2007). Biological transformations of chlorinated hydrocarbons follow a complicated process and depend on contaminant chemical properties, concentrations, and subsurface environmental parameters—such as oxygen, microorganisms, oxidation-reduction potential, and temperature. For example, under anaerobic conditions, PCE can be transformed to TCE, to DCEs, to VC (Vogel and McCarty 1985), and to ethene (Freedman and Gossett 1989) as shown in Figure G2. Among three DCE isomers produced theoretically, *cis*-1,2-dichloroethylene (1,2-cDCE) is the most common by-product, and 1,1-dichloroethylene (1,1-DCE) is the least prevalent one (Wiedemeier 1998). At some sites, the dechlorination of PCE and TCE has produced more 1,2-tDCE than 1,2-cDCE (Christiansen et al. 1997; Miller et al. 2005). For example, at a TCE-contaminated site in Key West, Florida, the ratio of 1,2-tDCE to 1,2-cDCE was greater than 2 (SWMU9 2002). Griffin et al. (2004) reported that the ratio reached 3.5. Among the three isomers of DCEs, 1,2-tDCE is selected as a representative of DCEs in this study because data on field measurements for 1,2-tDCE are available at and in the vicinity of Tarawa Terrace (Maslia et al. In press 2008a; Sautner et al. In press 2008). The transformation of TCE and DCEs requires a low oxidation-reduction potential (Vogel et al. 1987; Freedman and Gossett 1989). When TCE is dechlorinated under methanogenic conditions, a competition between methanogenesis and dechlorination of TCE for electron donors occurs (Wu et al. 1998). During reductive dechlorination of PCE, chlorinated hydrocarbons are used as electron acceptors, not as sources of carbon, and a chlorine atom is removed and replaced with a hydrogen atom (Wiedemeier 1998). Wu et al. (1998) studied the effect of different organic

materials as a substrate or an electron donor on dechlorination of TCE under methanogenic conditions. They reported that the fraction of a substrate used for dechlorination may increase when the substrate is slowly biodegraded. Davis et al. (2002) investigated the rate coefficients and associated half-lives for biodegradation of TCE, DCEs, and VC. In their study, higher concentration of halogenated compounds showed a lower degradation rate and longer half-life. Davis et al. (2002) found a diverse group of microorganisms, including iron reducers and anaerobic heterotrophs, in the anaerobic zone where reductive dechlorination of TCE occurred. In a field study of contaminated sites, Dyer (2003) found that parent and daughter contaminants exist in both the unsaturated and the saturated zones. DCEs and VC can be detoxified by aerobic and anaerobic microorganisms, generating benign products such as ethylene, inorganic chloride, and carbon dioxide (Vogel and McCarty 1985; Freedman and Gossett 1989; Coleman et al. 2002; He et al. 2003). Ethene as a by-product of VC is nontoxic and highly biodegradable, thus ethene is not considered in this study.

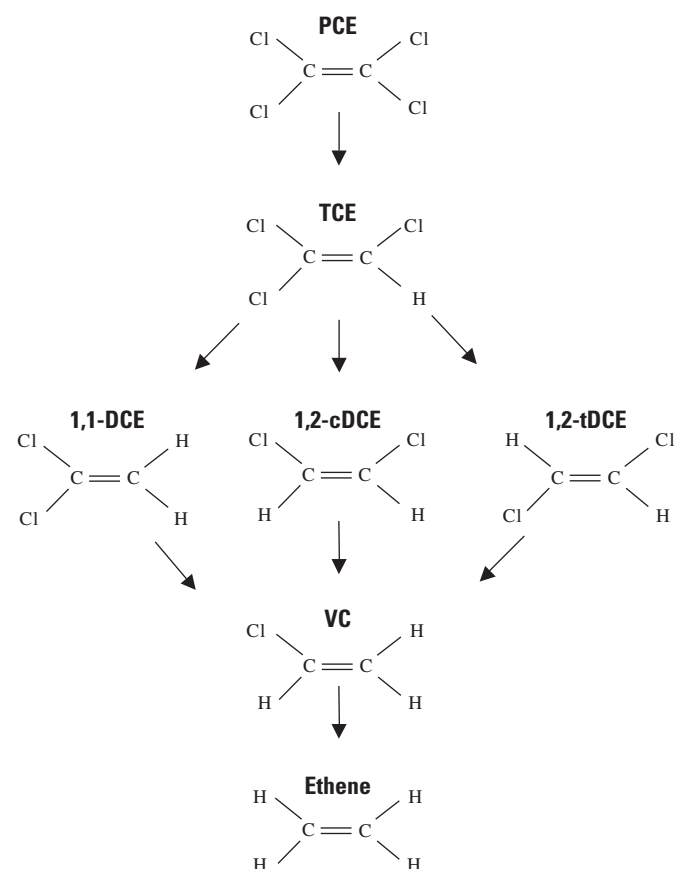


Figure G2. Reductive dehalogenation of tetrachloroethylene (PCE) (modified from Lorah et al. 1997). [TCE, trichloroethylene; 1,1-DCE, 1,1-dichloroethylene; 1,2-cDCE, *cis*-1,2-dichloroethylene; 1,2-tDCE, *trans*-1,2-dichloroethylene; VC, vinyl chloride; Cl, chlorine; C, carbon; H, hydrogen]

Biological degradation kinetics of contaminants are very important in determining natural attenuation of contaminants, and they also are required as components of fate and transport models (Alvarez-Cohen and Speitel 2001). Biological processes, which affect contaminant fate in the subsurface, are highly complex and are nonlinearly linked with a variety of biochemical and environmental factors—such as competition, inhibition, energy and carbon source, and heterogeneity of subsurface systems (Vogel et al. 1987; Murphy et al. 1997; Murphy and Ginn 2000; Alvarez-Cohen and Speitel 2001; Cupples et al. 2004; Yu et al. 2005). Therefore, it may be almost impossible to understand entirely and to express all biological reaction kinetics. In general, first-order kinetics is used to express reductive dechlorination of chlorinated hydrocarbons (Smith et al. 1997; Clement et al. 2000; Alvarez-Cohen and Speitel 2001). In field-scale applications, Clement et al. (2000) used first-order models to represent the sequential biotransformations of PCE and TCE in the saturated zone. The first-order model is reasonable for most natural attenuation modeling (Wiedemeier 1998; Jang and Aral 2005a) and for biodegradation at low-pollutant concentration in the groundwater flow (Schmidt et al. 1985; Jang and Aral 2007d). In this study, a first-order kinetics is used to describe sequential dechlorination of PCE, TCE, 1,2-tDCE, and VC. Reaction rates of contaminants may vary spatially across contaminated zones, and depend on the type and amount of bacteria present in the aquifer and availability of electron donors and carbon source. Biological processes of VOCs can occur in both saturated and unsaturated zones. Further, bioreactions of VOCs in the unsaturated zone make a parent and its daughter contaminants coexist within water and gas phases (Borch et al. 2003).

Governing Equations and Numerical Methods

The migration of contaminants in subsurface systems can be expressed in terms of two fundamental equations: (1) multiphase flow equation and (2) contaminant transport equation. These equations are coupled in terms of pressures, saturation levels, and contaminant concentrations. In this study, a subsurface system consisting of two fluid phases (water and gas) and the soil phase (solid soil particles) is considered. To express nonequilibrium mass transfer processes for dissolution, volatilization, and partitioning of contaminants, first-order relationships are used.

Multiphase Flow Equation

A simultaneous flow of groundwater and gas through a porous soil matrix is identified as multiphase flow in subsurface systems. Multiphase flow and contaminant transport equations are coupled in terms of pressures, saturation levels, and contaminant concentrations. The governing equation

of a multiphase flow (Bear and Bachmat 1990; Jang and Aral 2007b) can be written as

$$\frac{\partial(\phi s_f \rho_f)}{\partial t} = \nabla \left[\frac{\rho_f k_m k_{rf}}{\mu_f} (\nabla P_f + \rho_f g \nabla z) \right] + I_f \quad f = w, g, \quad (1)$$

where

- f is mobile fluids (w : water and g : gas),
- ϕ is porosity (L^0),
- s is fluid saturation (L^0),
- ρ is fluid density (ML^{-3}),
- μ is dynamic viscosity ($ML^{-1}T^{-1}$),
- k_r is relative permeability (L^0),
- k_m is intrinsic permeability tensor for soil media (L^2),
- P is fluid pressure ($ML^{-1}T^{-2}$),
- g is the gravitational constant (LT^{-2}),
- z is elevation (L), and
- I_f is a sink/source term for the gas phase due to partitioning processes of contaminants between phases ($ML^{-3}T^{-1}$).⁵

For a two-mobile-phase (gas-water) system, relative permeabilities of water and gas phases can be written in terms of effective water saturation (van Genuchten 1980; Parker et al. 1987),

$$k_{rw} = s_{we}^{1/2} \left[1 - \left(1 - s_{we}^{1/m} \right)^m \right]^2 \quad \text{for water phase and} \quad (2)$$

$$k_{rg} = (1 - s_{we})^{1/2} \left(1 - s_{we}^{1/m} \right)^{2m} \quad \text{for gas phase,} \quad (3)$$

with

$$s_{we} = \left[1 + \left(\alpha_{gw} \psi_{cgw} \right)^n \right]^{-m} \quad \psi_{cgw} > 0, \quad \text{and} \quad (4a)$$

$$s_{we} = 1.0 \quad \psi_{cgw} \leq 0, \quad (4b)$$

where

- s_{we} is the effective water-phase saturation (L^0),
- α_{gw} , n , and m are empirical parameters (L^0),
- ψ_{cgw} is the gas-water capillary pressure head (L), and
- ψ_f is water-equivalent pressure head of each phase (L).

⁵ For equations in this report (Chapter G), L^0 represents a dimensionless parameter, M represents mass units, L represents length units, and T represents time units.

Contaminant Transport Equation

The equation for advective-dispersive transport of multiple species in water and gas phases (Jang and Aral 2007b) can be written as

$$\begin{aligned} \frac{\partial(\phi s_f C_f^i)}{\partial t} &= \nabla(\phi s_f D_f^i \nabla C_f^i) \\ &\quad - \nabla(q_f C_f^i) \pm I_{f,MT}^i + I_{f,BT}^i \\ &\quad + I_{source}^i ; \quad f = w, g, \end{aligned} \quad (5)$$

where

- i is the index for contaminants (PCE, TCE, 1,2-tDCE, and VC),
- f is the index for the fluid phase,
- D is the dispersion tensor (L^2T^{-1}) term,
- q is the Darcy flux (LT^{-1}) term,
- I_{MT}^i is the interphase mass transfer ($ML^{-3}T^{-1}$),
- I_{BT}^i is biotransformation ($ML^{-3}T^{-1}$), and
- I_{source}^i is the source of contaminants ($ML^{-3}T^{-1}$).

Darcy velocity for each fluid phase can be written

$$q_f = -\frac{k_m k_{rf}}{\mu_f} \rho_w g \left(\nabla \psi_f + \frac{\rho_f}{\rho_w} \nabla z \right) ; \quad f = w, g. \quad (6)$$

The dispersion tensor of a species can be defined by Bear (1972) as

$$\begin{aligned} D_{f,mm}^i &= \alpha_T |v_f| \delta_{mm} + (\alpha_L - \alpha_T) \frac{v_{f,m} v_{f,n}}{|v_n|} \\ &\quad + \tau_f D_f^* \delta_{mm} \quad m, n = x, y, z, \end{aligned} \quad (7)$$

where

- α_L is the longitudinal dispersivity of the soil media (L),
- α_T is the transversal dispersivity of the soil media (L),
- v_f is the pore velocity (LT^{-1}),
- τ is tortuosity (L^0),
- D^* is a molecular diffusion coefficient (L^2T^{-1}), and
- δ_m is the Kronecker delta (L^0).

The tortuosity can be estimated using an empirical equation developed by Millington and Quirk (1961):

$$\tau_f = (\phi s_f)^{7/3} / \phi^2. \quad (8)$$

Weber and DiGiano (1996) suggested that first-order equations are widely applicable for description of various environmental reactions such as mass transfer between phases. By applying first-order relationships to water-gas partitioning processes of contaminants, mass transfer between water and gas phases can be written as

$$I_{MT}^i = \phi s_g \lambda_H^i (C_g^i - H^i C_w^i), \quad (9)$$

where

- λ_H is a first-order mass transfer coefficient between water and gas phases (T^{-1}), and
- H is a dimensionless Henry's law constant.

In sequential bioreactions of compounds in water phase, the reduction in a parent compound through a biotransformation implies an increase of concentration of its daughter compound. In terms of the daughter compound, biotransformation processes with first-order kinetics can be written as

$$I_{w,BT}^i = \phi s_w \lambda_B^{i-1} C_w^{i-1} - \phi s_w \lambda_B^i C_w^i, \quad (10)$$

where

- $i-1$ is the parent compound,
- i is the daughter compound, and
- λ_B is a first-order biological transformation coefficient (T^{-1}).

In this study, biological reactions are considered to be occurring only in the water phase because most microorganisms for biological reactions exist in the water phase, and bioreaction coefficients were assumed to be constant during each simulation within a modeling domain.

Four types of boundary conditions (Mendoza and Frind 1990; Jang and Aral 2005b) can be considered for Equation 5 as follows:

(i) Dirichlet (type I) condition is

$$C_f^i = C_{fo}^i ; \quad f = w, g, \quad (11)$$

where

- C_{fo} is a specified value of contaminant concentration in fluid phase on the boundaries.

(ii) Neuman (type II) condition is

$$\phi s_f D_f^i \frac{\partial C_f^i}{\partial \vec{n}} = b_{fo}^i ; \quad f = w, g, \quad (12)$$

where

- b_{fo} is a specified dispersive flux of a contaminant on the boundaries, and
- \vec{n} is a unit vector normal to the boundaries.

(iii) Cauchy (type III) condition is

$$\left(-\phi s_f D_f^i \nabla C_f^i + q_f C_f^i\right) \vec{n} = q_{fn} C_{fo}^i \quad ; \quad f = w, g, \quad (13)$$

where

q_{fn} is Darcy flux of water or gas phase on the boundaries.

In the gas phase, the release of vaporized organic contaminants into the atmosphere at the soil surface could play an important role in reducing a contaminant concentration in the subsurface (Jang and Aral 2007b). For the transport of vaporized contaminants, the ground surface is often treated as a stagnant boundary layer due to vegetation and surface roughness. The flux across the boundary layer can be represented as

$$b_{go} = \varepsilon_g \frac{D_g^i}{\delta_g} (C_{gs}^i - C_{atm}^i), \quad (14)$$

where

b_{go} is a contaminant flux,
 ε_g is a ground-surface boundary coefficient (GSBC, $0 \leq \varepsilon_g \leq 1$),
 δ_g is the thickness of a stagnant boundary layer of gas phase at the ground surface,
 C_{gs} is a contaminant concentration in soil gas phase at the ground surface, and
 C_{atm} is a contaminant concentration at the top of the stagnant layer.

A ground-surface boundary coefficient (GSBC), ε_g , indicates resistance against contaminant diffusion due to low permeable ground surface and/or barriers at the surface. Atmospheric release of vaporized contaminants through the ground surface highly depends on the boundary condition used at the surface (Mendoza and Frind 1990; Jang and Aral 2007b). Pavement, buildings with foundations, grassy areas, and ponds on the ground surface could become barriers, which could prevent gas phase from escaping to the atmosphere; thus the vaporized contaminant escape into the atmosphere can be inhibited at different degrees. High water saturation levels near the ground surface also could reduce the contaminant flux from the subsurface to the atmosphere. To evaluate such ground-surface conditions, a GSBC was implemented in this study, which is a function of the ratio of an available open surface area to total surface area. If no barrier is present at the ground surface, the ground surface is assumed to be a completely open boundary, and free flux of vaporized PCE is simulated. Under such an environment, the GSBC is equal to one ($\varepsilon_g = 1$). On the contrary, if the ground surface is completely blocked and no contaminant flux into the atmosphere is allowed, the GSBC becomes zero ($\varepsilon_g = 0$). The C_{atm} usually is set to zero for the atmosphere.

Numerical Methods

A three-dimensional Galerkin-finite-element-based numerical model—TechFlowMP, developed by Jang and Aral (2005b)—was used to solve the multiphase flow and contaminant transport equations given in Equations 1 and 5. The Picard method was used in the iterative solution of the fluid flow equation. To improve the accuracy and overcome discontinuity problems in calculating the flow velocities, the method for obtaining globally continuous Darcy velocity, proposed by Yeh (1981), was used. Time derivatives in flow and transport equations are approximated by a finite-difference technique. This technique commonly uses the ε -family approximation. All simulations in this study used a fully implicit method for the numerical solution of flow equations and a semi-implicit Crank-Nicolson technique for the numerical solution of transport equations. Mass lumping of time-derivative mass matrices was used to improve the stability of the solution of nonlinear flow equations (Frind 1982; Celia et al. 1990; Rathfelder and Abriola 1994; Jang and Aral 2006). To reduce numerical difficulty due to coupling and nonlinearity in multiphase flow and transport equations, a sequentially iterative scheme was used. This iterative scheme solves a set of decoupled system equations (Diersch and Kolditz 2002; Jang and Aral 2007b). Mass balance calculations were conducted to determine temporal changes in contaminant mass within each phase and to verify mass conservation during simulations (Huyakorn and Pinder 1983).

Groundwater Flow

In the groundwater modeling stage of this study, the TechFlowMP model was used to simulate groundwater flow in both the unsaturated and saturated zones using a finite element method numerical scheme. By comparison, the MODFLOW-96 model (McDonald and Harbaugh 1984), described in the Chapter C report (Faye and Valenzuela 2007), simulates groundwater flow solely in the saturated zone using a finite-difference method numerical scheme. In this section, descriptions and discussions are provided about the model domain used for the TechFlowMP model simulations. Additionally, comparisons of simulated hydraulic head (potentiometric levels) derived from the TechFlowMP and MODFLOW-96 models are discussed.

Model Domain for Groundwater Flow and Contaminant Transport

The model domain grid for Tarawa Terrace and vicinity (Figure G1) initially was designed for MODFLOW-96 simulations, based on the geohydrologic framework of the Castle Hayne aquifer system at Tarawa Terrace and vicinity (Faye 2007a). The MODFLOW-96 modeling domain was

discretized using 270 columns and 200 rows of square cells—this represented a length of 50 feet per cell side. The modeling domain was vertically divided into seven layers representing the Tarawa Terrace aquifer and Castle Hayne aquifer system (Faye and Valenzuela 2007). Table G1 lists the hydrogeologic units of the Tarawa Terrace aquifer and Castle Hayne aquifer system and corresponding MODFLOW-96 model layers.

The MODFLOW-96 domain grid was imported into TechFlowMP and converted into the finite-element mesh format of TechFlowMP (Jang and Aral 2007a). MODFLOW-96 model layer 1 was divided vertically into five sublayers to simulate fluid flow and contaminant transport in the variably saturated zone (layers VSZ1–VSZ5) and one layer to simulate fluid flow and contaminant transport in the saturated zone using the TechFlowMP model. The effective water saturation of layers VSZ1–VSZ5 was determined by Equation 4,

based on the gas-water capillary pressure head. Corresponding model layers between TechFlowMP and MODFLOW-96 model domains are listed in Table G1. The grid for TechFlowMP consists of 359,346 nodes and 326,688 elements.⁶ The same hydrogeologic model parameter values and site conditions derived from MODFLOW-96 model calibration—for example, horizontal hydraulic conductivity, porosity, and infiltration (Faye and Valenzuela 2007)—were applied to TechFlowMP simulations. Additional model parameter-value requirements of the TechFlowMP model—unsaturated zone properties such as water-phase saturation, fluid saturation, and

⁶ Mathematical and numerical properties of nodes and elements used to discretize a model domain using the TechFlowMP model are provided in Jang and Aral (2005b). This reference is provided in Adobe® PDF format on the CD-ROM included with this report.

Table G1. Correlation between geologic and hydrogeologic units and model layers, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[—, not applicable; 1 foot = 0.3048 meter]

Geologic units ¹			Hydrogeologic units ²	Thickness ²		Model layers ³		
System	Series	Formation	Aquifer and confining unit	Range		MODFLOW-96 and MT3DMS	TechFlowMP	
				Feet	Meters			
Quaternary	Holocene Pleistocene	Undifferentiated						
		Pliocene	Absent					
			Absent					
		Miocene	Belgrade Formation	Brewster Boulevard aquifer			Absent	
	Brewster Boulevard confining unit					Absent		
	Tarawa Terrace aquifer			10–60	3–18	1	*VSZ1–VSZ5	
	Tarawa Terrace confining unit			5–20	2–6	1		
Tertiary	Oligocene	River Bend Formation	Upper Castle Hayne aquifer–River Bend unit	10–55	3–17	1	1	
		Eocene	Castle Hayne Formation	Local confining unit	6–16	2–5	2	2
				Upper Castle Hayne aquifer–Lower unit	10–45	3–14	3	3
				Middle Castle Hayne confining unit	8–30	2–9	4	4
				Middle Castle Hayne aquifer	30–90	9–27	5	5
				Lower Castle Hayne confining unit	10–30	3–9	6	6
				Lower Castle Hayne aquifer	25–85	8–26	7	7
		Paleocene	Beaufort Formation	Beaufort confining unit	—	—	Base of model	

¹ Refer to the Chapter B report (Faye 2007) for details

² Refer to the Chapter C report (Faye and Valenzuela 2007) for details

³ MODFLOW-96 model described in the Chapter C report (Faye and Valenzuela 2007); MT3DMS model described in the Chapter F report (Faye 2008); TechFlowMP model described in this report (Chapter G)

⁴ VSZ1–VSZ5, TechFlowMP model variably saturated zone layers 1–5

intrinsic permeability—were calibrated specifically based on the application of TechFlowMP to site conditions for Tarawa Terrace and vicinity. For groundwater flow, the northern part of the boundary was assigned as the general head. For this boundary condition, groundwater flow is a function of the altitude of the groundwater table. The channel of Frenchmans Creek, in the western part of the domain, was represented in the model as a drain. Northeast Creek was represented as a specified-head boundary condition and was set to maintain a constant water-table head or level (Figure G1).

Groundwater-Flow Simulation Results

Groundwater simulation using TechFlowMP was required to generate groundwater heads⁷ and the flow field within the model domain. Groundwater-head data are used to calculate groundwater velocities in the subsurface and within each model layer, which is one of the principal parameters required for conducting the fate and transport simulation of PCE and associated degradation by-products.

Simulation results for distribution of groundwater heads obtained from TechFlowMP are compared with those obtained from MODFLOW-96 simulations (Faye and Valenzuela 2007; Wang and Aral 2008) for three time periods (December 1955, October 1971, and April 1984) and for three MODFLOW-96 model layers representing aquifers (layers 1, 3, and 5; Figure G3). The three model layers representing aquifers (layers 1, 3, and 5) are very important because most groundwater is pumped from these layers because of their high horizontal hydraulic conductivity. Comparisons of simulated groundwater heads between the TechFlowMP and MODFLOW-96 models show agreement. The difference between groundwater-head simulations obtained using the two models is most likely due to the different numerical methods used by the two models to approximate the equations of groundwater flow. Recall that TechFlowMP uses a finite-element technique, whereas MODFLOW-96 uses a finite-difference technique. A statistical difference, N_{head} , was calculated using the following equation:

$$N_{head} = \sqrt{\sum (h_{MF} - h_{TF})^2 / \sum h_{TF}^2}, \quad (15)$$

where

- h_{MF} is the hydraulic head simulated by the MODFLOW-96 model (L^1), and
- h_{TF} is the hydraulic head simulated by the TechFlowMP model (L^1).

The averaged values of N_{head} for the entire simulation period (January 1953–February 1987) for MODFLOW-96 model layers 1–2, 3, and 4–7 are 0.05, 0.07, and 0.05, respectively.

⁷ Throughout this report (Chapter G), the terms *groundwater* and *hydraulic head* are equivalent to the terms *water level* or *potentiometric level* that are used in the Chapter C report (Faye and Valenzuela 2007).

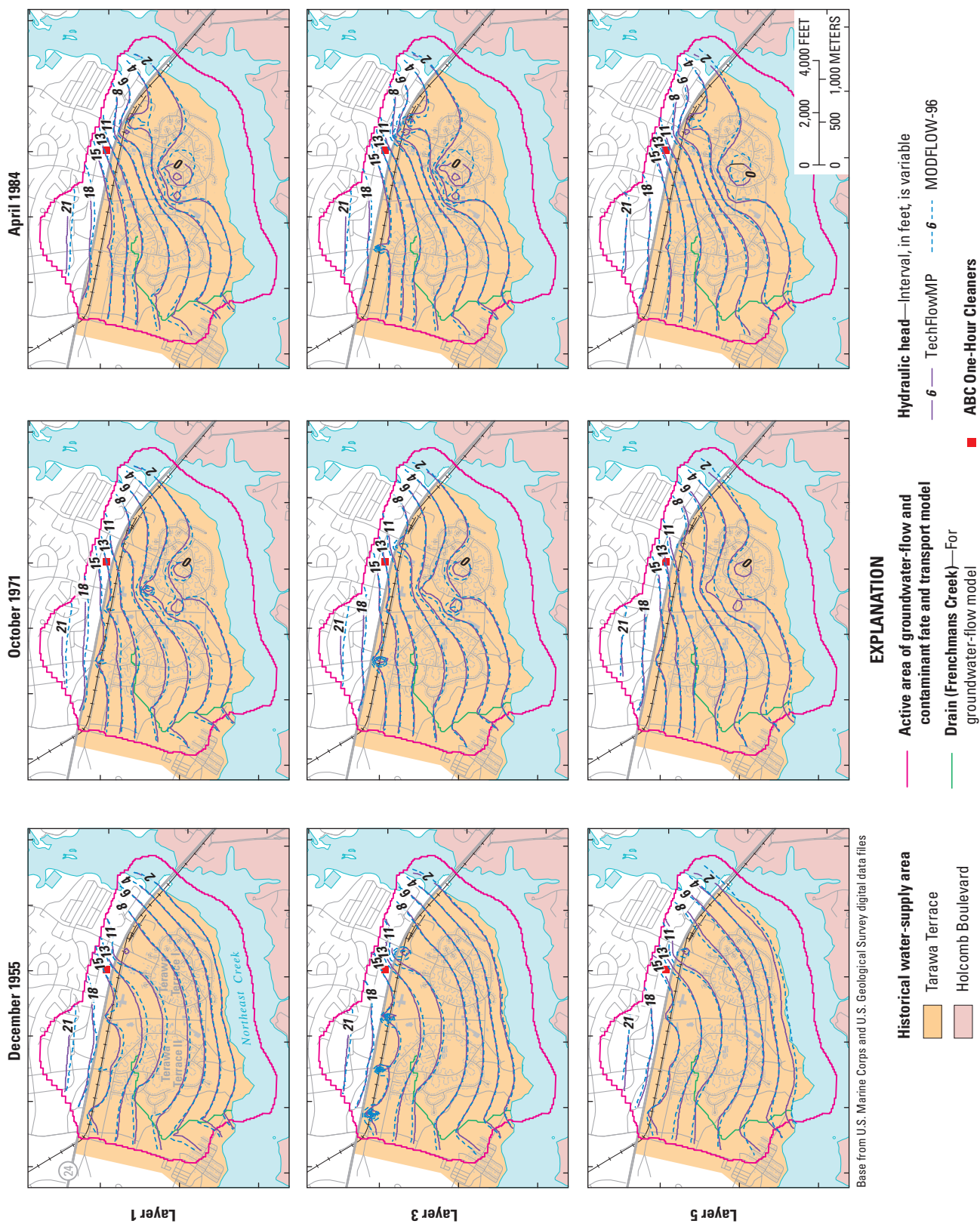
Contaminant Transport

Once VOCs are released into the ground, they may come in contact with indigenous microorganisms, which can biologically transform these compounds under anaerobic conditions. Biotransformation of a parent contaminant reduces its concentration, but it can introduce other toxic chemicals into the subsurface system. At Tarawa Terrace and vicinity, PCE that was released from ABC One-Hour Cleaners migrated with groundwater flow, and was biologically transformed, as shown in Figure G2. Degradation by-products of PCE—such as TCE and 1,2-tDCE—were detected in wells TT-23, TT-25, and TT-26 (Faye and Green 2007). To account completely for contaminants in the subsurface—such as TCE, 1,2-tDCE, and VC, as degradation by-products of PCE—the fate and transport of degradation by-products and the parent contaminant, PCE, should be investigated. Transport of contaminants in the subsurface system is a result of complicated interlinked processes, such as advection, dispersion, interphase mass transfer, and biological reaction. The biotransformation of a contaminant can play an important role in determining its fate and its by-product generation in the subsurface.

In this study, when TechFlowMP was used, the subsurface system consisted of three phases—water (or groundwater), gas, and solid soil particles. The source contaminant PCE and its associated degradation by-products (TCE, 1,2-tDCE, and VC) were considered target contaminants. The physical and chemical properties of the four contaminants considered herein are listed in Table G2. The source zone of PCE is located in the vicinity of ABC One-Hour Cleaners, and the altitude of the source ranges from 0 to 4 m (from 0 to 13 ft), which implies that the source PCE is partially released into the unsaturated zone and partially released into the saturated zone.⁸ At contaminated sites, toxic chemicals often are observed in both zones due to leakage of chemicals into the unsaturated zone and their downward migration into the saturated zone. At the ABC One-Hour Cleaners site, once PCE is released into groundwater, it can partition into the gas phase, and some of the PCE can be adsorbed onto solid soil grains (Kueper et al. 2003). In this study, dissolved PCE in groundwater is assumed to undergo sequential dehalogenation processes (PCE→TCE→1,2-tDCE→VC).

The spreading of PCE, TCE, 1,2-tDCE, and VC in the subsurface can occur in both water and gas phases. Their fate and transport were investigated through multiphase, multi-species transport simulations in a three-dimensional domain for Tarawa Terrace and vicinity (Jang and Aral 2007a). The contaminant fate and transport in the water phase occurs through advection (or transport by groundwater velocity), dispersion, biodegradation, and interphase mass transfer processes. The flow direction and velocity magnitude of groundwater play a key role in determining the migration of dissolved contaminants. The groundwater-flow direction and velocity

⁸ Throughout this report (Chapter G), an altitude of 0 meters (0 feet) is equivalent to sea level or the National Geodetic Vertical Datum of 1929 (NGVD 29).



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

Figure G3. Hydraulic-head distribution obtained by TechFlowMP and MODFLOW-96 for model layers 1, 3, and 5, December 1955, October 1971, and April 1984, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Table G2. Properties of selected chlorinated solvents used for analyses at Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[PCE, tetrachloroethylene; TCE, trichloroethylene; 1,2-tDCE, *trans*-1,2-dichloroethylene; VC, vinyl chloride; kg/m³, kilogram per cubic meter; m²/s, square meter per second; m³/kg, cubic meter per kilogram]

Parameters	PCE	TCE	1,2-tDCE	VC
^a Molecular weight	165.83	131.39	96.94	62.50
^b Vapor density, kg/m ³	7.02	5.56	4.10	2.64
^c Vapor dynamic viscosity, Pa s × 10 ⁶	9.24	9.38	9.29	9.27
^d Henry's constant, dimensionless	0.35	0.227	0.17	0.756
^e Molecular diffusion in air, m ² /s × 10 ⁶	7.05	7.87	8.73	10.42
^f Molecular diffusion in water, m ² /s × 10 ¹⁰	9.14*	8.206	10.3	10.65
^g Sorption coefficient, K _D , m ³ /kg × 10 ³	0.142*	0.1	0.04	0.003
^h Maximum C _g , kg/m ³	0.14	0.302	1.08	7.434
ⁱ Maximum C _w , kg/m ³	0.4	1.33	6.3	9.83
^j Bioreaction rate, λ _B , d ⁻¹	0.0005*	0.01	0.003	0.004
Mass transfer rate, λ _H , d ⁻¹	0.1	0.1	0.1	0.1

^a Montgomery (2000)

^b Calculated by the ideal gas law

^c Calculated by Thodos and co-workers' equation (Perry et al. 1984) based on data from Reid et al. (1987)

^d Calculated from regression data (Gossett 1987)

^e Calculated from the Fuller, Schettler, and Giddings relation (Perry et al. 1984)

^f Calculated by the Wilke-Chang method (Perry et al. 1984)

^g Values from Mackay et al. (1992)

^h Calculated using regression Equation 1 on page 657 (Reid et al. 1987)

ⁱ Calculated from Henry law constant

^j TCE and VC data were selected from Aronson and Howard (1997) and Lorah et al. (1997), and 1,2-tDCE value was selected from data of Barriolage et al. (1987), Tandoi et al. (1994), and vanEekert et al. (2001)

* Data from MODFLOW and MT3DMS simulation

under various groundwater pumping conditions, obtained from groundwater-flow simulations, are used in solving the transport equation for dissolved contaminants.

Contaminant transport in the gas phase occurs in the unsaturated zone. It is assumed that the gas phase does not exist in the saturated zone. For the gas phase, there is no soil vapor extraction in the unsaturated zone, and constant atmospheric pressure is assumed at the ground surface at Tarawa Terrace and vicinity. Therefore, potential gas flow in the unsaturated zone can be modeled as density-driven advection of gas, which is a local gas-flow condition initiated by a gas-density gradient due to high VOC concentration in the gas phase near the contaminant source (Jang and Aral 2007b). In this study, because the PCE source is close to the water table, PCE and its associated degradation by-products in the gas phase will be transported upward from the water table to the ground surface. Under such conditions, significant downward density-driven advection in the gas phase near the source at ABC One-Hour Cleaners is not expected to be observed. This results in a negligible effect on contaminant transport in the gas phase for the large study area of Tarawa Terrace. Thus, molecular diffusion in the gas phase, initiated by a concentration gradient in this phase, and mass transfer between water and gas phases become key processes for determining the contaminant spread in the gas phase.

Physical, chemical, and biological parameters of the four target VOCs (PCE, TCE, 1,2-tDCE, and VC) are listed in Table G2. Biological transformation and water-gas partitioning of the VOCs are represented by first-order relationships. Conversion coefficients for PCE to TCE, TCE to 1,2-tDCE, and 1,2-tDCE to VC are represented by $Y_{TCE/PCE} = 0.792$, $Y_{DCE/TCE} = 0.738$, and $Y_{VC/DCE} = 0.645$, respectively, which are calculated by dividing the molecular weight of a daughter compound by that of the parent compound.

After solving the governing equations for fluid flow and velocity given in Equations 1 and 6, respectively, the coupled contaminant transport equation was solved for four species (PCE, TCE, 1,2-tDCE, and VC) in water (groundwater) and gas phases (Equation 5). Based on these simulations, temporal and spatial concentration profiles of the species were analyzed at Tarawa Terrace and vicinity and are discussed in later sections.

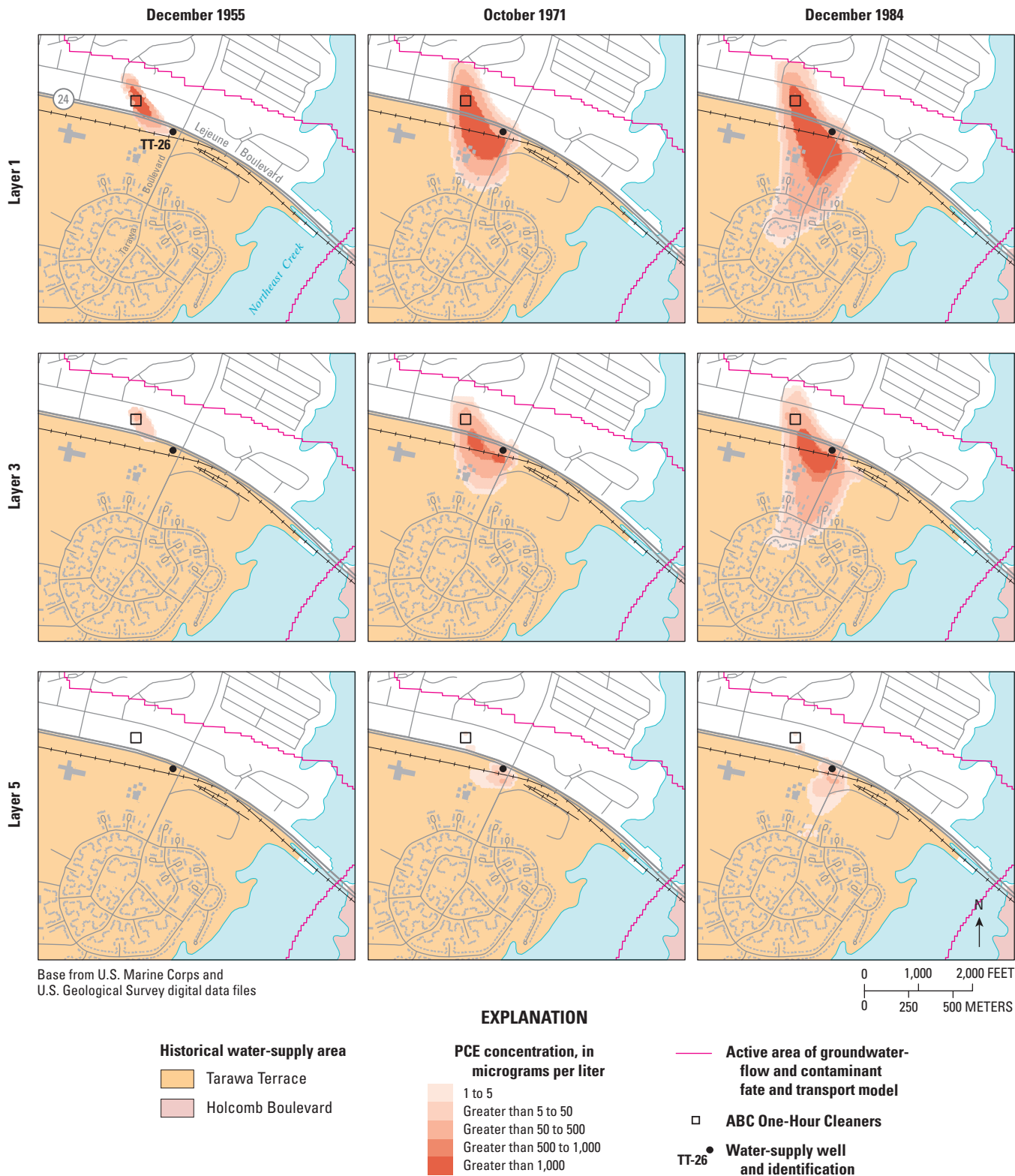


Figure G4. Simulated concentration distributions of tetrachloroethylene (PCE) in groundwater for model layers 1, 3, and 5, Original Pumping Schedule (PS-0), December 1955, October 1971, and December 1984, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Simulation I: Contaminant Transport Using Original Pumping Schedule (PS-0)

Distributions of PCE in groundwater in TechFlowMP model layers 1, 3, and 5 for three simulation times are shown in Figure G4. Because groundwater mostly is pumped from these three layers, which are highly permeable (Faye 2007), contaminant concentrations in model layers 1, 3, and 5 have the most effect on concentrations observed in finished water at the Tarawa Terrace water treatment plant (WTP⁹). As PCE is released from 0 to 4 m altitude (from 0 to 13 ft) in layer 1 of the TechFlowMP model domain, its concentration in groundwater in model layer 1 is higher than that observed in model layers 3 and 5. During December 1955, well TT-26 was the main groundwater-supply well, and it was located downgradient from ABC One-Hour Cleaners. Thus, the PCE plume developed in the direction of groundwater flow toward well TT-26 and Northeast Creek. Because it is assumed that PCE was released continuously during January 1953–December 1984, PCE concentrations in groundwater increased with time. For October 1971, PCE concentration in layer 1 near the location of the well TT-26 exceeds a concentration of 1,000 micrograms per liter ($\mu\text{g/L}$). Groundwater pumping plays an important role in the expansion of the PCE plume. Due to groundwater pumping (Figure G3), the PCE plume in the groundwater phase migrates into the center of the Tarawa

Terrace I family housing area as the plume expands down-gradient (Figure G4). PCE-plume migration in model layer 1 mostly depends on lateral and longitudinal migration of the dissolved PCE because the source is in model layer 1. PCE-plume migration in model layers 3 and 5, however, is affected by lateral, longitudinal, and also vertical migration of the dissolved PCE in groundwater through low permeable model layers 2 and 4. As transport of the dissolved PCE plume is retarded during its downward migration, PCE concentration decreases with increasing depth.

As previously discussed, contaminant plumes spread laterally and vertically by groundwater flow (advection) and dispersion in the saturated zone. Under predevelopment or no-pumping conditions, the lateral and longitudinal flow of groundwater is dominant. When groundwater pumping is occurring, however, pumping can produce local downward movement of groundwater within the zone of influence of a pumping well. The downward movement initiates vertical spreading of dissolved contaminants in aquifers. A vertical concentration profile of PCE in groundwater along section A–A' is shown in Figure G5. The PCE source at ABC One-Hour Cleaners is located at model coordinates $x=2,576$ m (8,451 ft) and $y=2,332$ m (7,651 ft). PCE released from ABC One-Hour Cleaners reaches the bottom of the modeling domain while it migrates toward the downstream direction (in the decreasing y -direction). Due to a dispersion process, PCE migrates in the upstream direction as well (in the increasing y -direction) and reaches the domain boundary.

⁹ Throughout this report (Chapter G), the term *water treatment plant* (WTP) refers solely to the Tarawa Terrace WTP.

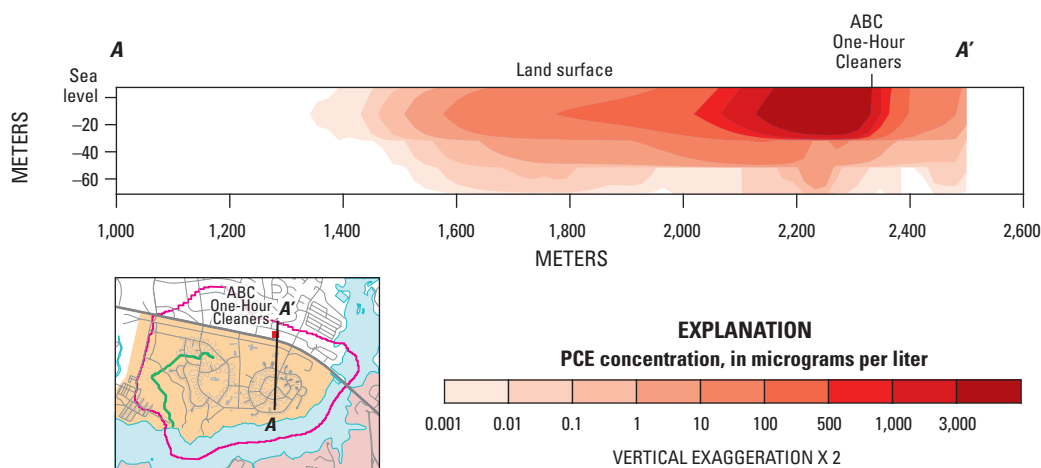


Figure G5. Vertical concentration profile of tetrachloroethylene (PCE) in groundwater, Original Pumping Schedule (PS-0), December 1984, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

As shown in Figure G4, water-supply well TT-26 could be the main source of PCE-contaminated groundwater found in finished water at the WTP. Temporal concentration profiles of PCE in well TT-26 and in finished water at the WTP, obtained from simulations using MT3DMS¹⁰ and TechFlowMP models (Jang and Aral 2007a; Wang and Aral 2007), are shown in Figure G6. Limited field data for PCE and associated contaminants are available in the Tarawa Terrace area; measured PCE concentration data in well TT-26 are shown in Figure G6. Due to the high fluctuation between measured PCE concentrations within a short period, the most dominant PCE concentration data were used in conducting the calibration of the PCE transport model. Calibrated parameters for PCE, including a biotransformation rate, are used in MT3DMS and TechFlowMP modeling. As seen in Figure G5, contaminant concentration varies with depth. Such a spatial (vertical) concentration variation is taken into account in determining a contaminant concentration of pumped groundwater. When groundwater is withdrawn throughout multiple layers at one well location, the concentration of a contaminant in pumped groundwater has been averaged based on a pumping rate and a contaminant concentration at the corresponding layer in a given time period. PCE concentrations at well TT-26 using TechFlowMP are less than those using MT3DMS (Figure G6a). This is partially due to TechFlowMP simulating (1) the release of PCE from the subsurface (groundwater) to the atmosphere, (2) PCE partitioning from the water phase to the soil vapor phase, and (3) the placement of the contaminant source at the ABC One-Hour Cleaners site in the unsaturated and saturated zones. The difference between MT3DMS and TechFlowMP in simulating PCE transport at Tarawa Terrace and vicinity is (1) TechFlowMP considers PCE in both water and gas phases while MT3DMS considers PCE only in the water phase and (2) in MT3DMS the source concentration is released solely to the saturated zone. In MT3DMS simulations (Faye 2008; Wang and Aral 2008), there is no PCE transfer into the gas phase. In TechFlowMP simulations, however, because PCE could be present in the gas phase, a portion of PCE in the gas phase could be released from the subsurface into the atmosphere through the ground surface. This results in the reduction of PCE concentration in the subsurface.

During the periods of July–August 1980 (stress periods 355–356) and January–February 1983 (stress periods 385–386), water-supply well TT-26 was not operated, thus PCE concentration in finished water at the WTP shows a sudden decrease (Figure G6b). Groundwater pumping at wells TT-23 and TT-26 stopped during February 1985 (stress period 410),

¹⁰ The MT3DMS model is a three-dimensional mass transport, multi-species model that uses a finite-difference numerical method. The model was developed by Zheng and Wang (1999) on behalf of the U.S. Army Corps of Engineers Research and Development Center in Vicksburg, Mississippi. As described in the Chapter F report (Faye 2008), the MT3DMS model was used to simulate the fate and transport of PCE as single specie at Tarawa Terrace and vicinity.

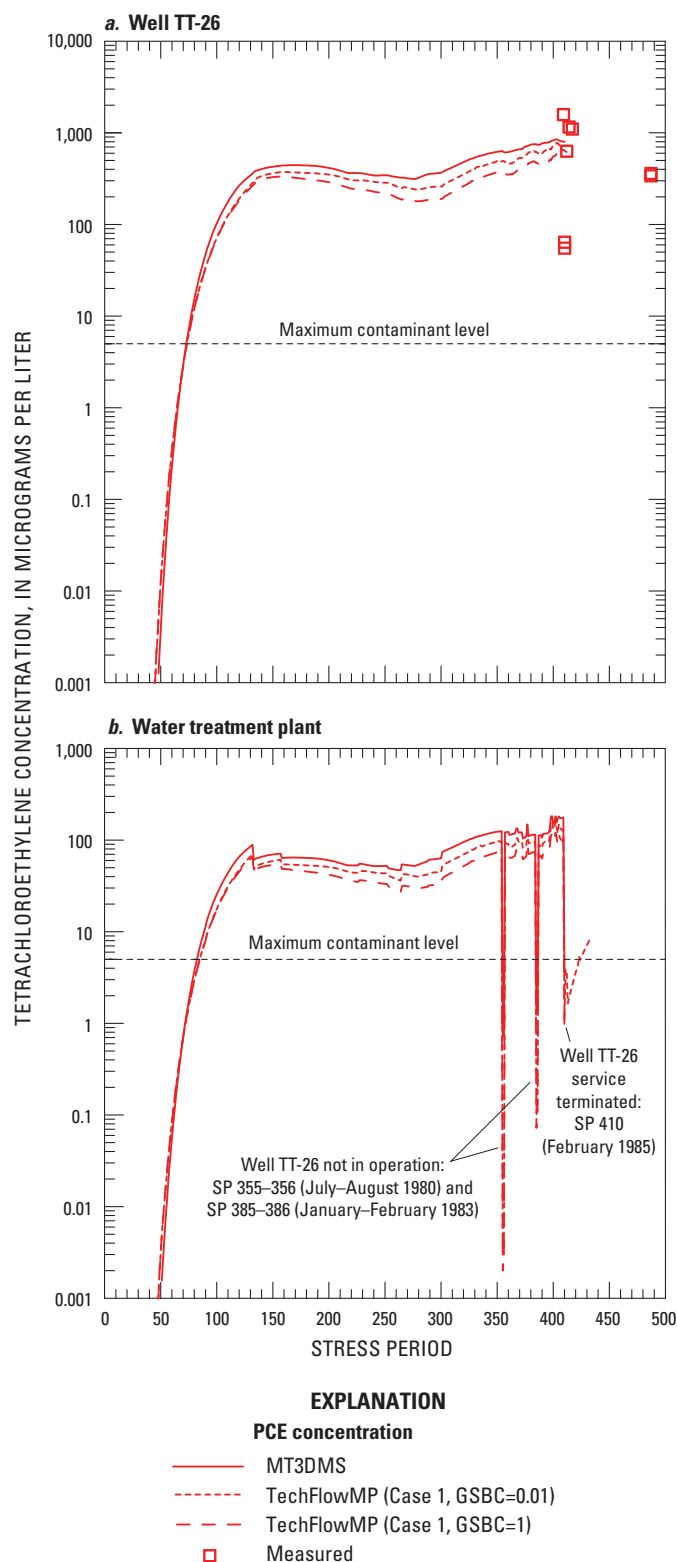


Figure G6. Concentration of tetrachloroethylene (PCE) (a) at water-supply well TT-26 and (b) in finished water from the water treatment plant, Original Pumping Schedule (PS-0), Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [GSBC, ground-surface boundary coefficient in Equation 14; see Appendix G1 for stress periods (SP)]

resulting in the significant drop of PCE concentration in the finished water at the WTP.¹¹

Atmospheric release of PCE from the subsurface is related to a complicated process including interphase mass transfer, transport in gas and water phases, and mass flux at the ground surface. As shown in Equation 14, the boundary condition of the ground surface is an important factor for the escape of vaporized PCE into the atmosphere (Mendoza and Frind 1990; Jang and Aral 2007b). In this study, two ground-surface boundary conditions with two different values of GSBC were used. For Case 1, $\varepsilon_g = 0.01$ for limited ground-surface boundary for mass transfer between the surface and the atmosphere. For Case 2, $\varepsilon_g = 1$ for an ideal, completely open ground-surface boundary without any diffusional resistance. In Figure G6, Case 1 of the TechFlowMP simulation is for a reduced PCE flux between the subsurface and the atmosphere, which could be caused by barriers such as pavement, pond, and high water saturation; Case 2 is for free diffusional PCE flux without any barrier between the subsurface and the atmosphere. For both cases, the diffusional stagnant layer of 0.3 m ($\delta_g = 0.3$ m) was implemented.

Contaminant concentration breakthrough curves are shown for PCE concentrations at water-supply well TT-26 (Figure G6a) and in finished water at the WTP (Figure G6b).¹² Also shown in Figure G6 is the current maximum contaminant level (MCL) for PCE of 5 $\mu\text{g/L}$.¹³ As can be seen, the current MCL for PCE is exceeded during February 1957 (stress period 74) for well TT-26 and during January 1958 (stress period 85) for the WTP. These results are similar to results obtained using MT3DMS. As PCE concentration in groundwater increases (for example, when $\text{PCE} \geq 30 \mu\text{g/L}$), PCE concentrations obtained from MT3DMS and TechFlowMP show similar trends but with some discrepancies. As previously discussed, owing to the atmospheric release of the vaporized PCE, concentration levels simulated by TechFlowMP are less than levels simulated by MT3DMS.¹⁴

¹¹ A listing of simulation stress periods and corresponding month and year is provided in Appendix G1 of this report.

¹² Simulated PCE and PCE degradation by-products in groundwater at water-supply wells TT-23, TT-25, and TT-26 and in finished water at the WTP during January 1951–March 1987 are listed in Appendix G2 of this report.

¹³ The maximum contaminant level, or MCL, is a legal threshold set by the USEPA on the amount of a hazardous substance that is allowed in drinking water under the Safe Drinking Water Act. For example, the MCL for PCE was set at 5 $\mu\text{g/L}$ during 1992 because, given the technology at that time, 5 $\mu\text{g/L}$ was the lowest level that water systems could be required to achieve. Effective dates for MCLs are: 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.).

¹⁴ A comparison of simulated PCE and PCE degradation by-products derived using MT3DMS and TechFlowMP in finished water at the WTP is provided in Appendix A2 of Maslia et al (2007).

The GSBC also plays an important role in determining the reduction of PCE concentration in the subsurface in Cases 1 and 2 (Figure G6). During January 1984 (stress period 397), PCE concentration reductions at water-supply well TT-26 for Cases 1 and 2 correspond to 15 and 35 percent, respectively, when compared with PCE concentrations obtained from MT3DMS simulations for the same period. In this study, all simulation results for PCE and associated degradation by-products are based on a value assigned to the boundary condition of GSBC $\varepsilon_g = 0.01$, unless it is specified otherwise. In those situations, the value assigned to the boundary condition is GSBC $\varepsilon_g = 1$.

Pumped groundwater from water-supply well TT-26 was mixed and diluted with clean and less-contaminated groundwater pumped from other water-supply wells at the WTP; therefore, the simulated PCE concentration in finished water at the WTP is lower than that in well TT-26. Historically, PCE concentrations in finished water at the WTP were much higher than the current MCL for PCE (5 $\mu\text{g/L}$) for most of the time after the initial exceedance was observed, exceptions being periods when well TT-26 was shut down for maintenance during July–August 1980 and January–February 1983 and when service was terminated for well TT-26 during February 1985 (Maslia et al. 2007).

The presence of VOCs in the gas phase within the unsaturated zone also is important and has potential for ecological and exposure impacts and for contaminant removal. When contaminants diffuse to the atmosphere from the unsaturated zone, high concentrations could affect plants, animals, and humans living nearby. Intrusion of contaminant vapor into buildings also can cause increased risk for human health due to indoor air pollution (Johnson and Ettinger 1991; Hers et al. 2002). Release of contaminants from the ground surface into the atmosphere is one of the subsurface processes for natural removal of contaminants from the ground (Jang and Aral 2007b).

In TechFlowMP simulations, PCE in the gas phase (vaporized PCE) in the unsaturated zone originates from the PCE plume in groundwater through interphase mass transfer because the source release occurs in the water phase. As the unsaturated zone is connected to the atmosphere, in which contaminant concentrations are assumed to be zero, contaminants in the unsaturated zone diffuse into the atmosphere through the ground surface due to concentration gradients. Based on a GSBC value of 0.01 (GSBC $\varepsilon_g = 0.01$) simulations for Case 1, vaporized PCE-concentration distributions at ground surface are shown in Figure G7. Temporal profiles

of the PCE plume in the gas phase indicate that the contaminated area becomes larger over time, and its concentration also increases. These profiles show patterns similar to those for PCE in groundwater for model layer 1 (Figure G4). Even though PCE released from ABC One-Hour Cleaners ceased during December 1984 (Figure G7), PCE had already leaked into the ground and spread out continuously with the groundwater flow at Tarawa Terrace and vicinity. The PCE plume in the gas phase at ground surface also expands throughout the simulation period until December 1994. This suggests that effects of soil contamination on the environment will continue for a long period of time after the PCE source release is stopped at ABC One-Hour Cleaners.

PCE that is in the groundwater system can be biologically transformed by indigenous microorganisms. As shown in Figure G2, through dehalogenation processes of PCE under anaerobic conditions, degradation by-products (TCE, DCEs, and VC) can be generated. These by-products become new contaminants in the subsurface. The generation of degradation

by-products depends on various factors including concentration of parent contaminants, chemical and biological conditions, and microbial activities. In this study, a sequential dechlorination of PCE, TCE, 1,2-tDCE, and VC is represented as a biological process. Each reaction is governed by the concentration of the by-product in the water phase, and the bioreaction rate is controlled by reaction coefficients listed in Table G2.

During the spread of the PCE plume in the water phase (Figure G4), sequential biotransformation also occurs. The resulting concentration plumes for TCE, 1,2-tDCE, and VC in groundwater are shown in Figure G8. The plume development of the three PCE degradation by-products (TCE, 1,2-tDCE, and VC) shown in Figure G8 are similar to those of PCE in groundwater shown in Figure G4. Concentrations of degradation by-products, however, are less than PCE concentrations. As shown in Figure G8, the area of the 1,2-tDCE plume is a little larger than the area of the TCE plume during December 1984. This is due to the higher bioreaction coefficient of TCE than that of 1,2-tDCE (Table G2).

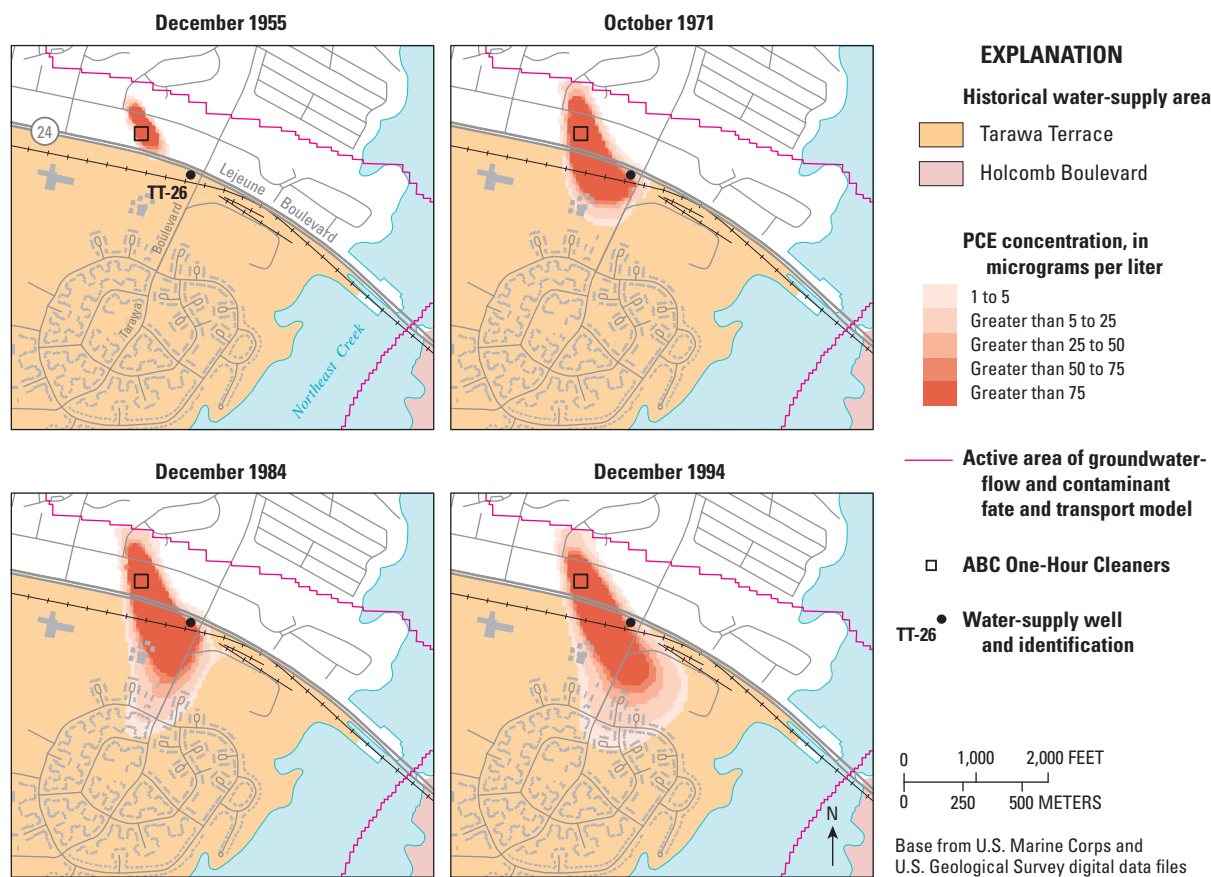


Figure G7. Simulated concentration distributions of tetrachloroethylene (PCE) in the gas phase at ground surface, Original Pumping Schedule (PS-O), December 1955, October 1971, December 1984, and December 1994, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

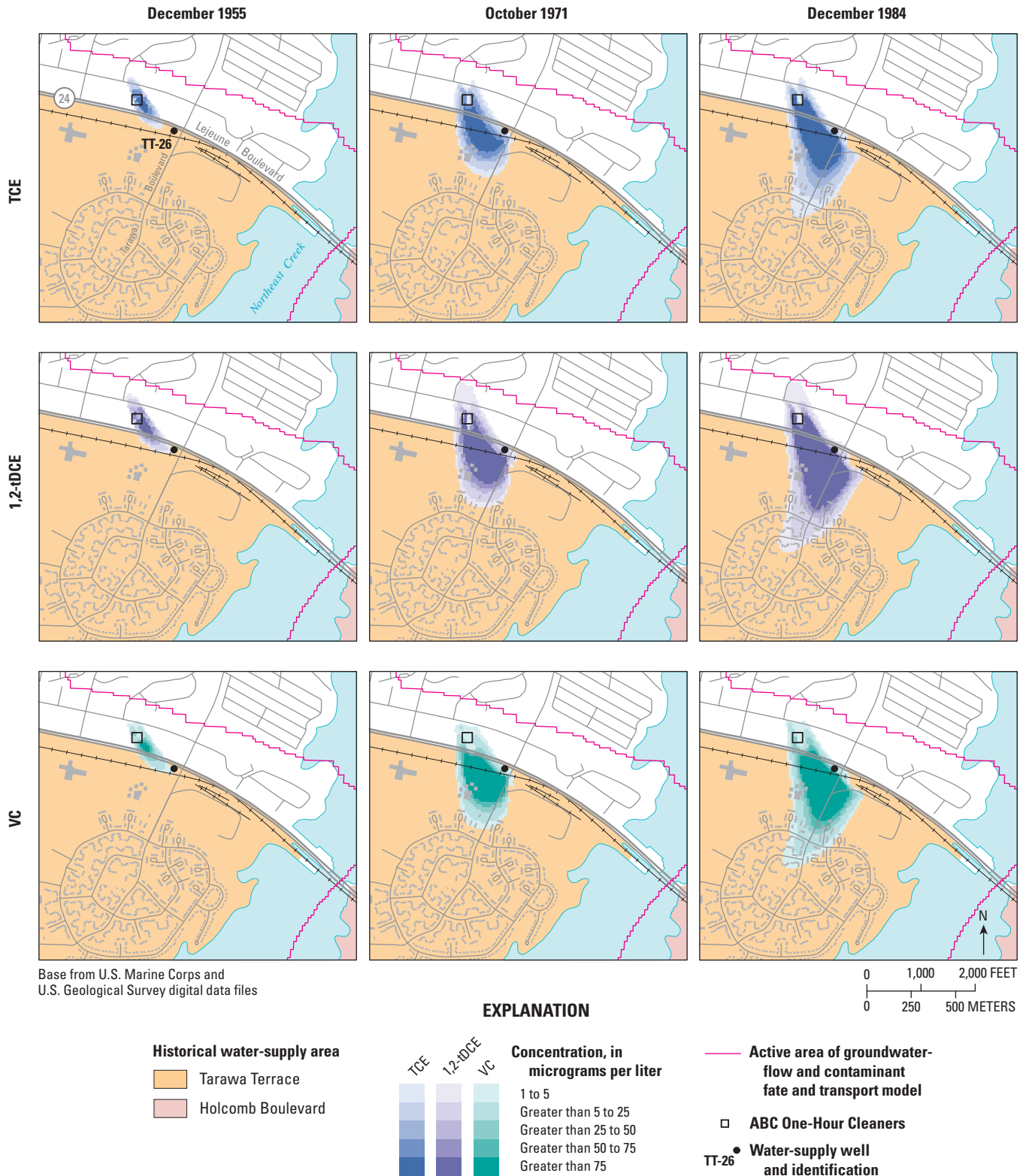


Figure G8. Simulated concentration distributions of trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) in the water phase for model layer 1, Original Pumping Schedule (PS-O), December 1955, October 1971, and December 1984, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Concentration profiles of TCE, 1,2-tDCE, and VC in the water phase along a vertical section line A-A' are shown in Figure G9. All three degradation by-products show the highest concentration zones near the PCE source at ABC One-Hour Cleaners. The downgradient migration distance for a TCE concentration of 0.001 µg/L is less than that of 1,2-tDCE or VC. The plume front for 1,2-tDCE is more than 50 m (164 ft) ahead of that of TCE in the decreasing y-direction (down-gradient groundwater-flow direction). This is mainly due to the higher retardation factor and bioreaction rate of TCE than for 1,2-tDCE and VC. Retardation factors for TCE, 1,2-tDCE, and VC are 2.4, 1.5, and 1.04, respectively; their bioreaction rates are listed in Table G2. Migration of TCE, 1,2-tDCE, and VC plumes in the subsurface is characterized by physical, chemical, and biological properties of these by-products, including sorption and partition coefficients, bioactivity, as well as advective and diffusive properties of the groundwater-flow domain in Tarawa Terrace aquifers.

Temporal concentration profiles of PCE and its three degradation by-products at water-supply well TT-26 and at the WTP are shown in Figure G10. Concentration profiles of

PCE are the same as shown in Figure G6 and are presented in Figure G10 for comparison purposes. At well TT-26 (Figure G10a), TCE and VC concentrations in groundwater exceed current MCL values for drinking water during November 1956 (stress period 71) and August 1957 (stress period 80), respectively. Concentrations of 1,2-tDCE, however, remain below the current MCL (100 µg/L) during all simulation periods except during June–August 1984.¹⁵

As degradation by-products (TCE, 1,2-tDCE, and VC) are generated and transformed due to bioactivity, their bioreaction coefficients for generation and transformation would be one of the most important factors in determining concentration of degradation by-products at the site. Results for water-supply well TT-26 (Figure G10a) are selected because this is the nearest water-supply well to the ABC One-Hour Cleaners site. Bioreaction rates assigned to contaminants are listed in Table G2. Bioreaction rates of TCE and 1,2-tDCE were

¹⁵ The current MCL values for PCE and its degradation by-products TCE, 1,2-tDCE, and VC are: PCE, 5 µg/L; TCE, 5 µg/L; 1,2-tDCE, 100 µg/L; and VC, 2 µg/L (40 CFR, Section 141.60, Effective Dates, July 1, 2002, ed.).

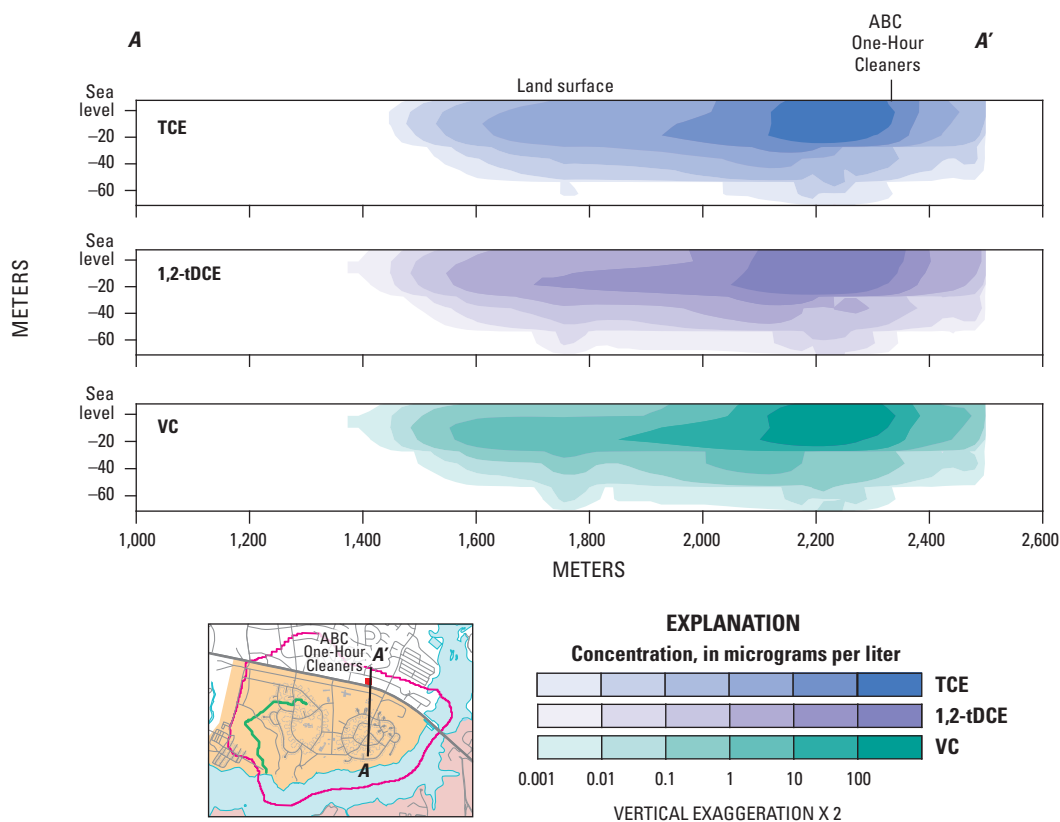


Figure G9. Vertical concentration profiles of trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) in the water phase, Original Pumping Schedule (PS-0), December 1984, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

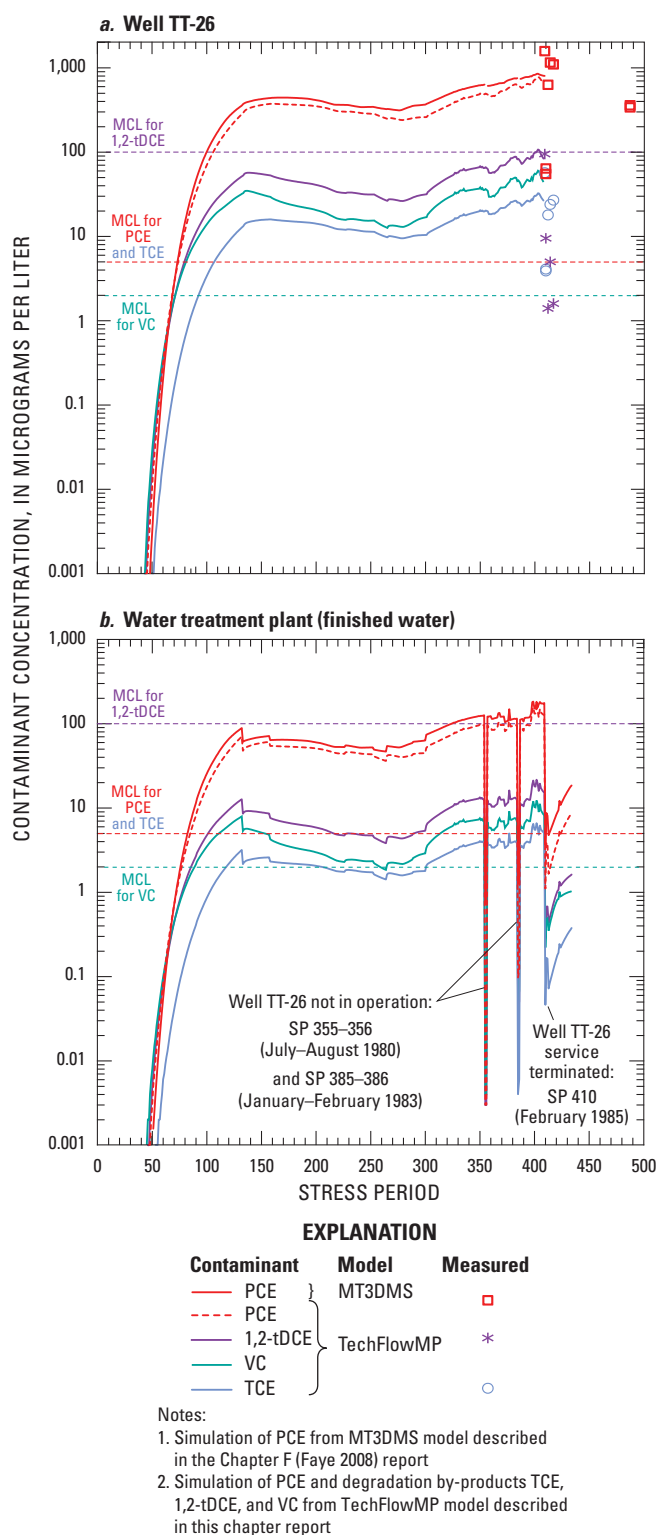


Figure G10. Concentration of tetrachloroethylene (PCE) and degradation by-products trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) (a) at water-supply well TT-26 and (b) in finished water from the water treatment plant, Original Pumping Schedule (PS-0), Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [MCL, maximum contaminant level; see Appendix G1 for stress periods (SP)]

selected from published ranges of biotransformation rates to calibrate concentration profiles to measured concentrations of each species at well TT-26. Measured concentrations of TCE and 1,2-tDCE at well TT-26 were highly varied even though most field data were collected during 1985. From this data, a bioreaction rate of TCE was determined so that simulated TCE concentrations would be encompassed within the most frequently detected concentration range from 18 to 27 $\mu\text{g/L}$. Measured data for 1,2-tDCE show great fluctuation (1–92 $\mu\text{g/L}$) because 1,2-tDCE has lower dechlorination reactivity than TCE under anaerobic conditions (Wiedemeier 1998); therefore, the lower bioreaction rate of 1,2-tDCE compared to TCE was implemented in contaminant transport modeling. As shown in Figure G10, TCE has the lowest concentration profile among the three by-products (TCE, 1,2-tDCE, and VC) at well TT-26 and at the WTP for the duration of the simulation period. This is due to the greater value assigned to the bioreaction rate of TCE (0.01 d^{-1}) than the values assigned to 1,2-tDCE (0.003 d^{-1}) and VC (0.004 d^{-1}). The higher value assigned to the bioreaction rate for TCE (0.01 d^{-1}) leads to lower TCE concentrations and contributes to the higher generation of 1,2-tDCE in groundwater. The generation rate of 1,2-tDCE in the aquifer system, which is due to the biotransformation of TCE, is greater than the biotransformation of 1,2-tDCE to its lower by-product, VC. This results in the accumulation of 1,2-tDCE in the subsurface system. The concentration of VC depends on the concentration of 1,2-tDCE and the VC bioreaction rate. Differences in concentrations for degradation by-products (Figure G10) is a consequence of the differences between bioreaction rates described previously. Because the concentration of degradation by-product contaminants is a function of the relation between generation and biotransformation (decomposition) of contaminants, simulation results shown in Figure G10 apply solely to degradation by-product plumes at the ABC One-Hour Cleaners site. In addition to the bioreaction rate, physical and chemical parameters—such as sorption coefficient, Henry’s constant, and diffusion coefficient—also play important roles in resulting contaminant concentration profiles.

Retardation initiated by the sorption process has an effect on the transport rate of contaminants in the subsurface. In the saturated zone, retardation factors of TCE, 1,2-tDCE, and VC—which are calculated based on sorption coefficient, soil density, and porosity—are about 2.4, 1.5, and 1.04, respectively. These values suggest that the migration of TCE in groundwater should be slower than that of 1,2-tDCE and VC. The late appearance of TCE (Figure G10) is the outcome of the higher retardation value assigned to TCE. As has been discussed, transport and biotransformation of multispecies contaminants in a subsurface system are affected simultaneously by several interlinked processes including advection, dispersion, vaporization, dissolution, generation, and degradation. Thus, it is extremely difficult to account quantitatively for impacts of each process individually on the overall contaminant fate and transport of a compound and its degradation by-products.

At the WTP (Figure G10*b*), simulated concentration of TCE in finished water is in the range of 1.5–6.6 µg/L during 1959–1984. This concentration level exceeds the current MCL of 5 µg/L between February 1984 and January 1985. Beginning during May 1958, VC concentration in finished water at the WTP exceeds its current MCL (2 µg/L) throughout the duration of the simulation period except for the period July 1972–December 1972. The simulated concentration of 1,2-tDCE in finished water at the WTP remains lower than the current MCL (100 µg/L) during the simulation period January 1951–December 1994. During July–August 1980 (stress periods 355–356), the sharp decline of contaminant concentrations in finished water at the WTP is due to the temporary removal of water-supply well TT-26 from service. This is further evidence that well TT-26 was the principal supplier of contaminated groundwater used in finished water at the WTP.

Due to the sequential biotransformation of PCE, by-products (TCE, 1,2-tDCE, and VC) are generated in the water phase. Because gas and water phases are in constant interaction in the unsaturated zone, a portion of generated contaminants in the water phase partitions into the gas phase. According to Henry's law, a higher concentration of dissolved contaminants leads to a higher concentration of contaminants in the gas

phase. In the saturated zone, groundwater flow is the main driving force for contaminant transport. In the unsaturated zone, however, diffusion of contaminants in the gas phase plays an important role in spreading contaminants vertically in an upward direction from the water table to the ground surface. From the ground surface, PCE and its degradation by-products (TCE, 1,2-tDCE, and VC) can be released to the atmosphere. The atmospheric release of contaminants is proportional to their concentrations at the ground surface. The concentration distributions of TCE, 1,2-tDCE, and VC in the gas phase at ground surface are shown in Figure G11, which shows a similar spreading pattern for each by-product. In terms of the size of the contaminant plume, as can be seen in Figure G8, the TCE plume is less than that of the 1,2-tDCE and VC plumes shown in Figure G11. Since concentration distributions of the contaminants at the ground surface are nearly proportional to their concentration distributions in groundwater, the former can be used to approximately delineate the latter. In this study, the plume developments of TCE, 1,2-tDCE, and VC at the ground surface follow those in groundwater in model layer 1 (Figure G8). As shown in Figure G11, such ground-surface contamination could cause the potential human exposure to the mixture of PCE, TCE, 1,2-tDCE, and VC vapors.

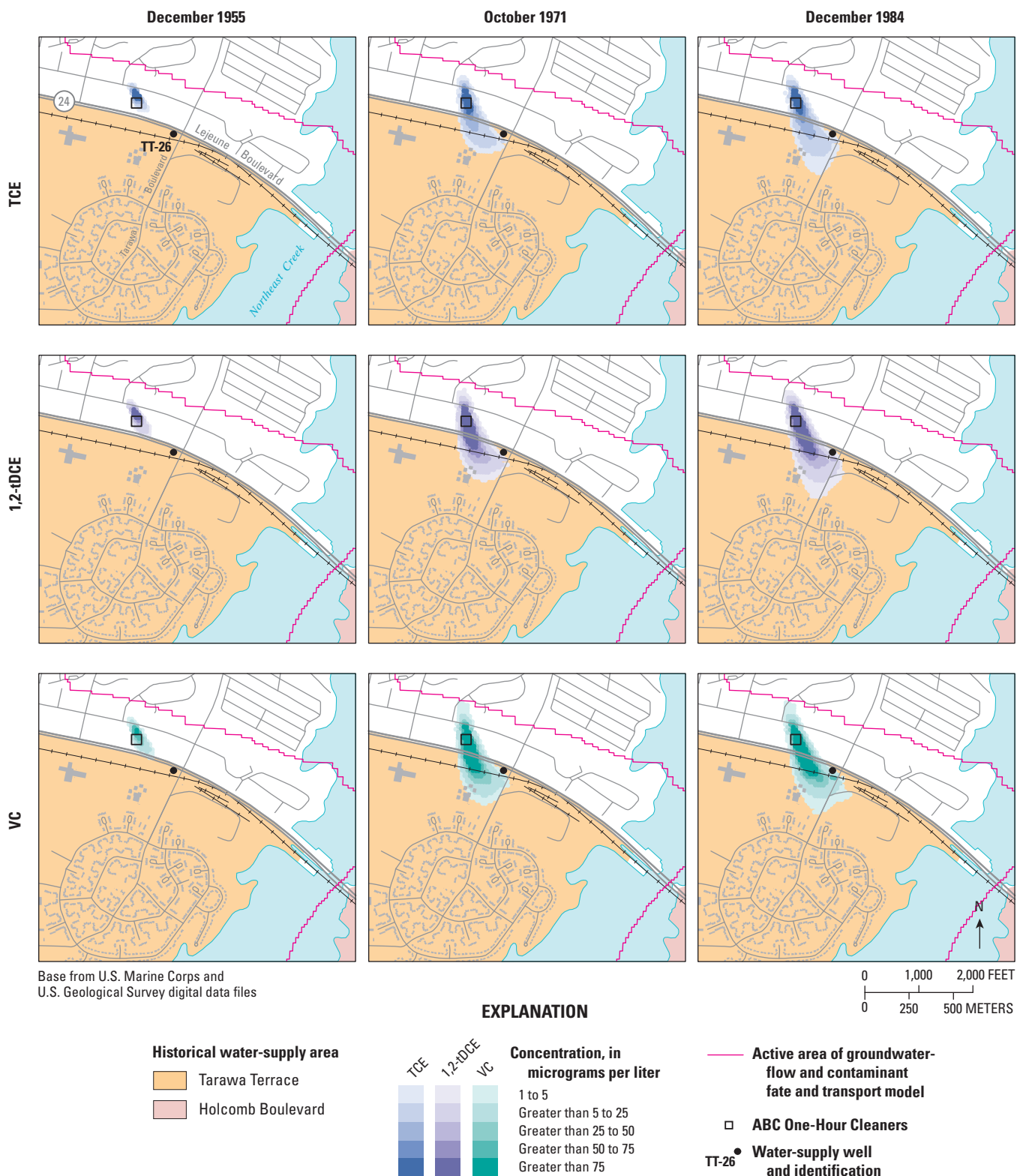


Figure G11. Simulated concentration distributions of trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) in the gas phase at ground surface, Original Pumping Schedule (PS-0), December 1955, October 1971, and December 1984, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

According to the contaminant fate and transport analysis conducted in this study, PCE released into the subsurface from ABC One-Hour Cleaners can be (1) partitioned into three phases (water, gas, and soil); (2) removed from the subsurface by two processes (atmospheric release and groundwater pumping); or (3) biotransformed into its degradation by-products by sequential dechlorination. The three degradation by-products (TCE, 1,2-tDCE, and VC) also can be partitioned into the three phases and biologically transformed in the subsurface. The fate and transport of contaminants in the subsurface is due to complicated and coupled processes that include advection, dispersion, biotransformation, and sorption. Using a materials balance calculation for PCE and its associated degradation by-products, the fate of PCE, TCE, 1,2-tDCE, and VC can be analyzed. Results of these analyses are shown in Figure G12.

In Figure G12a, PCE mass in water, gas, and soil phases relative to total PCE discharged to the subsurface is shown as a percentage. The gas-phase contaminants reside only in the unsaturated zone while the water and soil phases are present

in the unsaturated and saturated zones. The percentage of PCE concentration in water and soil phases decreases with time, which contributes to the loss of PCE in the subsurface due to its atmospheric release, biotransformation, and withdrawal by groundwater pumping. At ABC One-Hour Cleaners, PCE is released into the water phase in the subsurface beginning January 1953 (stress period 25). At the beginning of the PCE release, about 33 and 66 percent of the released PCE is present in water and soil phases, respectively. During October 1971 (stress period 250), the percentage of PCE in the water and soil phases decreases to 16.2 and 32.9 percent, respectively.

The percentages of PCE for the three pathways (atmospheric release, biotransformation, and pumping) also are shown in Figure G12a. With time, percentages of PCE in these three pathways increase; this accounts for the loss of PCE in the subsurface. Biotransformation of PCE is the largest loss relative to the other losses. During December 1984 (stress period 408), percentages of PCE loss for biotransformation, atmospheric release, and groundwater pumping reach

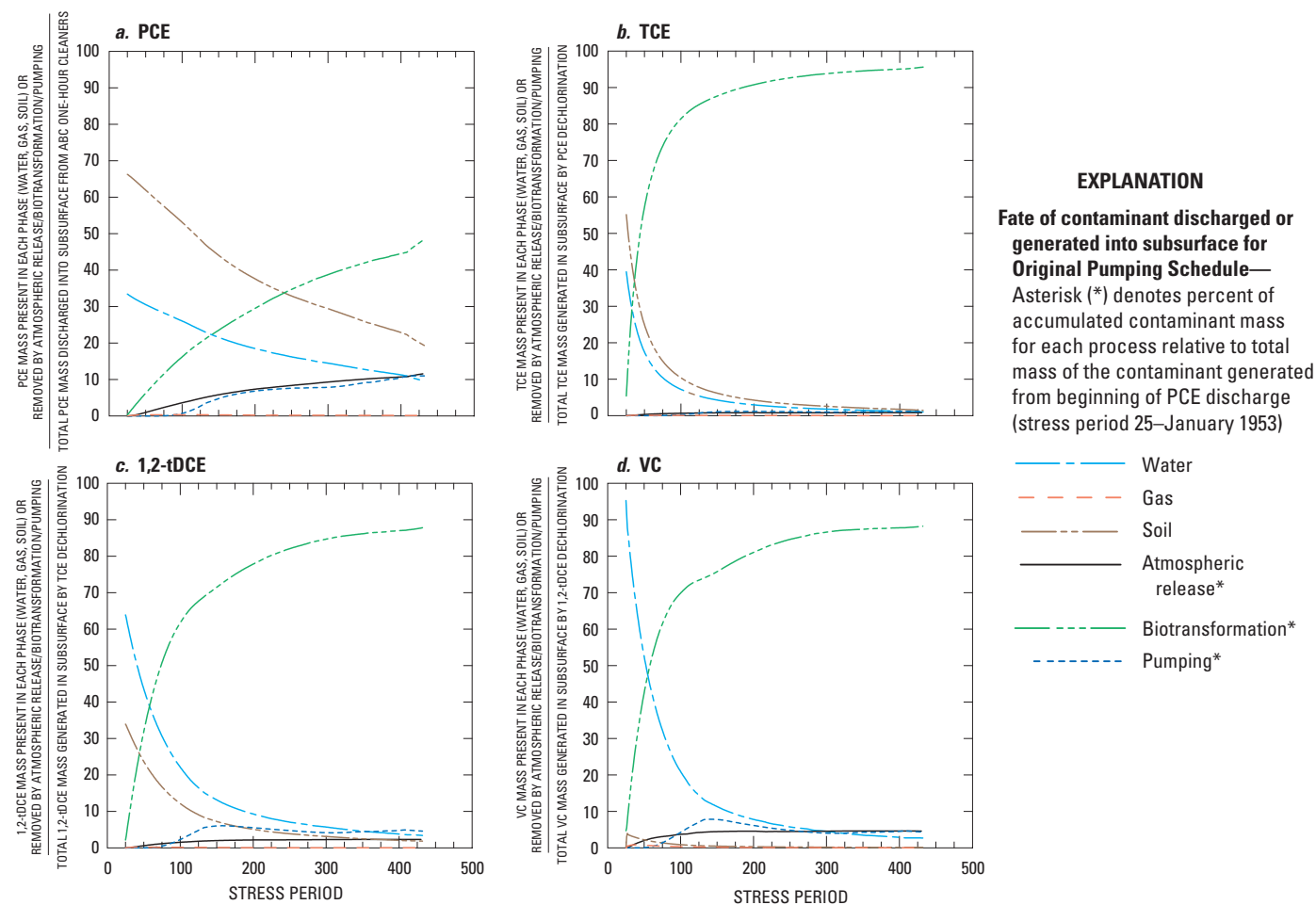


Figure G12. The fate of (a) tetrachloroethylene (PCE), and degradation by-products (b) trichloroethylene (TCE), (c) *trans*-1,2-dichloroethylene (1,2-tDCE), and (d) vinyl chloride (VC) derived from materials mass balance calculations, Original Pumping Schedule (PS-0), Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [y-axis value, in percent; see Appendix G1 for stress periods]

44.9, 10.8, and 10.9 percent, respectively. Percentages of PCE in water, gas, and soil phases are approximately 11, 0.14, and 22 percent, respectively. This suggests that the biotransformation of PCE plays a key role in reducing the PCE concentration in the subsurface. The increase in the biotransformed PCE mass begins with the discharge of PCE into the ground. Profiles of PCE for atmospheric release and groundwater pumping, however, show a lag time due to travel of PCE from the source to the ground surface or to groundwater pumping wells. The atmospheric release of PCE begins a month after the start of the PCE discharge to the subsurface system, and the percentage of PCE withdrawn by groundwater pumping begins to increase during August 1957 (stress period 80).

Biotransformation of dissolved PCE generates TCE, whose fate is shown in Figure G12*b*. The biotransformation process plays a dominant role in determining the fate of TCE. At the beginning of the PCE discharge (stress period 25), the relative ratios of TCE in water and soil phases to total TCE generated are 39 and 55 percent, respectively. These levels sharply decrease until April 1959 (stress period 100). During December 1984 (stress period 408), those relative ratios of TCE in water and soil phases are 1.2 and 1.7 percent, respectively. The ratio in the gas phase is less than 0.01 percent, and ratios for biotransformation, groundwater pumping, and atmospheric release are 95.1, 1.2, and 0.8 percent, respectively. TCE profiles shown suggest that TCE generated by PCE biotransformation is rapidly biodegraded into 1,2-tDCE, and, thus, only a small portion of generated TCE remains in the subsurface.

The fate of 1,2-tDCE, which is generated from the biotransformation of TCE in the water phase, is shown in Figure G12*c*. The bioreaction accounts for the greatest portion of the fate of 1,2-tDCE. During December 1984 (stress period 408), the percentage of 1,2-tDCE to total 1,2-tDCE generated in the subsurface for biotransformation is 87.1 percent; its losses to groundwater pumping and atmospheric release are 4.9 and 2.3 percent, respectively. At this time, the percentage of 1,2-tDCE in the water, gas, and soil phases are 3.6, 0.02, and 2.0 percent of its total mass that is generated in the subsurface, respectively. The biotransformation rate of 1,2-tDCE is lower than that of TCE (compare Figures G12*c* and G12*b*). This is primarily due to the smaller bioreaction coefficient value assigned to 1,2-tDCE than assigned to TCE (Table G2). During December 1984 (stress period 408), the percentage of 1,2-tDCE withdrawn by groundwater pumping is about four times greater than the percentage of TCE withdrawn by groundwater pumping. Starting from April 1958 (stress period 100), the percentage of 1,2-tDCE removal due to groundwater pumping is higher than from atmospheric release. This suggests that groundwater pumping has a greater impact on the reduction of 1,2-tDCE concentration in the subsurface than to atmospheric release. Unlike PCE and TCE, whose levels for the soil phase are higher than those for the water phase, the level of 1,2-tDCE mass for the water phase is greater than that for the soil phase. The reduction in sorption coefficients of the contaminants (PCE > TCE > 1,2-tDCE > VC

in Table G2) leads to the decrease in contaminant mass adsorbed to the soil. This also is consistent with the reduction of retardation factors of contaminants (2.9, 2.4, 1.5, and 1.04 for PCE, TCE, 1,2-tDCE, and VC, respectively).

VC is the last degradation by-product of the sequential dechlorination processes of PCE described in this report. Its fate is shown in Figure G12*d*. The percentage of VC biotransformation is dominant in profiles of VC; VC adsorbed to soil particles is negligible. During December 1984 (stress period 408), VC percentages for biotransformation, groundwater pumping, and atmospheric releases are 87.8, 4.7, and 4.6 percent, respectively. VC percentages for the water, gas, and soil phases are 2.74, 0.04, and 0.12 percent, respectively.

In Figures G12*b–d*, the temporal profiles of the three degradation by-products of PCE (TCE, 1,2-tDCE, and VC) are shown for the water, gas, and soil phases. In terms of atmospheric release of the degradation by-products, VC shows the greatest percentage of loss. During October 1971 (stress period 250), the percentages of loss due to atmospheric release for TCE, 1,2-tDCE, and VC are 0.8, 2.2, and 4.5 percent, respectively. The difference in these release rates results from the higher maximum concentration in the gas phase (C_g) and molecular diffusion in the air (or gaseous diffusivity) of VC when compared to those of TCE and 1,2-tDCE (Table G2).

As seen in Figure G12, the relative difference in temporal profiles of contaminants demonstrates the importance of different biotransformation rates for contaminants. Specifically, biotransformation will play a major role in determining the fate of contaminants in the long term as pointed out by Jang and Aral (2007*c*). This becomes an important factor in natural attenuation effects for these contaminants. In this study, the contribution of the biological process to the removal of PCE, TCE, 1,2-tDCE, and VC are about 45, 95, 87, and 88 percent, respectively, of their injected/generated mass until December 1984 (stress period 408). Atmospheric release of PCE also has a considerable impact on its fate. During the simulation period for PS-O, the atmospheric release of PCE is greater than or almost equal to PCE mass withdrawn through groundwater pumping. For TCE and 1,2-tDCE, their atmospheric losses are approximately half of their masses for groundwater pumping. For VC, starting from October 1971 (stress period 250), its atmospheric loss is almost equal to its mass that is pumped out.

The masses of PCE, TCE, 1,2-tDCE, and VC within the gas phase in the unsaturated zone correspond to only a small portion of their total masses that are in the subsurface. These percentages are as low as 0.14, 0.01, 0.02, and 0.04 percent for PCE, TCE, 1,2-tDCE, and VC, respectively. The gas phase in the unsaturated zone, however, is important in contaminant transport modeling because this phase becomes a pathway for contaminant migration from the subsurface into the atmosphere, referred to as atmospheric release of contaminants. This results in a reduction in contaminant concentration in the subsurface, as observed in natural attenuation processes at contaminated sites (Jang and Aral 2007*b*).

Simulation II: Contaminant Transport under Modified Pumping Schedule for Maximum and Minimum PCE Concentration Arrival Times

In conducting numerical simulations on fate and transport of multispecies contaminants within multiple phases at Tarawa Terrace and vicinity, a number of uncertain model parameter values were used (Maslia et al. In press 2008b; Wang and Aral 2008). One of the important uncertain model parameters was the groundwater pumping schedule assigned to water-supply wells. Complete records are not available for monthly pumping during the period of water-supply well operation (January 1953–February 1987). Monthly data are available solely for 1978 and intermittently during the period 1981–1985 (Maslia et al. 2007, Faye and Valenzuela 2007). To simulate the supply of finished water to the residents at Tarawa Terrace and vicinity, 14 water-supply wells were operated during the simulation period. These wells had varied pumping periods, pumpage rates, and capacities.

The operation of water-supply well TT-26 is a critical factor in determining the arrival time of PCE at this well and arrival times of the degradation by-products of this parent contaminant (Figures G6 and G10). Potential changes in the arrival times of these contaminants at water-supply wells also will affect concentrations of these compounds in finished water at the WTP. To consider the uncertainty regarding groundwater pumping rates at water-supply wells, an uncertainty analysis of groundwater pumping rates and their operational schedules was conducted, resulting in two pumping schedules:

1. *Pumping Schedule A (PS-A)*: This pumping schedule generated early arrival times of contaminants at water-supply wells and maximum PCE concentration profiles in finished water at the WTP.
2. *Pumping Schedule B (PS-B)*: This pumping schedule generated late arrival times of contaminants at water-supply wells and minimum PCE concentration profiles in finished water at the WTP.

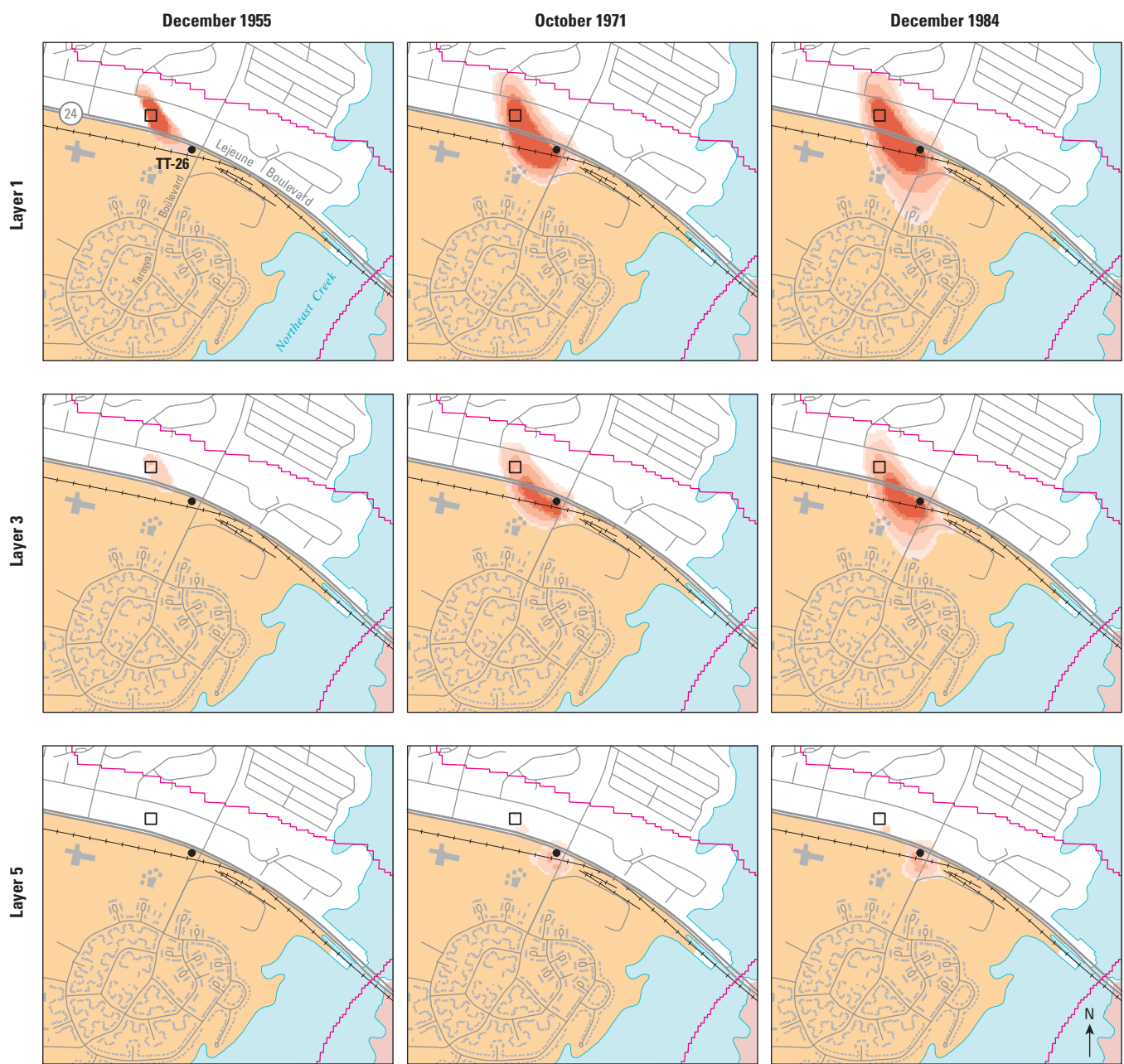
To determine effects of these two pumping schedules on the early and late arrival of contaminants at water-supply wells and the WTP, PS-A and PS-B are used in this report to analyze the transport and biotransformation of PCE, TCE, 1,2-tDCE, and VC. In these simulations, all model parameter

values, with the exception of groundwater pumping rates and their operational schedules, are identical to values assigned to model parameters described in the previous report section (*Simulation I: Contaminant Transport using Original Pumping Schedule*).

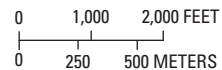
Development of PCE plumes under PS-A and PS-B in model layers 1, 3, and 5 are shown in Figures G13 and G14, respectively. For PS-A simulations, contaminant withdrawal is maximized from the subsurface system by groundwater pumping; thus, the PCE plume in groundwater decreases. By comparison, for PS-B simulations, contaminant withdrawal is minimized to reduce contaminant concentration in finished water at the WTP. Thus, PCE mass in the groundwater system becomes large, resulting in an increased size of the PCE plume. During December 1984 for model layer 1, for a PCE concentration of 0.001 µg/L using PS-A (Figure G13), the area of the plume is smaller than the area of the plume obtained using PS-O (Figure G4). By comparison, the area of the plume for a PCE concentration of 0.001 µg/L using PS-B (Figure G14) is larger than the area of the plume obtained using PS-O (Figure G4).

For PS-A and PS-B, the concentration profiles of PCE in the water phase are shown in Figure G15 in a vertical cross section. PCE concentration distributions along section A–A' show distinct differences when comparing PS-A with PS-B. For PS-A, the plume with a dissolved PCE concentration of ≥ 10 µg/L reaches a distance of $y=2,000$ m (6,560 ft) in the downgradient direction. By comparison, for PS-B, a dissolved PCE concentration of ≥ 10 µg/L reaches a distance of $y=1,500$ m (4,920 ft) in the downgradient direction.

Temporal variations of PCE concentration in water-supply well TT-26 and in finished water at the WTP under the aforementioned two pumping schedules (PS-A and PS-B) are shown in Figure G16. For PS-A, PCE concentrations obtained using MT3DMS and TechFlowMP are similar. After June 1963 (stress period 150), simulated concentrations derived by using TechFlowMP are a little higher than concentrations derived using MT3DMS (Wang and Aral 2007). For PS-A, the pumpage at well TT-26 is maximized for the scenario of maximum contaminant withdrawal from the groundwater system. Under this condition, the spread of the PCE plume in the subsurface decreases (Figure G13). As a consequence of this reduction, atmospheric release of PCE also is minimized.



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



EXPLANATION

Historical water-supply area

- Tarawa Terrace
- Holcomb Boulevard

PCE concentration, in micrograms per liter

- 1 to 5
- Greater than 5 to 50
- Greater than 50 to 500
- Greater than 500 to 1,000
- Greater than 1,000

- Active area of groundwater-flow and contaminant fate and transport model

- ABC One-Hour Cleaners
- Water-supply well and identification

Figure G13. Simulated concentration distributions of tetrachloroethylene (PCE) in groundwater for model layers 1, 3, and 5, Pumping Schedule A (PS-A), December 1955, October 1971, and December 1984, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

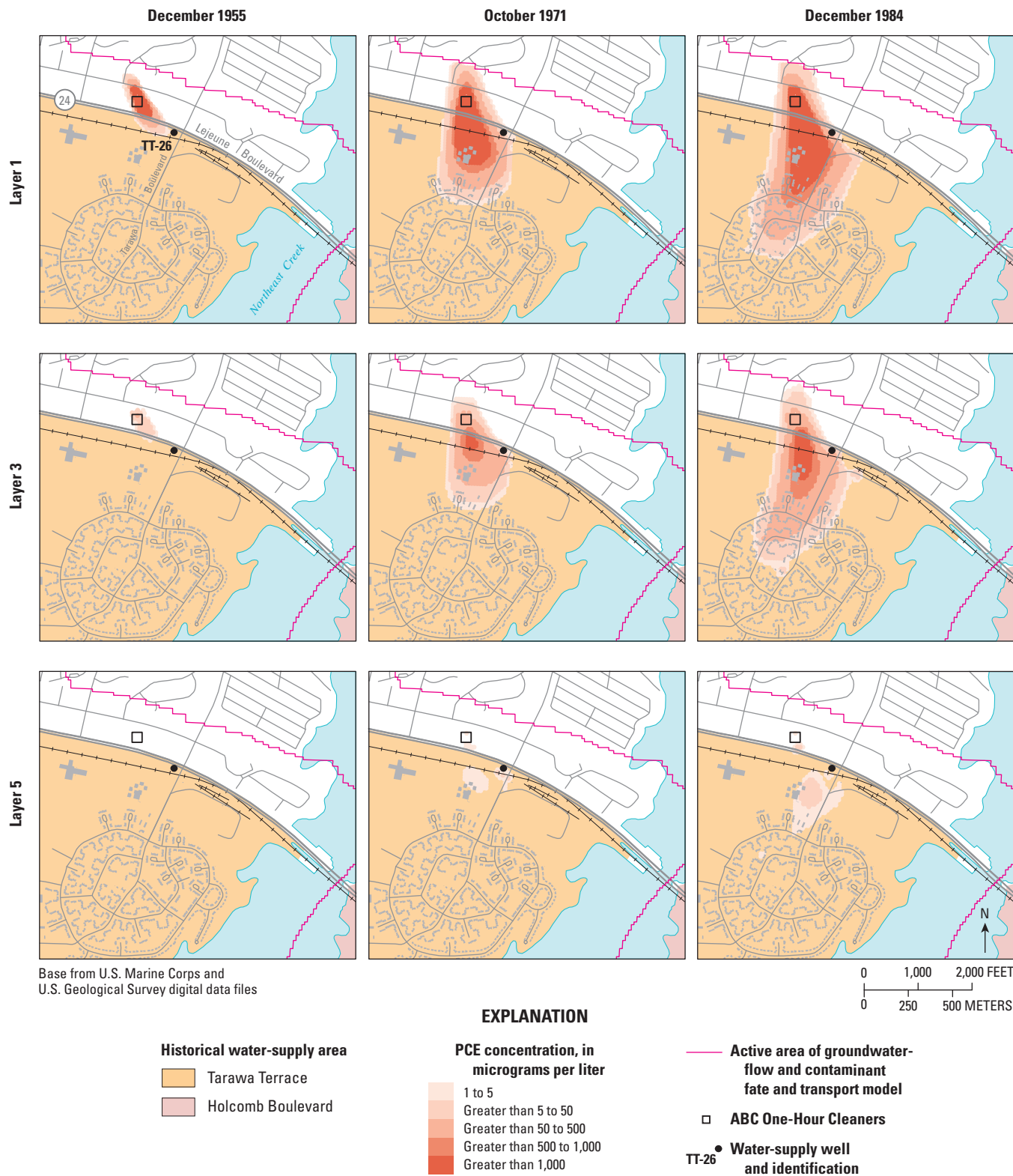


Figure G14. Simulated concentration distributions of tetrachloroethylene (PCE) in groundwater for model layers 1, 3, and 5, Pumping Schedule B (PS-B), December 1955, October 1971, and December 1984, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

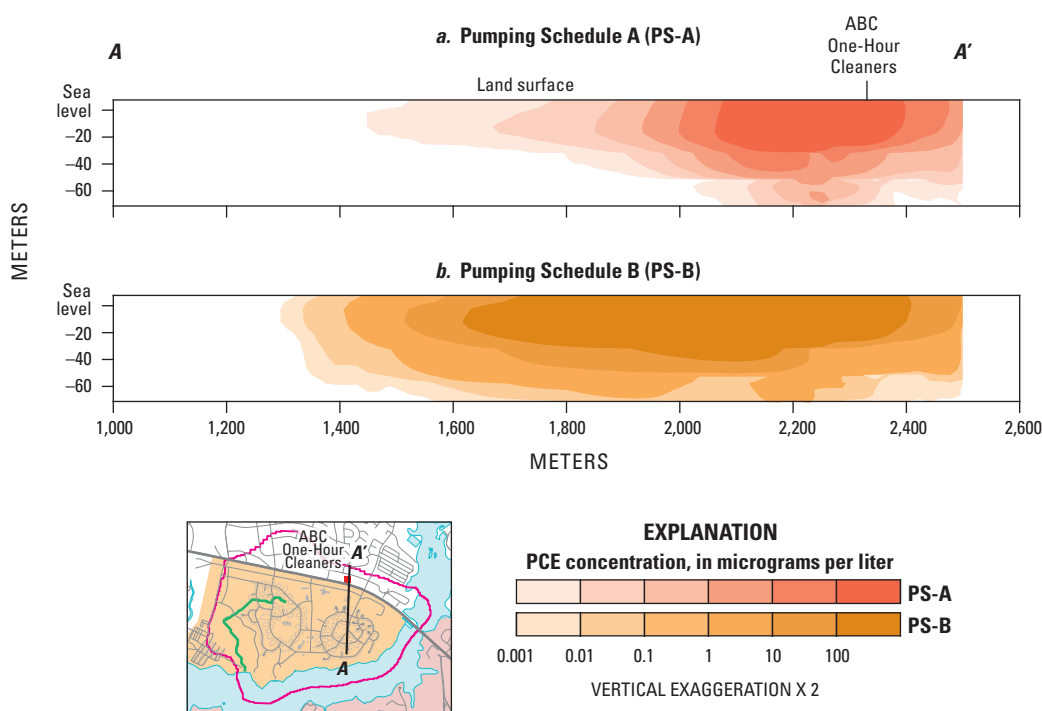


Figure G15. Vertical concentration profiles of tetrachloroethylene (PCE) in groundwater for (a) Pumping Schedule A and (b) Pumping Schedule B, December 1984, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

For PS-B during March 1962 (stress period 135), PCE concentrations at water-supply well TT-26 using TechFlowMP are significantly lower than those obtained using MT3DMS (Figure G16a). During February 1980, PCE concentration in the water phase at well TT-26 from TechFlowMP corresponds to approximately 25 percent of the concentration from MT3DMS. The significant difference in PCE concentrations between MT3DMS and TechFlowMP is due to the atmospheric release of PCE using the TechFlowMP simulation. For PS-B, the atmospheric release of PCE plays an important role in reducing PCE mass in the subsurface. In terms of the size of the PCE plume, the plume for PS-B is larger than the PS-A plume, as can be seen in Figures G13–G15. For PS-B, since the PCE plume is located in a large area and PCE remains in high concentration in the groundwater system (Figures G14 and G15), PCE in the gas phase has more opportunity to form and be released into the atmosphere. The high PCE concentration in the groundwater system leads to the faster release of PCE from the subsurface to the atmosphere because the higher concentration in the subsurface (or at the ground surface) generates the stronger driving force for molecular diffusion of PCE in gas phase from the ground surface to the atmosphere.

The temporal change in PCE concentration at the WTP also shows similar patterns observed in water-supply well TT-26 (Figure G16b). Arrival time of PCE at its current MCL is almost the same for MT3DMS and TechFlowMP. For PS-A, PCE concentrations in the water phase obtained

from MT3DMS and TechFlowMP far exceed the current MCL for PCE. For PS-B, PCE concentration obtained from TechFlowMP is above its current MCL during September 1959 (stress period 105) through November 1964 (stress period 167). PCE concentration obtained from MT3DMS is above its current MCL for all simulation periods after January 1960 (stress period 109), except the period between February 1970 (stress period 230) and August 1977 (stress period 320). PCE concentration profiles derived from the TechFlowMP simulations based on the two extreme pumping schedules, PS-A and PS-B, are in agreement with measured field data shown in Figure G16.

Concentration distributions of PCE in the gas phase at the ground surface for PS-A and PS-B are shown in Figure G17. During December 1984 for PS-A, a plume of high concentration of PCE ($\geq 100 \mu\text{g/L}$) is located between ABC One-Hour Cleaners and water-supply well TT-26. At that time, for PS-B, the plume passes through well TT-26 and expands toward wells TT-23 and TT-54. The appearance of the smaller PCE plume at the ground surface for PS-A, when compared to that for PS-B, is due to the greater PCE removal by groundwater pumping in PS-A when compared to that in PS-B. In Figure G16, since PCE concentration at well TT-26 is higher in PS-A than in PS-B, PCE removal per the volume of pumped groundwater at well TT-26 will be greater in PS-A than in PS-B. The volumetric rate of groundwater pumping at well TT-26 also is greater in PS-A than in PS-B.

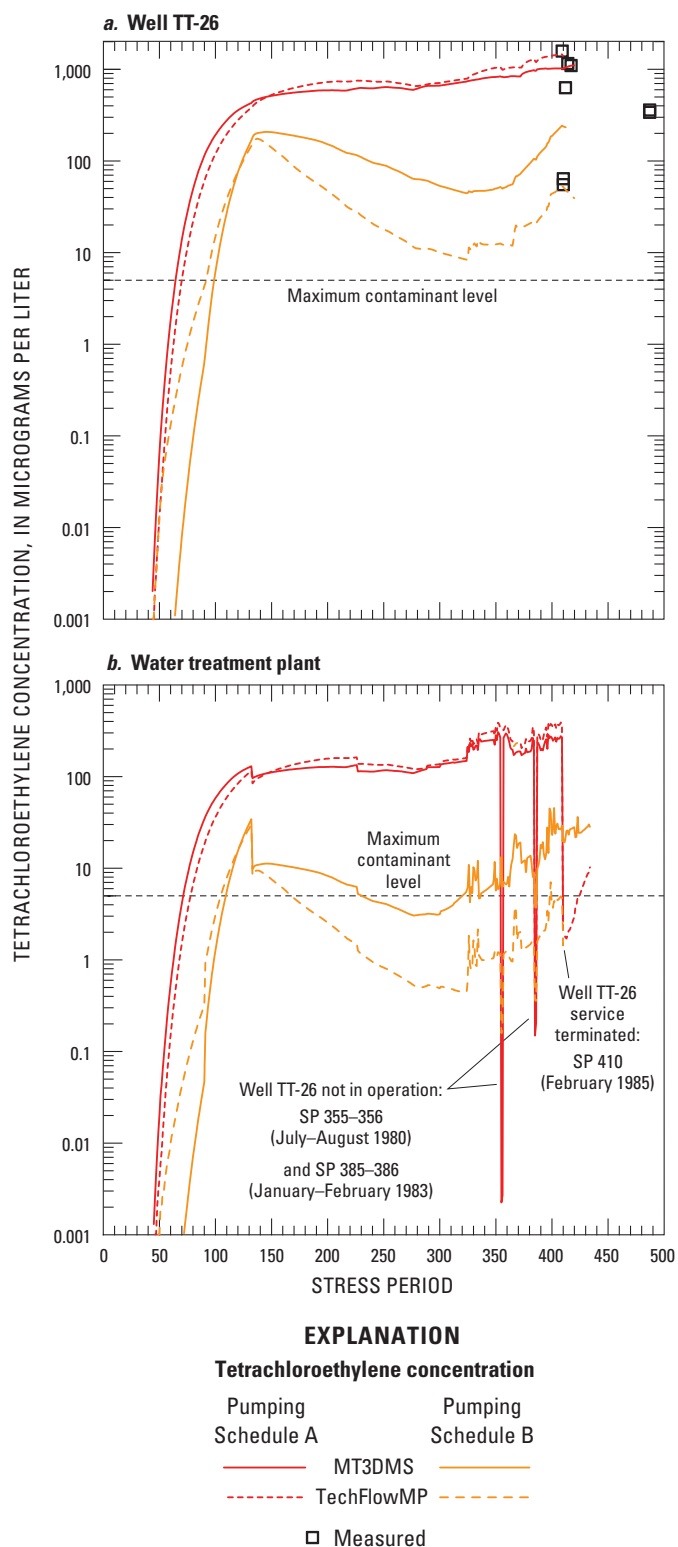


Figure G16. Concentration of tetrachloroethylene (a) at water-supply well TT-26 and (b) in finished water from the water treatment plant for Pumping Schedule A and Pumping Schedule B, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [see Appendix G1 for stress periods (SP)]

Simulated plumes of TCE, 1,2-tDCE, and VC in the water phase are shown in Figures G18 and G19 for PS-A and PS-B, respectively. The concentration distributions in model layer 1 are used for the three species because the highest concentrations are detected in model layer 1 from among the seven layers of the modeling domain. Model layer 1 corresponds to the top layer in the saturated zone. All three species migrate toward water-supply well TT-26 and then are diverted into Tarawa Terrace housing areas. Plume shapes are similar to those of PCE in the water phase. As expected, the plume development for PS-B (Figure G19) is larger than that for PS-A (Figure G18).

Concentration profiles of TCE, 1,2-tDCE, and VC in a vertical cross section provide information about the downward spreading of the contaminants. Figure G20 is a vertical representation of the model domain, which is important for contaminant transport because it is the source layer for PCE released at ABC One-Hour Cleaners. PS-A and PS-B have a significant effect on the contaminant spreading in the decreasing y-direction (downstream direction). For PS-A, the plume front for the 1,2-tDCE plume (at a simulated concentration $\geq 0.001 \mu\text{g/L}$) is located at $y = 1,650 \text{ m}$ (5,413 ft), whereas, the plume front for VC is located at $y = 1,750 \text{ m}$ (5,741 ft). For PS-B, however, the fronts of 1,2-tDCE and VC are located close to each other at a downstream location of about $y = 1,325 \text{ m}$ (4,347 ft). For plume development of TCE, 1,2-tDCE, and VC near $y = 1,350 \text{ m}$ (4,347 ft) for PS-B, the vertically downward spreading areas of 1,2-tDCE and VC are greater than that of TCE, which is due to the difference in sorption and molecular diffusion coefficients of the contaminants. TCE has the largest sorption coefficient and the smallest molecular diffusion coefficient in water among the three by-product compounds listed in Table G2.

As shown in Figure G21a for PS-A, the time when the concentration of TCE first exceeds the current MCL is February 1959 (stress period 98) for water-supply well TT-26 and July 1963 (stress period 151) for the WTP. The dilution of contaminated groundwater at the WTP lowers the dissolved contaminant concentration in finished water at the WTP when compared to contaminated groundwater observed in well TT-26. At the WTP, the concentration of 1,2-tDCE remains below its current MCL ($100 \mu\text{g/L}$). Beginning during August 1957 (stress period 80), VC concentrations at well TT-26 and the WTP exceed the current MCL for VC of $2 \mu\text{g/L}$. During October 1971 (stress period 250), simulated VC concentrations are $47.8 \mu\text{g/L}$ and $8.7 \mu\text{g/L}$ at well TT-26 and at the WTP, respectively.

As shown in Figure G21b for PS-B, VC concentration at the WTP exceeds its current MCL ($2 \mu\text{g/L}$) from January 1960 (stress period 109) through January 1962 (stress period 133). Concentrations of TCE and 1,2-tDCE for PS-B remain below their current MCLs ($5 \mu\text{g/L}$ for TCE and $100 \mu\text{g/L}$ for 1,2-tDCE) throughout the simulation period at the WTP.

For PS-A (Figure G21a), concentration profiles of PCE, TCE, 1,2-tDCE, and VC simulated using TechFlowMP show somewhat distinct intervals between concentrations of the contaminants (the vertical distance between concentration lines

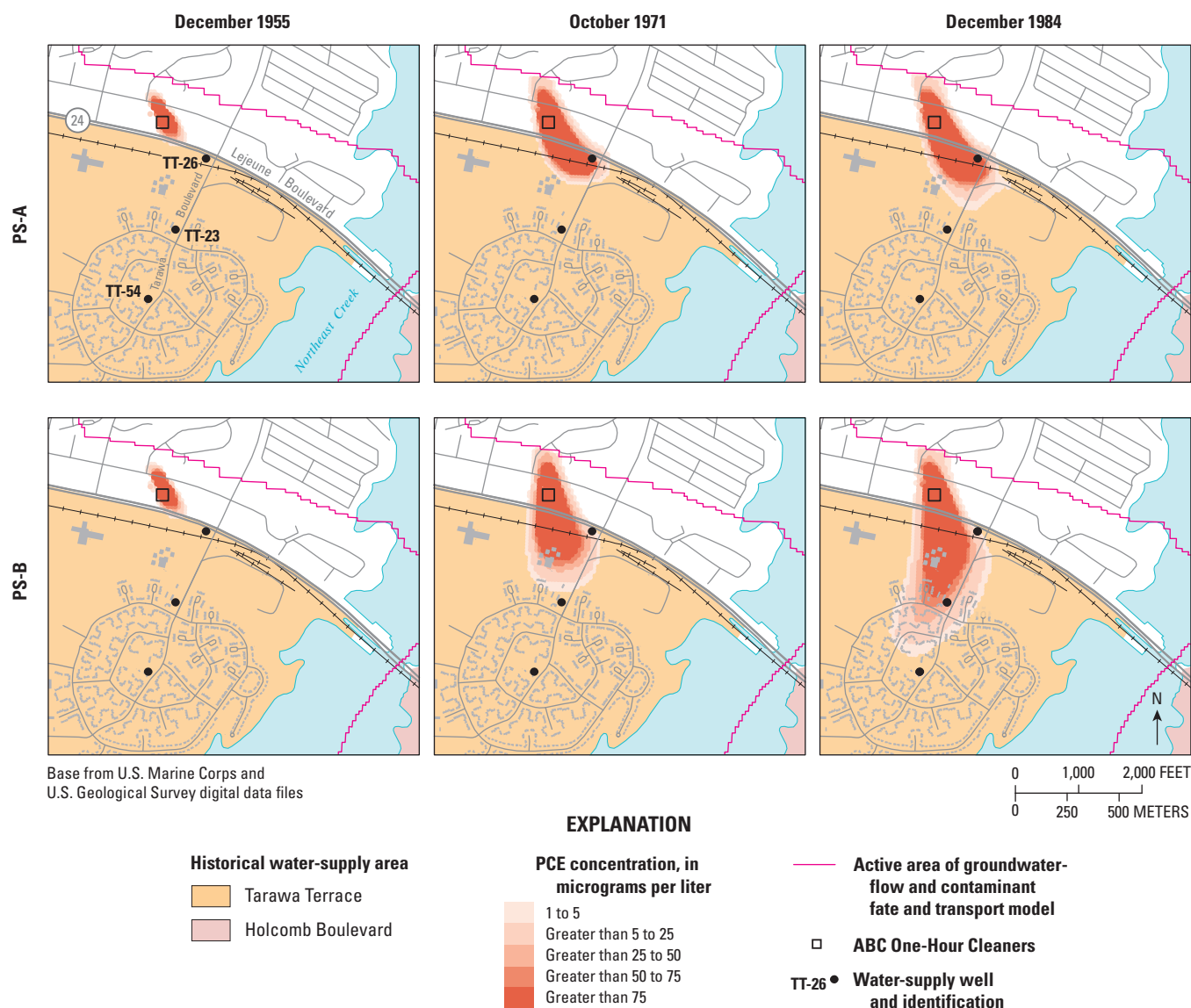


Figure G17. Simulated concentration distributions of tetrachloroethylene (PCE) in the gas phase at ground surface, Pumping Schedule A (PS-A) and Pumping Schedule B (PS-B), December 1955, October 1971, and December 1984, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

of two contaminants) from January 1963 (stress period 133) through June 1980 (stress period 354). During this time, concentrations of the four contaminants are ranked as: PCE > 1,2-tDCE > VC > TCE.

For PS-B (Figure G21b), concentrations of PCE, TCE, and 1,2-tDCE simulated using TechFlowMP also are ranked as PCE > 1,2-tDCE > VC > TCE during January 1963 (stress period 133). After that period, VC concentrations decrease and then become nearly equal to TCE concentrations until April 1974 (stress period 280), while other contaminant concentrations are ranked as PCE > 1,2-tDCE > TCE. Concentration profiles of VC for PS-B might be a result of the greater release of VC from the subsurface into the atmosphere than the release of PCE, TCE, and 1,2-tDCE. This is

initiated because of VC having the greatest vapor pressure and molecular diffusion among the four contaminants (PCE, TCE, 1,2-tDCE, and VC) as listed in Table G2.

Distribution and concentration of contaminant plumes at the ground surface are important factors in determining mass transfer from the ground to the atmosphere. Because by-product contaminants in the gas phase at the ground surface interact with contaminants in the water phase in the saturated zone, their concentrations in the two regions are interdependent. Concentration distributions of TCE, 1,2-tDCE, and VC in the gas phase at the ground surface for PS-A (Figure G22) and PS-B (Figure G23) show similar patterns to concentration distributions of the contaminants in the water phase for model layer 1 (Figures G18 and G19).

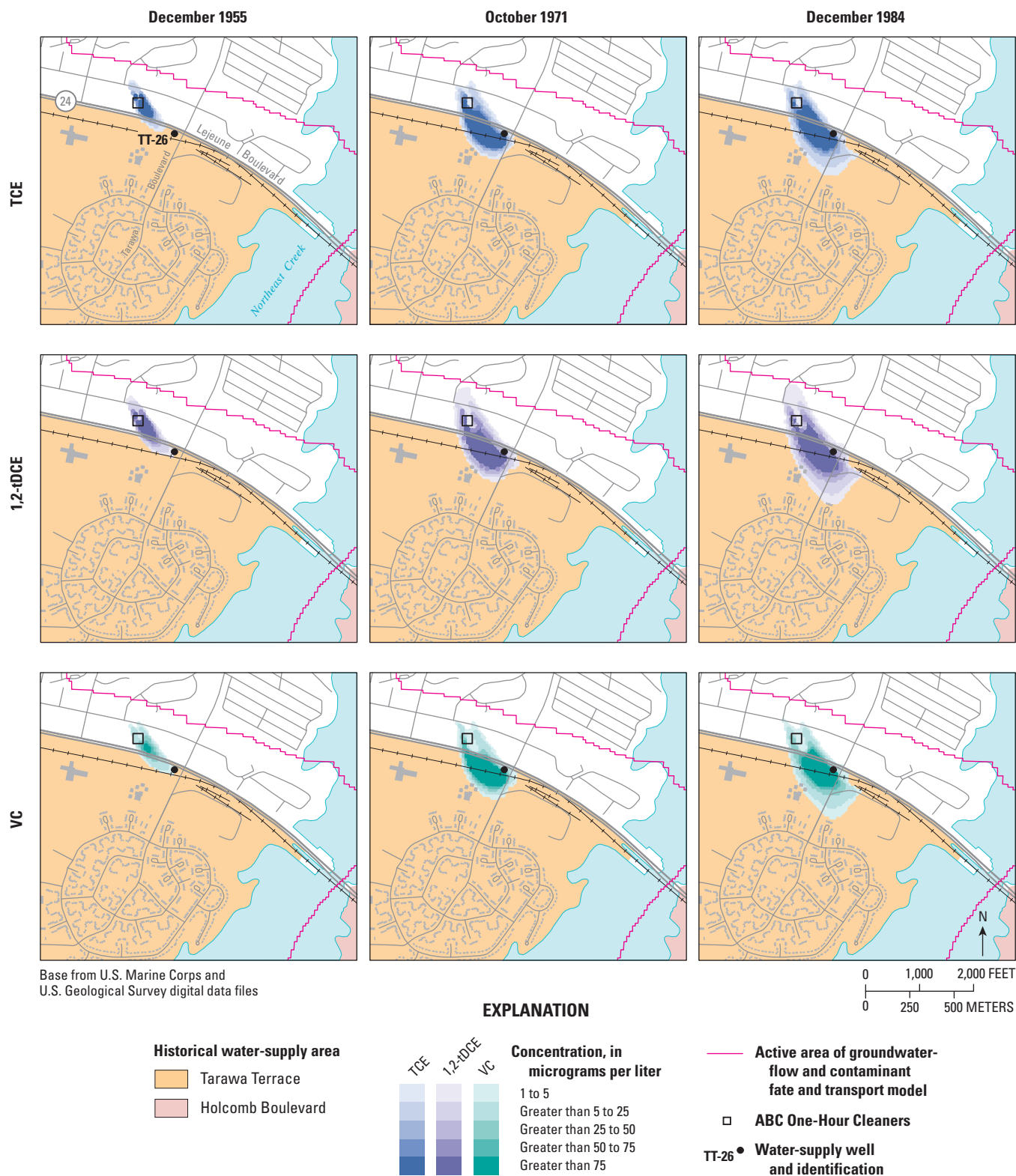


Figure G18. Simulated concentration distributions of trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) in the water phase for model layer 1, Pumping Schedule A (PS-A), December 1955, October 1971, and December 1984, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

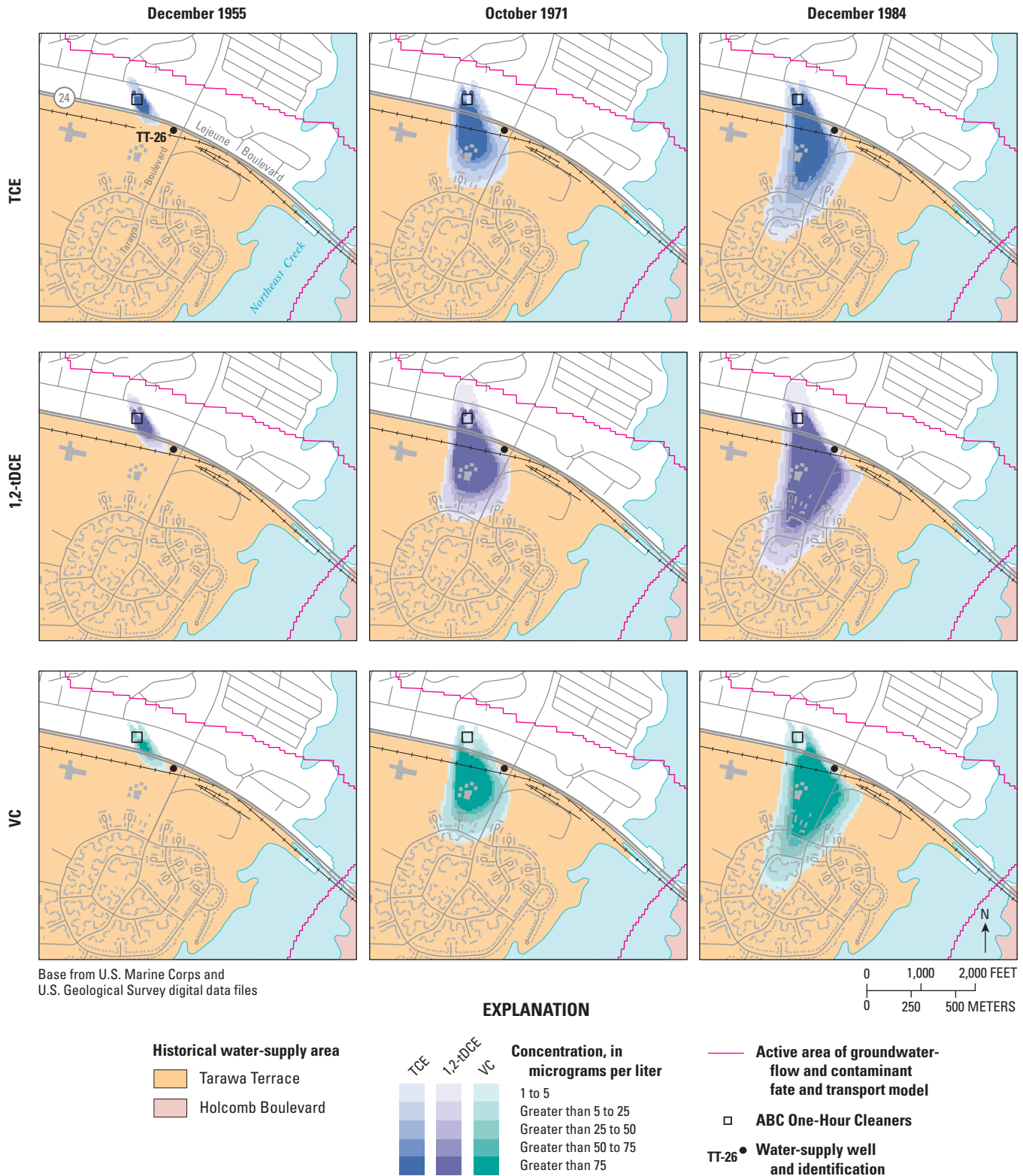


Figure G19. Simulated concentration distributions of trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) in the water phase for model layer 1, Pumping Schedule B (PS-B), December 1955, October 1971, and December 1984, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

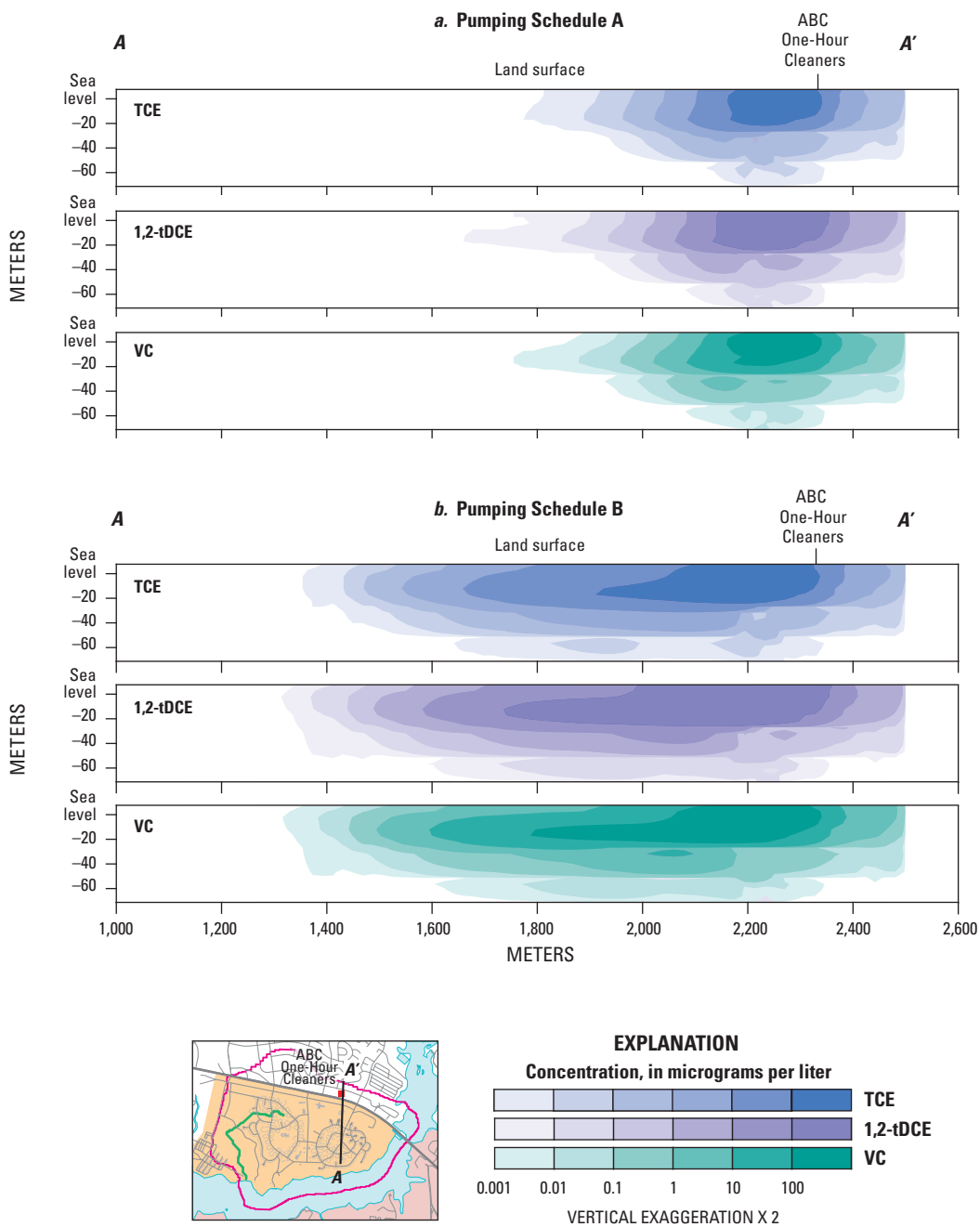
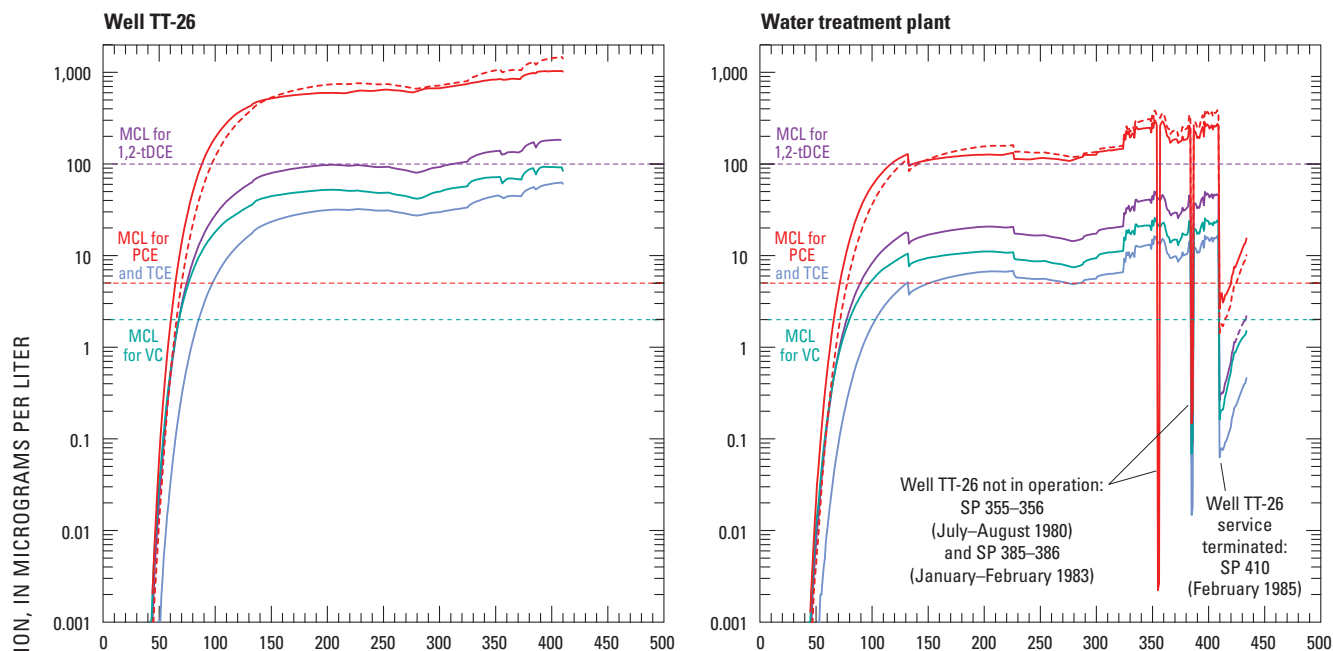


Figure G20. Vertical concentration profiles of trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) in the water phase for (a) Pumping Schedule A and (b) Pumping Schedule B, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

a. Pumping Schedule A



b. Pumping Schedule B

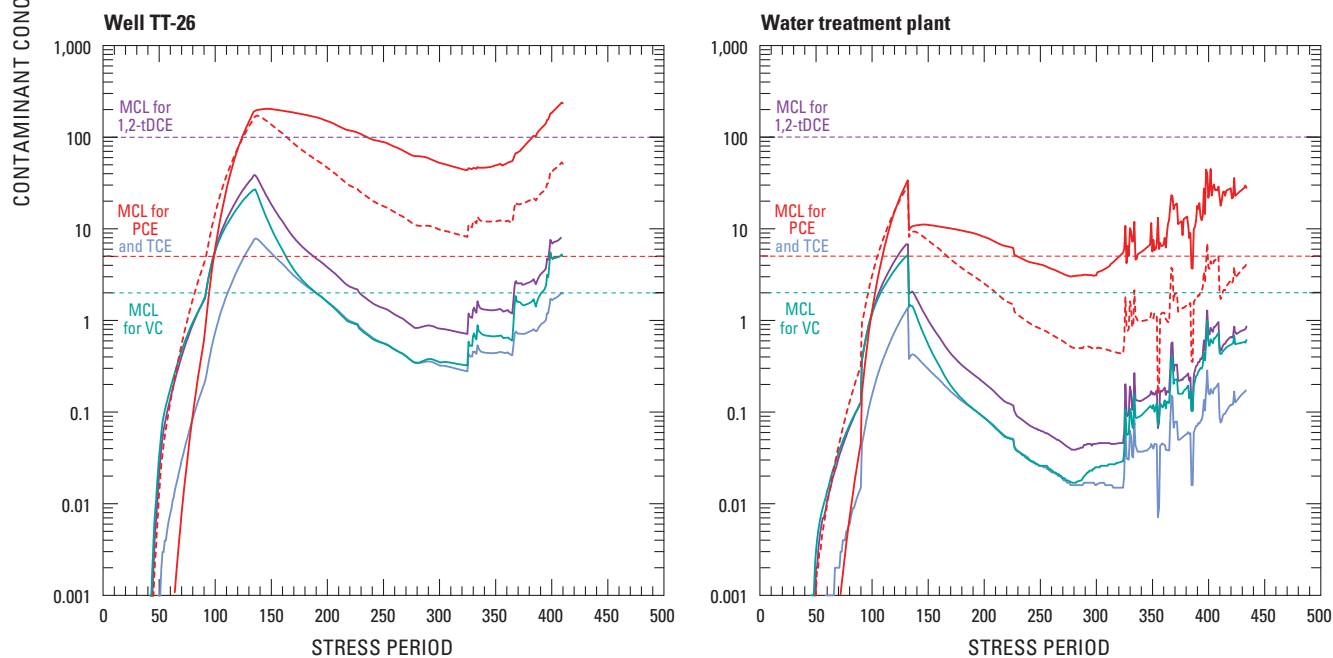


Figure G21. Concentration of tetrachloroethylene (PCE) and degradation by-products trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at water-supply well TT-26 and in finished water from the water treatment plant for (a) Pumping Schedule A and (b) Pumping Schedule B, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [MCL, maximum contaminant level; see Appendix G1 for stress periods (SP)]

EXPLANATION	
Contaminant	Model
— (solid red)	} MT3DMS
- - - (dashed red)	
— (solid purple)	} TechFlowMP
— (solid green)	
— (solid blue)	

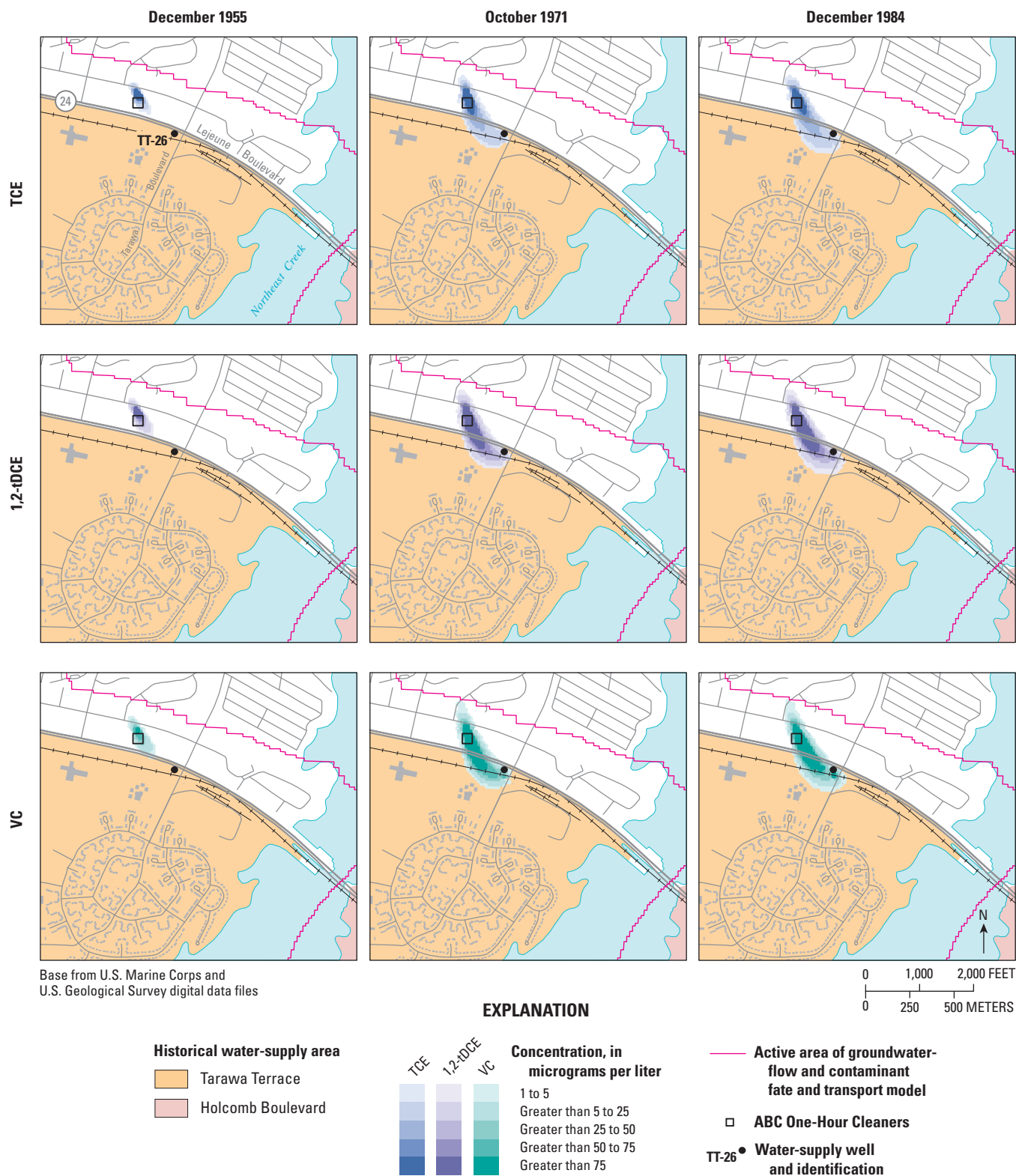


Figure G22. Simulated concentration distributions of trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) in the gas phase for model layer 1, Pumping Schedule A (PS-A), December 1955, October 1971, and December 1984, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

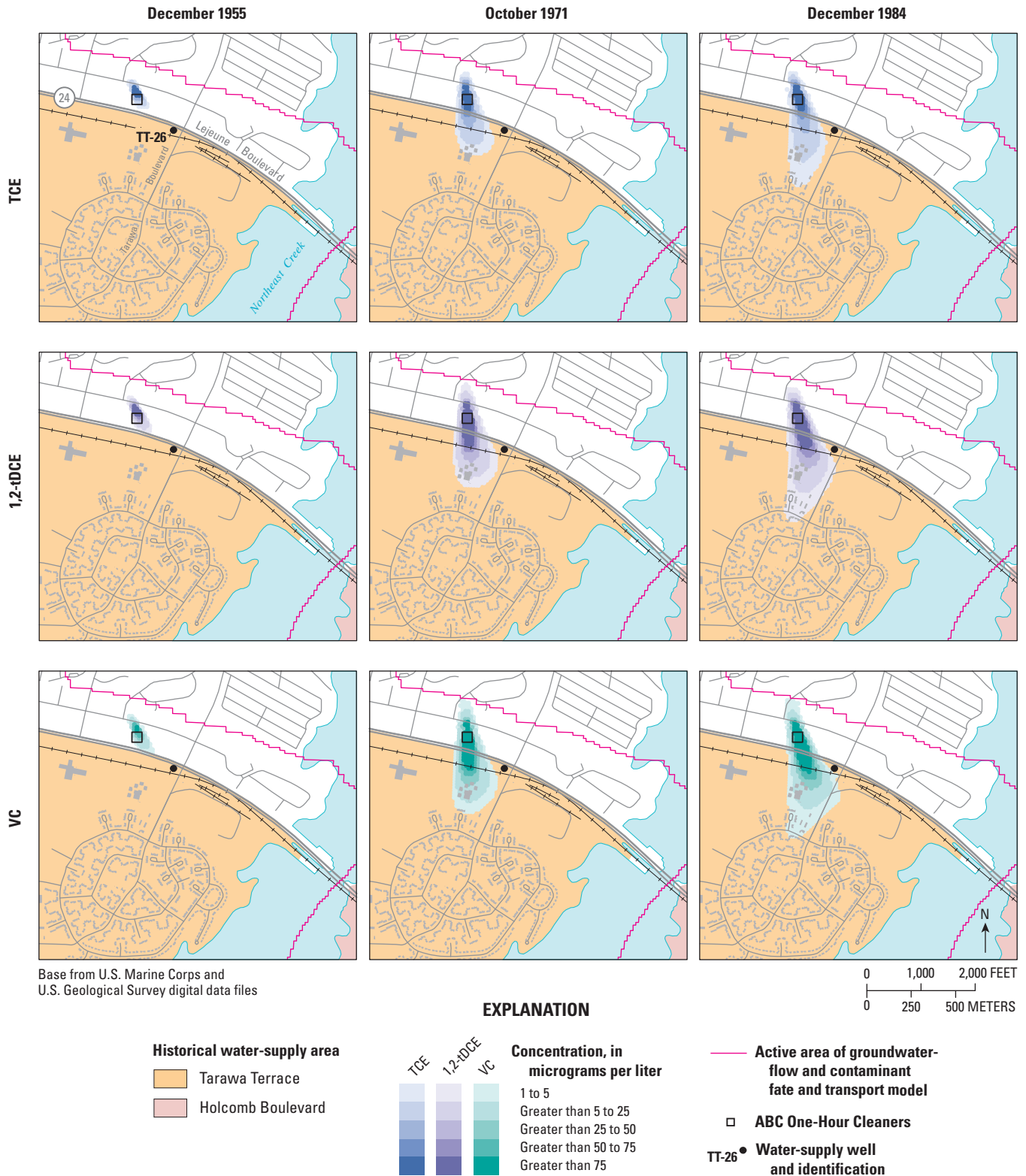


Figure G23. Simulated concentration distributions of trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) in the gas phase for model layer 1, Pumping Schedule B (PS-B), December 1955, October 1971, and December 1984, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

The simulated mass balances of the fate of PCE, TCE, 1,2-tDCE, and VC are presented in Figures G24 and G25 for PS-A and PS-B, respectively. PS-A is intended to maximize contaminant withdrawal by groundwater pumping. In Figure G24a, the percentage of PCE during groundwater pumping shows significant increases when compared to that observed under PS-O (Figure G12a). During October 1971 (stress period 250), the percentage of PCE for groundwater pumping approaches 17.8 percent for PS-A compared with about 7.6 percent for PS-O. The higher withdrawal of PCE by groundwater pumping for PS-A results in a greater reduction in PCE mass in water and soil phases and a lower atmospheric release of PCE (Figure G24a). Reduction of PCE concentration in the water phase leads to a decrease in PCE biotransformation in the subsurface. During December 1984 (stress period 408) for PS-A, the groundwater pumping percentage of PCE is 27.3 percent, which exceeds the percentage of PCE under PS-O conditions (10.8 percent) by a factor of 2. During December 1984 (stress period 408) for PS-A, PCE biotransformation and atmospheric release percentages are 39.1 and 9.6 percent, respectively, and

the percentages of PCE in water, gas, and soil phases are 7.8, 0.11, and 16.0 percent, respectively.

As shown in Figure G24b, the withdrawal of TCE by groundwater pumping increases, but other temporal TCE profiles for water, gas, soil, biotransformation, and atmospheric release show smaller values than those occurring under PS-O. During December 1984 (stress period 408), the percentage of TCE in groundwater is 3.3 percent for PS-A, which is greater than the 1.2 percent for PS-O. Percentages of TCE for biotransformation and atmospheric release for PS-A are 93.5 and 0.79 percent, respectively; the relative percentages of TCE in water, gas, and soil phases for PS-A are 0.89, 0.01, and 1.29 percent, respectively.

Profiles of 1,2-tDCE (Figure G24c) and VC (Figure G24d) for PS-A have similar trends when compared with corresponding profiles occurring for PS-O (Figures G12c and G12d), with the exception of profiles of the contaminant removal by groundwater pumping. For PS-A, removal of 1,2-tDCE and VC by groundwater pumping also is enhanced. During December 1984 (stress period 408) for PS-A, the

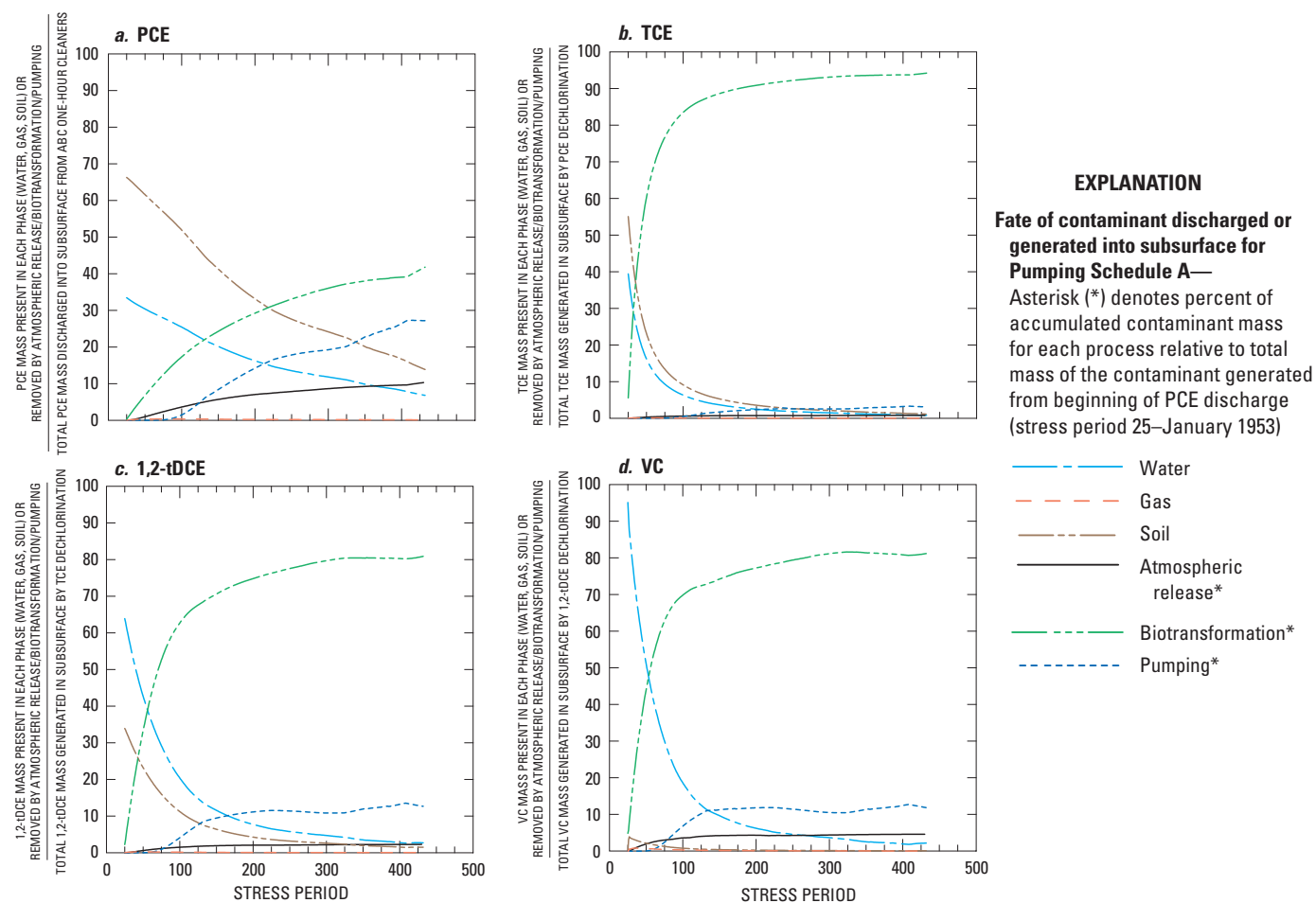


Figure G24. The fate of (a) tetrachloroethylene (PCE) and degradation by-products (b) trichloroethylene (TCE), (c) *trans*-1,2-dichloroethylene (1,2-tDCE), and (d) vinyl chloride (VC) derived from materials mass balance calculations, Pumping Schedule A, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [y-axis value, in percent; see Appendix G1 for stress periods]

percentages of 1,2-tDCE and VC removed by groundwater pumping approach 13.5 and 12.6 percent, respectively. These percentages exceed the percentages obtained under PS-O during December 1984 (stress period 408) for 1,2-tDCE (4.9 percent) and VC (4.7 percent) by more than a factor of 2.

PS-B intends to minimize contaminant removal by groundwater pumping. This results in an increase of contaminant mass in the subsurface. Simulated mass balances for the fate of PCE, TCE, 1,2-tDCE, and VC for PS-B are shown in Figure G25. The PCE percentage for groundwater pumping (Figure G25a) is reduced considerably compared to PS-O (Figure G12a) and PS-A (Figure G24a). For PS-B, during December 1984 (stress period 408), the percentages of PCE, TCE, 1,2-tDCE, and VC extracted by groundwater pumping are about 0.7, 0.07, 0.40, and 0.47 percent, respectively, of the total mass of each compound generated in the subsurface. For PS-B, as contaminant extraction by groundwater pumping from the subsurface decreases, contaminant mass in the subsurface increases. During December 1984 (stress period 408), the relative ratios of PCE in water, gas, and soil phases to the total PCE discharged are approximately 12.4, 0.14, and

25.2 percent, respectively. These percentages are greater than those for PS-A and PS-O. During this same stress period (408) for PS-B, percentages of PCE for biotransformation and atmospheric release are about 50.6 and 11.0 percent, respectively.

In Figures G12, G24, and G25 for the three pumping schedules (PS-O, PS-A, and PS-B), changes in groundwater pumping schedules cause variation in total contaminant mass within each phase (or contaminant percentages within each phase) and contaminant fate in the subsurface because the contaminant partitioning between phases and transport processes are coupled in determining the overall fate of contaminants. Regardless of the three pumping schedules, however, distribution ratios of contaminants within phases in the subsurface (excluding contaminants for biotransformation, groundwater pumping, and atmospheric release) show almost uniform values throughout the simulation period. For PCE, average values of distribution ratios (contaminant mass in each phase divided by contaminant total mass solely within the subsurface) are approximately 32.8 percent in water (30.7 percent in the saturated-zone water and 2.1 percent in the unsaturated-zone water), 66.8 percent in soil, and 0.4 percent in the gas phase in the unsaturated zone.

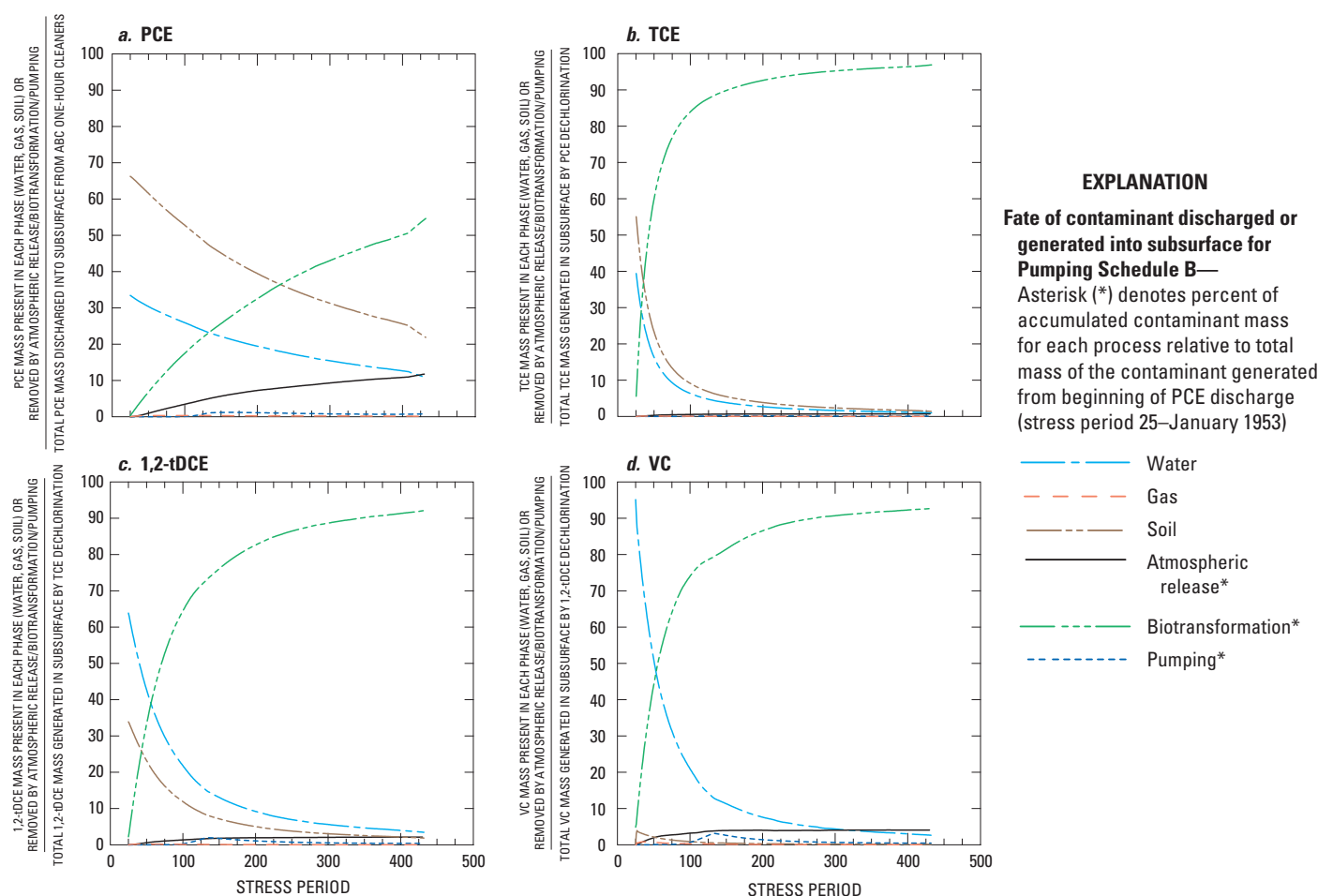


Figure G25. The fate of (a) tetrachloroethylene (PCE) and degradation by-products (b) trichloroethylene (TCE), (c) *trans*-1,2-dichloroethylene (1,2-tDCE), and (d) vinyl chloride (VC) derived from materials mass balance calculations, Pumping Schedule B, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [y-axis value, in percent; see Appendix G1 for stress periods]

Summary and Conclusions

The transport and biotransformation of tetrachloroethylene (PCE) and its associated by-products—trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC)—were simulated for the period January 1951–December 1994 using the TechFlowMP model (Jang and Aral 2005b). In modeling groundwater flow, geological and hydraulic parameters—initially calibrated using the MODFLOW model (Faye and Valenzuela 2007)—were imported into TechFlowMP, and then used in TechFlowMP simulations without modification. There was agreement between groundwater-flow results obtained from the MODFLOW and TechFlowMP model simulations. Groundwater piezometric head results obtained from TechFlowMP were used to calculate groundwater-flow directions and velocities, which are required in multispecies transport modeling.

Using TechFlowMP groundwater-flow results, three simulations were conducted to determine the fate and transport of PCE and its by-products. The three simulations had different pumping schedules for Tarawa Terrace water-supply wells: (1) Original Pumping Schedule (PS-O), (2) Pumping Schedule A (PS-A), and (3) Pumping Schedule B (PS-B). Under PS-A conditions, the concentration in finished water at the Tarawa Terrace water treatment plant (WTP) is maximized; under PS-B conditions, the concentration in finished water at the WTP is minimized. For the three pumping schedules, plume development of PCE, TCE, 1,2-tDCE, and VC in water and gas phases were simulated and are presented as a series of maps and graphs. Contaminant plume development in the subsurface under PS-A conditions is smaller than under PS-O conditions due to greater contaminant removal by water-supply wells under PS-A conditions. As a comparison, contaminant plume development under PS-B conditions is greater than under PS-O conditions.

For the three pumping schedules, PCE concentration profiles at water-supply well TT-26 and at the WTP, derived using the TechFlowMP simulations, are compared with those obtained from MT3DMS simulations (Faye 2008). The increase in the plume size of PCE-contaminated groundwater and the concentration of PCE in the subsurface raised the atmospheric release of PCE from the subsurface. The greatest effect of the atmospheric release occurs under PS-B conditions, which show the largest PCE plume in the subsurface among the three pumping schedules during the same stress period.

For PS-O, TechFlowMP simulation shows that PCE concentration exceeds the current maximum contaminant level (MCL) for PCE (5 micrograms per liter [$\mu\text{g/L}$]) at water-supply well TT-26 during February 1957 and at the WTP during January 1958. During the simulation period of 1951–1984, the maximum concentration of PCE in groundwater at well TT-26 is 775 $\mu\text{g/L}$, and the maximum concentration in finished water at the WTP is 158 $\mu\text{g/L}$. During the period February 1957–February 1985, the average

concentration of PCE in groundwater at well TT-26 is approximately 336 $\mu\text{g/L}$, and the average concentration in finished water at the WTP is approximately 57 $\mu\text{g/L}$. During this period, the average concentrations of TCE, 1,2-tDCE, and VC in finished water at the WTP are about 2, 8, and 4 $\mu\text{g/L}$, respectively.

For PS-A, the concentration of PCE exceeds the current MCL (5 $\mu\text{g/L}$) for groundwater at water-supply well TT-26 during November 1956 and in finished water at the WTP during June 1957. During November 1956–February 1985, the average concentrations of PCE, TCE, 1,2-tDCE, and VC in finished water at the WTP are about 155, 7, 21, and 11 $\mu\text{g/L}$, respectively. For PS-B, the concentration of PCE exceeds its current MCL for groundwater at well TT-26 during August 1958 and in finished water at the WTP during September 1959. During August 1958–February 1985, average concentrations of PCE, TCE, 1,2-tDCE, and VC at the WTP are 4, 0.1, 0.7, and 0.5 $\mu\text{g/L}$, respectively.

Simulation results indicate that pumping schedules play an important role in determining the fate of PCE and its associated by-products. As contaminant withdrawals increase, owing to increasing water-supply well pumping, contaminant concentrations in the subsurface decrease. In this study, the percentage of biotransformation is the largest component among the fate of all contaminants, and the percentage increases continuously with time. The percentage of atmospheric release of contaminants in the overall contaminant mass balance also increases with contaminant plume spread, which contributes to the reduction of contaminant mass in the subsurface.

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Appendix G1. Simulation Stress Periods and Corresponding Month and Year

Appendix G1. Simulation stress periods and corresponding month and year.

[Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Nov, November; Dec, December]

Stress period	Month and year	Stress period	Month and year	Stress period	Month and year	Stress period	Month and year	Stress period	Month and year	Stress period	Month and year
1	Jan 1951	49	Jan 1955	97	Jan 1959	145	Jan 1963	193	Jan 1967	241	Jan 1971
2	Feb 1951	50	Feb 1955	98	Feb 1959	146	Feb 1963	194	Feb 1967	242	Feb 1971
3	Mar 1951	51	Mar 1955	99	Mar 1959	147	Mar 1963	195	Mar 1967	243	Mar 1971
4	Apr 1951	52	Apr 1955	100	Apr 1959	148	Apr 1963	196	Apr 1967	244	Apr 1971
5	May 1951	53	May 1955	101	May 1959	149	May 1963	197	May 1967	245	May 1971
6	June 1951	54	June 1955	102	June 1959	150	June 1963	198	June 1967	246	June 1971
7	July 1951	55	July 1955	103	July 1959	151	July 1963	199	July 1967	247	July 1971
8	Aug 1951	56	Aug 1955	104	Aug 1959	152	Aug 1963	200	Aug 1967	248	Aug 1971
9	Sept 1951	57	Sept 1955	105	Sept 1959	153	Sept 1963	201	Sept 1967	249	Sept 1971
10	Oct 1951	58	Oct 1955	106	Oct 1959	154	Oct 1963	202	Oct 1967	250	Oct 1971
11	Nov 1951	59	Nov 1955	107	Nov 1959	155	Nov 1963	203	Nov 1967	251	Nov 1971
12	Dec 1951	60	Dec 1955	108	Dec 1959	156	Dec 1963	204	Dec 1967	252	Dec 1971
13	Jan 1952	61	Jan 1956	109	Jan 1960	157	Jan 1964	205	Jan 1968	253	Jan 1972
14	Feb 1952	62	Feb 1956	110	Feb 1960	158	Feb 1964	206	Feb 1968	254	Feb 1972
15	Mar 1952	63	Mar 1956	111	Mar 1960	159	Mar 1964	207	Mar 1968	255	Mar 1972
16	Apr 1952	64	Apr 1956	112	Apr 1960	160	Apr 1964	208	Apr 1968	256	Apr 1972
17	May 1952	65	May 1956	113	May 1960	161	May 1964	209	May 1968	257	May 1972
18	June 1952	66	June 1956	114	June 1960	162	June 1964	210	June 1968	258	June 1972
19	July 1952	67	July 1956	115	July 1960	163	July 1964	211	July 1968	259	July 1972
20	Aug 1952	68	Aug 1956	116	Aug 1960	164	Aug 1964	212	Aug 1968	260	Aug 1972
21	Sept 1952	69	Sept 1956	117	Sept 1960	165	Sept 1964	213	Sept 1968	261	Sept 1972
22	Oct 1952	70	Oct 1956	118	Oct 1960	166	Oct 1964	214	Oct 1968	262	Oct 1972
23	Nov 1952	71	Nov 1956	119	Nov 1960	167	Nov 1964	215	Nov 1968	263	Nov 1972
24	Dec 1952	72	Dec 1956	120	Dec 1960	168	Dec 1964	216	Dec 1968	264	Dec 1972
25	Jan 1953	73	Jan 1957	121	Jan 1961	169	Jan 1965	217	Jan 1969	265	Jan 1973
26	Feb 1953	74	Feb 1957	122	Feb 1961	170	Feb 1965	218	Feb 1969	266	Feb 1973
27	Mar 1953	75	Mar 1957	123	Mar 1961	171	Mar 1965	219	Mar 1969	267	Mar 1973
28	Apr 1953	76	Apr 1957	124	Apr 1961	172	Apr 1965	220	Apr 1969	268	Apr 1973
29	May 1953	77	May 1957	125	May 1961	173	May 1965	221	May 1969	269	May 1973
30	June 1953	78	June 1957	126	June 1961	174	June 1965	222	June 1969	270	June 1973
31	July 1953	79	July 1957	127	July 1961	175	July 1965	223	July 1969	271	July 1973
32	Aug 1953	80	Aug 1957	128	Aug 1961	176	Aug 1965	224	Aug 1969	272	Aug 1973
33	Sept 1953	81	Sept 1957	129	Sept 1961	177	Sept 1965	225	Sept 1969	273	Sept 1973
34	Oct 1953	82	Oct 1957	130	Oct 1961	178	Oct 1965	226	Oct 1969	274	Oct 1973
35	Nov 1953	83	Nov 1957	131	Nov 1961	179	Nov 1965	227	Nov 1969	275	Nov 1973
36	Dec 1953	84	Dec 1957	132	Dec 1961	180	Dec 1965	228	Dec 1969	276	Dec 1973
37	Jan 1954	85	Jan 1958	133	Jan 1962	181	Jan 1966	229	Jan 1970	277	Jan 1974
38	Feb 1954	86	Feb 1958	134	Feb 1962	182	Feb 1966	230	Feb 1970	278	Feb 1974
39	Mar 1954	87	Mar 1958	135	Mar 1962	183	Mar 1966	231	Mar 1970	279	Mar 1974
40	Apr 1954	88	Apr 1958	136	Apr 1962	184	Apr 1966	232	Apr 1970	280	Apr 1974
41	May 1954	89	May 1958	137	May 1962	185	May 1966	233	May 1970	281	May 1974
42	June 1954	90	June 1958	138	June 1962	186	June 1966	234	June 1970	282	June 1974
43	July 1954	91	July 1958	139	July 1962	187	July 1966	235	July 1970	283	July 1974
44	Aug 1954	92	Aug 1958	140	Aug 1962	188	Aug 1966	236	Aug 1970	284	Aug 1974
45	Sept 1954	93	Sept 1958	141	Sept 1962	189	Sept 1966	237	Sept 1970	285	Sept 1974
46	Oct 1954	94	Oct 1958	142	Oct 1962	190	Oct 1966	238	Oct 1970	286	Oct 1974
47	Nov 1954	95	Nov 1958	143	Nov 1962	191	Nov 1966	239	Nov 1970	287	Nov 1974
48	Dec 1954	96	Dec 1958	144	Dec 1962	192	Dec 1966	240	Dec 1970	288	Dec 1974

Appendix G1. Simulation stress periods and corresponding month and year.—Continued

[Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Nov, November; Dec, December]

Stress period	Month and year	Stress period	Month and year	Stress period	Month and year	Stress period	Month and year	Stress period	Month and year
289	Jan 1975	337	Jan 1979	385	Jan 1983	433	Jan 1987	481	Jan 1991
290	Feb 1975	338	Feb 1979	386	Feb 1983	434	Feb 1987	482	Feb 1991
291	Mar 1975	339	Mar 1979	387	Mar 1983	435	Mar 1987	483	Mar 1991
292	Apr 1975	340	Apr 1979	388	Apr 1983	436	Apr 1987	484	Apr 1991
293	May 1975	341	May 1979	389	May 1983	437	May 1987	485	May 1991
294	June 1975	342	June 1979	390	June 1983	438	June 1987	486	June 1991
295	July 1975	343	July 1979	391	July 1983	439	July 1987	487	July 1991
296	Aug 1975	344	Aug 1979	392	Aug 1983	440	Aug 1987	488	Aug 1991
297	Sept 1975	345	Sept 1979	393	Sept 1983	441	Sept 1987	489	Sept 1991
298	Oct 1975	346	Oct 1979	394	Oct 1983	442	Oct 1987	490	Oct 1991
299	Nov 1975	347	Nov 1979	395	Nov 1983	443	Nov 1987	491	Nov 1991
300	Dec 1975	348	Dec 1979	396	Dec 1983	444	Dec 1987	492	Dec 1991
301	Jan 1976	349	Jan 1980	397	Jan 1984	445	Jan 1988	493	Jan 1992
302	Feb 1976	350	Feb 1980	398	Feb 1984	446	Feb 1988	494	Feb 1992
303	Mar 1976	351	Mar 1980	399	Mar 1984	447	Mar 1988	495	Mar 1992
304	Apr 1976	352	Apr 1980	400	Apr 1984	448	Apr 1988	496	Apr 1992
305	May 1976	353	May 1980	401	May 1984	449	May 1988	497	May 1992
306	June 1976	354	June 1980	402	June 1984	450	June 1988	498	June 1992
307	July 1976	355	July 1980	403	July 1984	451	July 1988	499	July 1992
308	Aug 1976	356	Aug 1980	404	Aug 1984	452	Aug 1988	500	Aug 1992
309	Sept 1976	357	Sept 1980	405	Sept 1984	453	Sept 1988	501	Sept 1992
310	Oct 1976	358	Oct 1980	406	Oct 1984	454	Oct 1988	502	Oct 1992
311	Nov 1976	359	Nov 1980	407	Nov 1984	455	Nov 1988	503	Nov 1992
312	Dec 1976	360	Dec 1980	408	Dec 1984	456	Dec 1988	504	Dec 1992
313	Jan 1977	361	Jan 1981	409	Jan 1985	457	Jan 1989	505	Jan 1993
314	Feb 1977	362	Feb 1981	410	Feb 1985	458	Feb 1989	506	Feb 1993
315	Mar 1977	363	Mar 1981	411	Mar 1985	459	Mar 1989	507	Mar 1993
316	Apr 1977	364	Apr 1981	412	Apr 1985	460	Apr 1989	508	Apr 1993
317	May 1977	365	May 1981	413	May 1985	461	May 1989	509	May 1993
318	June 1977	366	June 1981	414	June 1985	462	June 1989	510	June 1993
319	July 1977	367	July 1981	415	July 1985	463	July 1989	511	July 1993
320	Aug 1977	368	Aug 1981	416	Aug 1985	464	Aug 1989	512	Aug 1993
321	Sept 1977	369	Sept 1981	417	Sept 1985	465	Sept 1989	513	Sept 1993
322	Oct 1977	370	Oct 1981	418	Oct 1985	466	Oct 1989	514	Oct 1993
323	Nov 1977	371	Nov 1981	419	Nov 1985	467	Nov 1989	515	Nov 1993
324	Dec 1977	372	Dec 1981	420	Dec 1985	468	Dec 1989	516	Dec 1993
325	Jan 1978	373	Jan 1982	421	Jan 1986	469	Jan 1990	517	Jan 1994
326	Feb 1978	374	Feb 1982	422	Feb 1986	470	Feb 1990	518	Feb 1994
327	Mar 1978	375	Mar 1982	423	Mar 1986	471	Mar 1990	519	Mar 1994
328	Apr 1978	376	Apr 1982	424	Apr 1986	472	Apr 1990	520	Apr 1994
329	May 1978	377	May 1982	425	May 1986	473	May 1990	521	May 1994
330	June 1978	378	June 1982	426	June 1986	474	June 1990	522	June 1994
331	July 1978	379	July 1982	427	July 1986	475	July 1990	523	July 1994
332	Aug 1978	380	Aug 1982	428	Aug 1986	476	Aug 1990	524	Aug 1994
333	Sept 1978	381	Sept 1982	429	Sept 1986	477	Sept 1990	525	Sept 1994
334	Oct 1978	382	Oct 1982	430	Oct 1986	478	Oct 1990	526	Oct 1994
335	Nov 1978	383	Nov 1982	431	Nov 1986	479	Nov 1990	527	Nov 1994
336	Dec 1978	384	Dec 1982	432	Dec 1986	480	Dec 1990	528	Dec 1994

Appendix G2. Simulated Tetrachloroethylene (PCE) and PCE Degradation By-Products in Finished Water at the Tarawa Terrace Water Treatment Plant and in Groundwater at Water-Supply Wells TT-23, TT-25, and TT-26, January 1951–December 1994, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina

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Table G2.1. Simulated tetrachloroethylene (PCE) and PCE degradation by-products in finished water at the Tarawa Terrace water treatment plant, January 1951–December 1994,¹ Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[TCE, trichloroethylene; 1,2-tDCE, trans-1,2-dichloroethylene; VC, vinyl chloride; all values are in micrograms per liter and were obtained using the TechFlowMP model]

Stress period	Month and year	PCE	TCE	1,2-tDCE	VC	Stress period	Month and year	PCE	TCE	1,2-tDCE	VC	
1–12	Jan 1951–Dec 1951	No pumping					61	Jan 1956	0.11	0.01	0.10	0.12
13	Jan 1952	0.00	0.00	0.00	0.00	62	Feb 1956	0.14	0.01	0.12	0.14	
14	Feb 1952	0.00	0.00	0.00	0.00	63	Mar 1956	0.17	0.01	0.15	0.17	
15	Mar 1952	0.00	0.00	0.00	0.00	64	Apr 1956	0.22	0.01	0.18	0.20	
16	Apr 1952	0.00	0.00	0.00	0.00	65	May 1956	0.27	0.02	0.21	0.23	
17	May 1952	0.00	0.00	0.00	0.00	66	June 1956	0.33	0.02	0.25	0.26	
18	June 1952	0.00	0.00	0.00	0.00	67	July 1956	0.40	0.02	0.29	0.30	
19	July 1952	0.00	0.00	0.00	0.00	68	Aug 1956	0.49	0.03	0.33	0.34	
20	Aug 1952	0.00	0.00	0.00	0.00	69	Sept 1956	0.59	0.03	0.38	0.39	
21	Sept 1952	0.00	0.00	0.00	0.00	70	Oct 1956	0.70	0.04	0.44	0.44	
22	Oct 1952	0.00	0.00	0.00	0.00	71	Nov 1956	0.83	0.05	0.50	0.49	
23	Nov 1952	0.00	0.00	0.00	0.00	72	Dec 1956	0.97	0.06	0.57	0.55	
24	Dec 1952	0.00	0.00	0.00	0.00	73	Jan 1957	1.14	0.06	0.64	0.61	
25	Jan 1953	0.00	0.00	0.00	0.00	74	Feb 1957	1.33	0.07	0.72	0.68	
26	Feb 1953	0.00	0.00	0.00	0.00	75	Mar 1957	1.52	0.08	0.79	0.74	
27	Mar 1953	0.00	0.00	0.00	0.00	76	Apr 1957	1.75	0.10	0.88	0.81	
28	Apr 1953	0.00	0.00	0.00	0.00	77	May 1957	2.00	0.11	0.97	0.89	
29	May 1953	0.00	0.00	0.00	0.00	78	June 1957	2.28	0.12	1.08	0.97	
30	June 1953	0.00	0.00	0.00	0.00	79	July 1957	2.59	0.14	1.18	1.05	
31	July 1953	0.00	0.00	0.00	0.00	80	Aug 1957	2.93	0.16	1.29	1.13	
32	Aug 1953	0.00	0.00	0.00	0.00	81	Sept 1957	3.30	0.17	1.41	1.23	
33	Sept 1953	0.00	0.00	0.00	0.00	82	Oct 1957	3.69	0.19	1.53	1.32	
34	Oct 1953	0.00	0.00	0.00	0.00	83	Nov 1957	4.13	0.22	1.66	1.41	
35	Nov 1953	0.00	0.00	0.00	0.00	84	Dec 1957	4.59	0.24	1.80	1.51	
36	Dec 1953	0.00	0.00	0.00	0.00	85	Jan 1958	5.11	0.26	1.94	1.62	
37	Jan 1954	0.00	0.00	0.00	0.00	86	Feb 1958	5.65	0.29	2.09	1.72	
38	Feb 1954	0.00	0.00	0.00	0.00	87	Mar 1958	6.17	0.31	2.22	1.81	
39	Mar 1954	0.00	0.00	0.00	0.00	88	Apr 1958	6.79	0.34	2.38	1.92	
40	Apr 1954	0.00	0.00	0.00	0.00	89	May 1958	7.41	0.37	2.53	2.02	
41	May 1954	0.00	0.00	0.00	0.00	90	June 1958	8.10	0.41	2.70	2.13	
42	June 1954	0.00	0.00	0.00	0.00	91	July 1958	9.09	0.45	2.96	2.32	
43	July 1954	0.00	0.00	0.00	0.00	92	Aug 1958	9.88	0.49	3.14	2.44	
44	Aug 1954	0.00	0.00	0.00	0.00	93	Sept 1958	10.73	0.53	3.33	2.56	
45	Sept 1954	0.00	0.00	0.00	0.00	94	Oct 1958	11.58	0.57	3.52	2.68	
46	Oct 1954	0.00	0.00	0.00	0.00	95	Nov 1958	12.52	0.61	3.72	2.81	
47	Nov 1954	0.00	0.00	0.00	0.00	96	Dec 1958	13.46	0.66	3.92	2.94	
48	Dec 1954	0.00	0.00	0.00	0.00	97	Jan 1959	14.48	0.71	4.13	3.07	
49	Jan 1955	0.00	0.00	0.00	0.01	98	Feb 1959	15.54	0.76	4.34	3.21	
50	Feb 1955	0.00	0.00	0.01	0.01	99	Mar 1959	16.54	0.80	4.54	3.33	
51	Mar 1955	0.01	0.00	0.01	0.01	100	Apr 1959	17.70	0.85	4.77	3.48	
52	Apr 1955	0.01	0.00	0.01	0.02	101	May 1959	18.84	0.91	4.99	3.61	
53	May 1955	0.01	0.00	0.01	0.02	102	June 1959	20.09	0.96	5.23	3.77	
54	June 1955	0.01	0.00	0.02	0.03	103	July 1959	21.34	1.02	5.46	3.91	
55	July 1955	0.02	0.00	0.03	0.03	104	Aug 1959	22.66	1.08	5.69	4.05	
56	Aug 1955	0.03	0.00	0.03	0.04	105	Sept 1959	24.01	1.14	5.93	4.19	
57	Sept 1955	0.04	0.00	0.04	0.05	106	Oct 1959	25.35	1.20	6.16	4.32	
58	Oct 1955	0.05	0.00	0.05	0.07	107	Nov 1959	26.77	1.27	6.40	4.46	
59	Nov 1955	0.06	0.00	0.07	0.08	108	Dec 1959	28.18	1.33	6.64	4.60	
60	Dec 1955	0.08	0.01	0.08	0.10							

Table G2.1. Simulated tetrachloroethylene (PCE) and PCE degradation by-products in finished water at the Tarawa Terrace water treatment plant, January 1951–December 1994,¹ Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[TCE, trichloroethylene; 1,2-tDCE, trans-1,2-dichloroethylene; VC, vinyl chloride; all values are in micrograms per liter and were obtained using the TechFlowMP model]

Stress period	Month and year	PCE	TCE	1,2-tDCE	VC	Stress period	Month and year	PCE	TCE	1,2-tDCE	VC
109	Jan 1960	29.67	1.40	6.88	4.74	157	Jan 1964	60.89	2.59	8.67	4.83
110	Feb 1960	31.17	1.46	7.12	4.86	158	Feb 1964	54.39	2.31	7.69	4.27
111	Mar 1960	32.58	1.52	7.33	4.97	159	Mar 1964	54.42	2.30	7.58	4.17
112	Apr 1960	34.16	1.59	7.57	5.10	160	Apr 1964	54.43	2.29	7.50	4.10
113	May 1960	35.67	1.66	7.79	5.21	161	May 1964	54.36	2.29	7.42	4.04
114	June 1960	37.24	1.73	8.03	5.33	162	June 1964	54.29	2.28	7.35	3.98
115	July 1960	38.79	1.80	8.26	5.45	163	July 1964	54.21	2.27	7.28	3.93
116	Aug 1960	40.45	1.87	8.51	5.59	164	Aug 1964	54.14	2.26	7.22	3.88
117	Sept 1960	42.13	1.94	8.76	5.73	165	Sept 1964	54.06	2.26	7.16	3.84
118	Oct 1960	43.80	2.02	9.02	5.86	166	Oct 1964	53.99	2.25	7.10	3.79
119	Nov 1960	45.57	2.09	9.28	6.01	167	Nov 1964	53.92	2.24	7.05	3.75
120	Dec 1960	47.31	2.17	9.54	6.15	168	Dec 1964	53.85	2.24	7.00	3.72
121	Jan 1961	49.15	2.25	9.82	6.30	169	Jan 1965	53.78	2.23	6.95	3.68
122	Feb 1961	51.03	2.33	10.10	6.46	170	Feb 1965	53.72	2.23	6.90	3.65
123	Mar 1961	52.73	2.41	10.35	6.61	171	Mar 1965	53.64	2.22	6.86	3.61
124	Apr 1961	54.69	2.49	10.64	6.77	172	Apr 1965	53.59	2.22	6.82	3.58
125	May 1961	56.57	2.58	10.92	6.92	173	May 1965	53.52	2.21	6.78	3.55
126	June 1961	58.53	2.66	11.20	7.07	174	June 1965	53.47	2.21	6.74	3.52
127	July 1961	60.43	2.75	11.46	7.22	175	July 1965	53.40	2.20	6.70	3.50
128	Aug 1961	62.42	2.83	11.74	7.36	176	Aug 1965	53.34	2.20	6.66	3.47
129	Sept 1961	64.40	2.92	12.01	7.51	177	Sept 1965	53.27	2.19	6.63	3.44
130	Oct 1961	66.32	3.00	12.27	7.64	178	Oct 1965	53.20	2.19	6.59	3.42
131	Nov 1961	68.33	3.09	12.55	7.79	179	Nov 1965	53.14	2.18	6.56	3.40
132	Dec 1961	70.28	3.17	12.80	7.92	180	Dec 1965	53.07	2.18	6.53	3.37
133	Jan 1962	47.74	2.15	8.63	5.32	181	Jan 1966	53.00	2.17	6.50	3.35
134	Feb 1962	49.86	2.25	9.00	5.56	182	Feb 1966	52.93	2.17	6.47	3.33
135	Mar 1962	51.28	2.31	9.17	5.64	183	Mar 1966	52.84	2.16	6.44	3.31
136	Apr 1962	52.37	2.36	9.25	5.67	184	Apr 1966	52.78	2.16	6.41	3.29
137	May 1962	53.18	2.39	9.28	5.66	185	May 1966	52.70	2.15	6.38	3.27
138	June 1962	53.88	2.41	9.28	5.63	186	June 1966	52.63	2.15	6.35	3.25
139	July 1962	54.48	2.43	9.28	5.60	187	July 1966	52.54	2.14	6.33	3.23
140	Aug 1962	55.06	2.45	9.26	5.56	188	Aug 1966	52.46	2.14	6.30	3.21
141	Sept 1962	55.59	2.46	9.24	5.52	189	Sept 1966	52.38	2.13	6.27	3.20
142	Oct 1962	56.07	2.48	9.22	5.47	190	Oct 1966	52.28	2.13	6.25	3.18
143	Nov 1962	56.54	2.49	9.19	5.42	191	Nov 1966	52.20	2.12	6.22	3.16
144	Dec 1962	56.97	2.50	9.16	5.38	192	Dec 1966	52.11	2.12	6.19	3.14
145	Jan 1963	57.40	2.51	9.13	5.33	193	Jan 1967	52.02	2.11	6.17	3.13
146	Feb 1963	57.78	2.52	9.09	5.28	194	Feb 1967	51.90	2.11	6.14	3.11
147	Mar 1963	58.11	2.53	9.06	5.24	195	Mar 1967	51.76	2.10	6.11	3.09
148	Apr 1963	58.49	2.54	9.02	5.20	196	Apr 1967	51.61	2.09	6.08	3.07
149	May 1963	58.81	2.55	8.98	5.15	197	May 1967	51.43	2.08	6.04	3.05
150	June 1963	59.14	2.56	8.94	5.11	198	June 1967	51.23	2.07	6.00	3.03
151	July 1963	59.42	2.57	8.90	5.06	199	July 1967	51.02	2.06	5.96	3.00
152	Aug 1963	59.70	2.57	8.86	5.02	200	Aug 1967	50.79	2.05	5.92	2.98
153	Sept 1963	59.97	2.57	8.82	4.98	201	Sept 1967	50.57	2.04	5.87	2.95
154	Oct 1963	60.21	2.58	8.78	4.94	202	Oct 1967	50.34	2.03	5.83	2.92
155	Nov 1963	60.45	2.58	8.74	4.90	203	Nov 1967	50.11	2.02	5.79	2.90
156	Dec 1963	60.67	2.59	8.70	4.86	204	Dec 1967	49.89	2.01	5.75	2.87

Table G2.1. Simulated tetrachloroethylene (PCE) and PCE degradation by-products in finished water at the Tarawa Terrace water treatment plant, January 1951–December 1994,¹ Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[TCE, trichloroethylene; 1,2-tDCE, trans-1,2-dichloroethylene; VC, vinyl chloride; all values are in micrograms per liter and were obtained using the TechFlowMP model]

Stress period	Month and year	PCE	TCE	1,2-tDCE	VC	Stress period	Month and year	PCE	TCE	1,2-tDCE	VC
205	Jan 1968	49.66	2.00	5.70	2.85	253	Jan 1972	41.02	1.63	4.53	2.22
206	Feb 1968	49.40	1.99	5.66	2.82	254	Feb 1972	40.49	1.61	4.44	2.17
207	Mar 1968	49.10	1.97	5.60	2.79	255	Mar 1972	40.01	1.58	4.37	2.13
208	Apr 1968	48.77	1.96	5.55	2.76	256	Apr 1972	39.51	1.56	4.30	2.09
209	May 1968	48.43	1.94	5.49	2.73	257	May 1972	39.03	1.54	4.24	2.06
210	June 1968	48.07	1.93	5.43	2.69	258	June 1972	38.55	1.52	4.17	2.02
211	July 1968	47.67	1.91	5.36	2.65	259	July 1972	38.11	1.50	4.11	1.98
212	Aug 1968	47.26	1.89	5.29	2.61	260	Aug 1972	37.68	1.48	4.05	1.95
213	Sept 1968	46.84	1.87	5.23	2.57	261	Sept 1972	37.26	1.46	3.99	1.92
214	Oct 1968	46.43	1.85	5.16	2.54	262	Oct 1972	36.88	1.45	3.94	1.89
215	Nov 1968	46.03	1.84	5.10	2.50	263	Nov 1972	36.51	1.43	3.89	1.86
216	Dec 1968	45.63	1.82	5.04	2.46	264	Dec 1972	36.15	1.42	3.85	1.84
217	Jan 1969	45.24	1.80	4.98	2.43	265	Jan 1973	41.48	1.62	4.40	2.10
218	Feb 1969	44.91	1.79	4.93	2.40	266	Feb 1973	42.32	1.67	4.57	2.21
219	Mar 1969	44.64	1.78	4.88	2.37	267	Mar 1973	42.49	1.68	4.60	2.23
220	Apr 1969	44.47	1.77	4.86	2.35	268	Apr 1973	42.42	1.68	4.60	2.24
221	May 1969	44.32	1.76	4.83	2.34	269	May 1973	42.25	1.67	4.59	2.24
222	June 1969	44.20	1.76	4.81	2.32	270	June 1973	42.05	1.66	4.58	2.25
223	July 1969	44.09	1.75	4.79	2.31	271	July 1973	41.78	1.65	4.56	2.24
224	Aug 1969	44.01	1.75	4.78	2.30	272	Aug 1973	41.53	1.64	4.53	2.23
225	Sept 1969	43.92	1.75	4.77	2.29	273	Sept 1973	41.27	1.63	4.51	2.22
226	Oct 1969	43.83	1.74	4.76	2.29	274	Oct 1973	41.01	1.62	4.48	2.21
227	Nov 1969	45.75	1.82	4.97	2.38	275	Nov 1973	40.75	1.61	4.45	2.20
228	Dec 1969	45.96	1.83	5.01	2.42	276	Dec 1973	40.48	1.60	4.42	2.19
229	Jan 1970	46.05	1.84	5.03	2.43	277	Jan 1974	40.22	1.59	4.40	2.17
230	Feb 1970	46.03	1.84	5.03	2.43	278	Feb 1974	40.13	1.59	4.39	2.17
231	Mar 1970	45.94	1.83	5.03	2.43	279	Mar 1974	40.10	1.58	4.38	2.16
232	Apr 1970	45.84	1.83	5.03	2.44	280	Apr 1974	40.20	1.59	4.40	2.17
233	May 1970	45.70	1.82	5.01	2.44	281	May 1974	40.35	1.60	4.43	2.18
234	June 1970	45.54	1.82	5.00	2.43	282	June 1974	40.59	1.61	4.48	2.21
235	July 1970	45.37	1.81	4.98	2.43	283	July 1974	40.82	1.62	4.52	2.24
236	Aug 1970	45.20	1.80	4.96	2.42	284	Aug 1974	41.08	1.63	4.57	2.27
237	Sept 1970	45.00	1.79	4.94	2.41	285	Sept 1974	41.35	1.64	4.62	2.31
238	Oct 1970	44.79	1.78	4.91	2.40	286	Oct 1974	41.61	1.65	4.68	2.34
239	Nov 1970	44.58	1.78	4.89	2.39	287	Nov 1974	41.91	1.67	4.74	2.39
240	Dec 1970	44.37	1.77	4.87	2.38	288	Dec 1974	42.19	1.68	4.81	2.43
241	Jan 1971	44.17	1.76	4.84	2.37	289	Jan 1975	43.76	1.74	5.02	2.55
242	Feb 1971	43.99	1.75	4.82	2.35	290	Feb 1975	43.90	1.75	5.06	2.59
243	Mar 1971	43.86	1.74	4.80	2.34	291	Mar 1975	44.03	1.75	5.11	2.63
244	Apr 1971	43.76	1.74	4.79	2.34	292	Apr 1975	44.18	1.76	5.16	2.68
245	May 1971	43.66	1.74	4.78	2.33	293	May 1975	44.29	1.77	5.20	2.71
246	June 1971	43.60	1.73	4.78	2.33	294	June 1975	44.38	1.77	5.24	2.75
247	July 1971	43.53	1.73	4.77	2.33	295	July 1975	44.45	1.77	5.28	2.78
248	Aug 1971	43.47	1.73	4.77	2.33	296	Aug 1975	44.52	1.78	5.31	2.81
249	Sept 1971	43.41	1.73	4.77	2.33	297	Sept 1975	44.57	1.78	5.34	2.83
250	Oct 1971	43.35	1.72	4.77	2.33	298	Oct 1975	44.62	1.78	5.36	2.85
251	Nov 1971	43.31	1.72	4.77	2.33	299	Nov 1975	44.69	1.78	5.39	2.87
252	Dec 1971	43.26	1.72	4.77	2.34	300	Dec 1975	44.74	1.78	5.41	2.89

Table G2.1. Simulated tetrachloroethylene (PCE) and PCE degradation by-products in finished water at the Tarawa Terrace water treatment plant, January 1951–December 1994,¹ Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[TCE, trichloroethylene; 1,2-tDCE, trans-1,2-dichloroethylene; VC, vinyl chloride; all values are in micrograms per liter and were obtained using the TechFlowMP model]

Stress period	Month and year	PCE	TCE	1,2-tDCE	VC	Stress period	Month and year	PCE	TCE	1,2-tDCE	VC
301	Jan 1976	51.53	2.06	6.24	3.34	349	Jan 1980	95.56	3.92	13.03	7.27
302	Feb 1976	53.43	2.15	6.62	3.60	350	Feb 1980	98.20	4.04	13.49	7.56
303	Mar 1976	54.44	2.20	6.80	3.72	351	Mar 1980	96.35	3.94	12.98	7.19
304	Apr 1976	55.38	2.24	6.99	3.85	352	Apr 1980	97.86	4.01	13.28	7.39
305	May 1976	56.21	2.28	7.16	3.98	353	May 1980	96.00	3.90	12.78	7.03
306	June 1976	57.07	2.32	7.34	4.10	354	June 1980	96.23	3.91	12.80	7.03
307	July 1976	57.86	2.35	7.51	4.22	355	July 1980	0.00	0.00	0.00	0.00
308	Aug 1976	58.73	2.39	7.69	4.34	356	Aug 1980	0.00	0.00	0.00	0.00
309	Sept 1976	59.58	2.43	7.86	4.46	357	Sept 1980	95.07	3.92	12.43	6.83
310	Oct 1976	60.41	2.46	8.02	4.57	358	Oct 1980	91.40	3.63	11.24	5.84
311	Nov 1976	61.28	2.50	8.19	4.68	359	Nov 1980	91.00	3.63	11.17	5.82
312	Dec 1976	62.10	2.53	8.35	4.79	360	Dec 1980	90.64	3.62	11.14	5.81
313	Jan 1977	62.97	2.57	8.52	4.89	361	Jan 1981	84.14	3.37	10.41	5.46
314	Feb 1977	63.98	2.62	8.71	5.01	362	Feb 1981	84.80	3.41	10.53	5.55
315	Mar 1977	64.81	2.65	8.86	5.11	363	Mar 1981	84.13	3.37	10.37	5.44
316	Apr 1977	65.83	2.70	9.05	5.22	364	Apr 1981	85.90	3.46	10.74	5.69
317	May 1977	66.76	2.74	9.21	5.32	365	May 1981	87.53	3.54	11.02	5.87
318	June 1977	67.76	2.78	9.38	5.43	366	June 1981	88.90	3.60	11.26	6.03
319	July 1977	68.70	2.82	9.55	5.53	367	July 1981	102.10	4.17	13.12	7.09
320	Aug 1977	69.70	2.86	9.72	5.63	368	Aug 1981	105.46	4.33	13.75	7.50
321	Sept 1977	70.70	2.90	9.88	5.72	369	Sept 1981	96.34	3.96	12.64	6.93
322	Oct 1977	71.65	2.94	10.04	5.82	370	Oct 1981	96.29	3.95	12.60	6.90
323	Nov 1977	72.71	2.99	10.21	5.92	371	Nov 1981	96.69	3.96	12.67	6.93
324	Dec 1977	73.68	3.03	10.36	6.00	372	Dec 1981	97.27	3.98	12.74	6.97
325	Jan 1978	74.73	3.07	10.53	6.10	373	Jan 1982	81.28	3.33	10.65	5.81
326	Feb 1978	76.25	3.14	10.80	6.26	374	Feb 1982	83.47	3.43	11.06	6.09
327	Mar 1978	78.73	3.26	11.26	6.56	375	Mar 1982	85.42	3.51	11.40	6.31
328	Apr 1978	77.97	3.21	11.02	6.37	376	Apr 1982	87.32	3.60	11.75	6.55
329	May 1978	79.28	3.27	11.27	6.53	377	May 1982	120.45	4.98	16.30	9.13
330	June 1978	79.72	3.28	11.29	6.51	378	June 1982	92.65	3.86	12.81	7.26
331	July 1978	82.31	3.41	11.78	6.83	379	July 1982	92.98	3.86	12.77	7.21
332	Aug 1978	83.81	3.47	12.00	6.96	380	Aug 1982	94.09	3.91	12.97	7.34
333	Sept 1978	84.16	3.48	12.00	6.93	381	Sept 1982	95.33	3.96	13.18	7.46
334	Oct 1978	84.92	3.51	12.09	6.97	382	Oct 1982	96.51	4.01	13.37	7.57
335	Nov 1978	87.48	3.63	12.55	7.25	383	Nov 1982	96.63	4.00	13.31	7.51
336	Dec 1978	85.67	3.52	12.04	6.87	384	Dec 1982	93.14	3.80	12.43	6.88
337	Jan 1979	85.41	3.50	11.95	6.79	385	Jan 1983	0.10	0.00	0.04	0.05
338	Feb 1979	86.75	3.56	12.16	6.91	386	Feb 1983	0.12	0.01	0.05	0.07
339	Mar 1979	87.55	3.60	12.23	6.93	387	Mar 1983	88.43	3.65	11.55	6.37
340	Apr 1979	88.43	3.63	12.32	6.97	388	Apr 1983	86.39	3.43	10.85	5.77
341	May 1979	89.21	3.66	12.40	7.00	389	May 1983	87.67	3.52	11.04	5.88
342	June 1979	90.09	3.70	12.49	7.05	390	June 1983	82.26	3.33	10.54	5.70
343	July 1979	90.82	3.73	12.56	7.07	391	July 1983	92.03	3.75	11.95	6.52
344	Aug 1979	91.67	3.76	12.65	7.11	392	Aug 1983	94.46	3.87	12.45	6.87
345	Sept 1979	92.44	3.79	12.72	7.14	393	Sept 1983	96.92	3.99	12.94	7.21
346	Oct 1979	93.22	3.82	12.81	7.18	394	Oct 1983	96.60	3.96	12.82	7.12
347	Nov 1979	94.00	3.85	12.88	7.21	395	Nov 1983	95.49	3.89	12.58	6.95
348	Dec 1979	94.78	3.89	12.96	7.24	396	Dec 1983	95.52	3.89	12.60	6.96

Table G2.1. Simulated tetrachloroethylene (PCE) and PCE degradation by-products in finished water at the Tarawa Terrace water treatment plant, January 1951–December 1994,¹ Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued [TCE, trichloroethylene; 1,2-tDCE, trans-1,2-dichloroethylene; VC, vinyl chloride; all values are in micrograms per liter and were obtained using the TechFlowMP model]

Stress period	Month and year	PCE	TCE	1,2-tDCE	VC	Stress period	Month and year	PCE	TCE	1,2-tDCE	VC
397	Jan 1984	111.52	4.61	15.09	8.43	417	Sept 1985	2.62	0.12	0.71	0.59
398	Feb 1984	145.48	5.94	19.20	10.56	418	Oct 1985	2.91	0.13	0.79	0.65
399	Mar 1984	155.54	6.47	21.34	11.97	419	Nov 1985	3.24	0.15	0.87	0.71
400	Apr 1984	132.07	5.52	18.23	10.26	420	Dec 1985	3.58	0.16	0.95	0.76
401	May 1984	132.19	5.49	18.09	10.13	421	Jan 1986	3.95	0.18	1.04	0.82
402	June 1984	158.14	6.60	21.85	12.28	422	Feb 1986	4.24	0.19	1.08	0.83
403	July 1984	140.96	5.92	19.72	11.14	423	Mar 1986	5.40	0.24	1.34	1.01
404	Aug 1984	118.88	4.81	16.05	8.94	424	Apr 1986	4.93	0.22	1.20	0.89
405	Sept 1984	149.36	6.17	19.60	11.20	425	May 1986	5.25	0.23	1.25	0.91
406	Oct 1984	136.04	5.56	17.33	9.39	426	June 1986	5.61	0.25	1.30	0.92
407	Nov 1984	131.63	5.34	16.46	8.87	427	July 1986	5.97	0.26	1.35	0.94
408	Dec 1984	128.47	5.18	15.83	8.46	428	Aug 1986	6.36	0.28	1.39	0.96
409	Jan 1985	127.80	5.13	15.48	8.20	429	Sept 1986	6.75	0.30	1.44	0.97
410	Feb 1985	1.10	0.05	0.29	0.22	430	Oct 1986	7.12	0.31	1.48	0.99
411	Mar 1985	3.88	0.17	0.68	0.47	431	Nov 1986	7.52	0.33	1.52	1.00
412	Apr 1985	3.70	0.16	0.68	0.49	432	Dec 1986	7.89	0.34	1.56	1.01
413	May 1985	1.65	0.07	0.44	0.35	433	Jan 1987	8.28	0.36	1.59	1.01
414	June 1985	1.88	0.08	0.50	0.41	434	Feb 1987	8.71	0.38	1.64	1.03
415	July 1985	2.10	0.09	0.56	0.47	435–	Mar 1987–				
416	Aug 1985	2.34	0.10	0.63	0.52	528	Dec 1994			No pumping	

¹ Current maximum contaminant levels (MCLs) are as follows: tetrachloroethylene (PCE) and trichloroethylene (TCE), 5 micrograms per liter ($\mu\text{g/L}$); *trans*-1,2-dichloroethylene (1,2-tDCE), 100 $\mu\text{g/L}$; and vinyl chloride (VC), 2 $\mu\text{g/L}$ (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.)

Table G2.2. Simulated tetrachloroethylene (PCE) and PCE degradation by-products in groundwater at water-supply well TT-23, January 1951–December 1994,¹ Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[TCE, trichloroethylene; 1,2-tDCE, trans-1,2-dichloroethylene; VC, vinyl chloride; all values are in micrograms per liter and were obtained using the TechFlowMP model]

Stress period	Month and year	PCE	TCE	1,2-tDCE	VC
1–	Jan 1951–				
403	July 1984			No pumping	
404	Aug 1984	48.34	1.39	5.01	2.60
405	Sept 1984	167.26	7.02	20.71	13.07
406	Oct 1984	157.87	6.55	18.52	10.00
407	Nov 1984	154.45	6.37	17.76	9.77
408	Dec 1984	152.76	6.29	17.34	9.52
409	Jan 1985	151.88	6.24	17.10	9.38
410	Feb 1985			No pumping	
411	Mar 1985	149.47	6.31	17.27	9.66
412	Apr 1985	162.42	7.01	21.03	12.82
413–	May 1985–				
528	Dec 1994			No pumping	

¹ Current maximum contaminant levels (MCLs) are as follows: tetrachloroethylene (PCE) and trichloroethylene (TCE), 5 micrograms per liter ($\mu\text{g/L}$); *trans*-1,2-dichloroethylene (1,2-tDCE), 100 $\mu\text{g/L}$; and vinyl chloride (VC), 2 $\mu\text{g/L}$ (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.)

Table G2.3. Simulated tetrachloroethylene (PCE) and PCE degradation by-products in groundwater at water-supply well TT-25, January 1951–December 1994,¹ Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[TCE, trichloroethylene; 1,2-tDCE, trans-1,2-dichloroethylene; VC, vinyl chloride; all values are in micrograms per liter and were obtained using the TechFlowMP model]

Stress period	Month and year	PCE	TCE	1,2-tDCE	VC	Stress period	Month and year	PCE	TCE	1,2-tDCE	VC
1–372	Jan 1951–Dec 1981	No pumping				404	Aug 1984	4.72	0.22	1.70	1.55
373	Jan 1982	0.00	0.00	0.00	0.00	405	Sept 1984	4.77	0.22	1.60	1.41
374	Feb 1982	0.01	0.00	0.00	0.00	406	Oct 1984	4.73	0.21	1.49	1.27
375	Mar 1982	0.02	0.00	0.01	0.01	407	Nov 1984	4.67	0.20	1.39	1.14
376	Apr 1982	0.04	0.00	0.01	0.01	408	Dec 1984	4.61	0.20	1.31	1.05
377	May 1982	0.06	0.00	0.02	0.02	409	Jan 1985	4.55	0.19	1.22	0.95
378	June 1982	0.08	0.00	0.02	0.02	410	Feb 1985	4.57	0.19	1.18	0.91
379	July 1982	0.11	0.01	0.03	0.04	411	Mar 1985	5.62	0.24	1.52	1.19
380	Aug 1982	0.15	0.01	0.05	0.06	412	Apr 1985	6.65	0.29	1.78	1.41
381	Sept 1982	0.19	0.01	0.06	0.08	413	May 1985	7.39	0.32	1.95	1.56
382	Oct 1982	0.24	0.01	0.08	0.11	414	June 1985	8.41	0.37	2.23	1.82
383	Nov 1982	0.29	0.01	0.11	0.15	415	July 1985	9.46	0.42	2.53	2.01
384	Dec 1982	0.33	0.02	0.13	0.17	416	Aug 1985	10.52	0.47	2.82	2.34
385	Jan 1983	0.39	0.02	0.15	0.21	417	Sept 1985	11.83	0.53	3.20	2.65
386	Feb 1983	0.50	0.02	0.21	0.29	418	Oct 1985	13.19	0.59	3.57	2.94
387	Mar 1983	0.62	0.03	0.27	0.37	419	Nov 1985	14.71	0.66	3.96	3.22
388	Apr 1983	0.71	0.03	0.32	0.42	420	Dec 1985	16.28	0.74	4.34	3.47
389	May 1983	0.81	0.04	0.37	0.48	421	Jan 1986	18.01	0.81	4.73	3.72
390	June 1983	0.94	0.05	0.45	0.57	422	Feb 1986	19.31	0.87	4.93	3.78
391	July 1983	1.19	0.06	0.61	0.77	423	Mar 1986	20.59	0.92	5.14	3.87
392	Aug 1983	1.39	0.07	0.71	0.87	424	Apr 1986	22.48	1.01	5.50	4.07
393	Sept 1983	1.64	0.08	0.83	0.99	425	May 1986	23.99	1.07	5.70	4.13
394	Oct 1983	1.85	0.09	0.92	1.05	426	June 1986	25.65	1.14	5.93	4.21
395	Nov 1983	2.06	0.10	0.99	1.09	427	July 1986	27.31	1.21	6.15	4.29
396	Dec 1983	2.29	0.11	1.06	1.15	428	Aug 1986	29.08	1.28	6.37	4.36
397	Jan 1984	2.68	0.13	1.23	1.30	429	Sept 1986	30.87	1.35	6.57	4.43
398	Feb 1984	2.77	0.13	1.19	1.20	430	Oct 1986	32.61	1.43	6.76	4.48
399	Mar 1984	3.09	0.15	1.31	1.32	431	Nov 1986	34.42	1.50	6.94	4.53
400	Apr 1984	3.42	0.16	1.41	1.39	432	Dec 1986	36.15	1.57	7.11	4.57
401	May 1984	3.67	0.17	1.45	1.39	433	Jan 1987	37.94	1.64	7.27	4.61
402	June 1984	4.00	0.19	1.54	1.45	434	Feb 1987	39.89	1.72	7.46	4.68
403	July 1984	4.43	0.21	1.66	1.55	435–528	Mar 1987–Dec 1994	No pumping			

¹ Current maximum contaminant levels (MCLs) are as follows: tetrachloroethylene (PCE) and trichloroethylene (TCE), 5 micrograms per liter (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.)

Table G2.4. Simulated tetrachloroethylene (PCE) and PCE degradation by-products in groundwater at water-supply well TT-26, January 1951–December 1994,¹ Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[TCE, trichloroethylene; 1,2-tDCE, trans-1,2-dichloroethylene; VC, vinyl chloride; all values are in micrograms per liter and were obtained using the TechFlowMP model]

Stress period	Month and year	PCE	TCE	1,2-tDCE	VC	Stress period	Month and year	PCE	TCE	1,2-tDCE	VC	
1–12	Jan 1951–Dec 1951	No pumping					61	Jan 1956	0.45	0.03	0.42	0.49
13	Jan 1952	0.00	0.00	0.00	0.00	62	Feb 1956	0.58	0.04	0.52	0.59	
14	Feb 1952	0.00	0.00	0.00	0.00	63	Mar 1956	0.72	0.05	0.62	0.69	
15	Mar 1952	0.00	0.00	0.00	0.00	64	Apr 1956	0.90	0.06	0.74	0.82	
16	Apr 1952	0.00	0.00	0.00	0.00	65	May 1956	1.12	0.07	0.87	0.95	
17	May 1952	0.00	0.00	0.00	0.00	66	June 1956	1.38	0.08	1.03	1.01	
18	June 1952	0.00	0.00	0.00	0.00	67	July 1956	1.67	0.10	1.20	1.26	
19	July 1952	0.00	0.00	0.00	0.00	68	Aug 1956	2.03	0.12	1.39	1.44	
20	Aug 1952	0.00	0.00	0.00	0.00	69	Sept 1956	2.45	0.14	1.61	1.63	
21	Sept 1952	0.00	0.00	0.00	0.00	70	Oct 1956	2.91	0.17	1.83	1.84	
22	Oct 1952	0.00	0.00	0.00	0.00	71	Nov 1956	3.46	0.20	2.09	2.06	
23	Nov 1952	0.00	0.00	0.00	0.00	72	Dec 1956	4.05	0.23	2.36	2.30	
24	Dec 1952	0.00	0.00	0.00	0.00	73	Jan 1957	4.76	0.27	2.67	2.55	
25	Jan 1953	0.00	0.00	0.00	0.00	74	Feb 1957	5.54	0.31	2.99	2.83	
26	Feb 1953	0.00	0.00	0.00	0.00	75	Mar 1957	6.33	0.35	3.31	3.09	
27	Mar 1953	0.00	0.00	0.00	0.00	76	Apr 1957	7.31	0.40	3.69	3.40	
28	Apr 1953	0.00	0.00	0.00	0.00	77	May 1957	8.36	0.45	4.07	3.70	
29	May 1953	0.00	0.00	0.00	0.00	78	June 1957	9.55	0.51	4.49	4.04	
30	June 1953	0.00	0.00	0.00	0.00	79	July 1957	10.81	0.58	4.92	4.37	
31	July 1953	0.00	0.00	0.00	0.00	80	Aug 1957	12.23	0.65	5.40	4.74	
32	Aug 1953	0.00	0.00	0.00	0.00	81	Sept 1957	13.80	0.73	5.90	5.12	
33	Sept 1953	0.00	0.00	0.00	0.00	82	Oct 1957	15.44	0.81	6.40	5.50	
34	Oct 1953	0.00	0.00	0.00	0.00	83	Nov 1957	17.28	0.90	6.95	5.90	
35	Nov 1953	0.00	0.00	0.00	0.00	84	Dec 1957	19.19	0.99	7.51	6.32	
36	Dec 1953	0.00	0.00	0.00	0.00	85	Jan 1958	21.34	1.01	8.11	6.75	
37	Jan 1954	0.00	0.00	0.00	0.00	86	Feb 1958	23.63	1.21	8.73	7.19	
38	Feb 1954	0.00	0.00	0.00	0.00	87	Mar 1958	25.80	1.31	9.28	7.56	
39	Mar 1954	0.00	0.00	0.00	0.00	88	Apr 1958	28.37	1.44	9.93	8.01	
40	Apr 1954	0.00	0.00	0.00	0.00	89	May 1958	30.98	1.56	10.57	8.44	
41	May 1954	0.00	0.00	0.00	0.00	90	June 1958	33.85	1.70	11.27	8.91	
42	June 1954	0.00	0.00	0.00	0.00	91	July 1958	36.79	1.84	11.96	9.38	
43	July 1954	0.00	0.00	0.00	0.00	92	Aug 1958	39.99	1.99	12.69	9.86	
44	Aug 1954	0.00	0.00	0.00	0.00	93	Sept 1958	43.40	2.15	13.46	10.36	
45	Sept 1954	0.00	0.00	0.00	0.00	94	Oct 1958	46.87	2.31	14.23	10.86	
46	Oct 1954	0.00	0.00	0.00	0.01	95	Nov 1958	50.65	2.49	15.04	11.38	
47	Nov 1954	0.00	0.00	0.01	0.01	96	Dec 1958	54.45	2.66	15.84	11.89	
48	Dec 1954	0.01	0.00	0.01	0.02	97	Jan 1959	58.58	2.85	16.69	12.42	
49	Jan 1955	0.01	0.00	0.01	0.02	98	Feb 1959	62.89	3.05	17.57	12.98	
50	Feb 1955	0.01	0.00	0.02	0.03	99	Mar 1959	66.92	3.24	18.37	13.49	
51	Mar 1955	0.02	0.00	0.03	0.04	100	Apr 1959	71.61	3.46	19.29	14.07	
52	Apr 1955	0.03	0.00	0.04	0.06	101	May 1959	76.23	3.67	20.18	14.62	
53	May 1955	0.04	0.00	0.06	0.08	102	June 1959	81.28	3.90	21.15	15.24	
54	June 1955	0.06	0.00	0.08	0.11	103	July 1959	86.34	4.13	22.08	15.80	
55	July 1955	0.08	0.01	0.10	0.14	104	Aug 1959	91.69	4.37	23.03	16.38	
56	Aug 1955	0.11	0.01	0.14	0.18	105	Sept 1959	97.17	4.62	24.00	16.96	
57	Sept 1955	0.15	0.01	0.17	0.22	106	Oct 1959	102.57	4.86	24.93	17.50	
58	Oct 1955	0.20	0.01	0.22	0.28	107	Nov 1959	108.32	5.12	25.90	18.06	
59	Nov 1955	0.27	0.02	0.28	0.34	108	Dec 1959	114.04	5.38	26.86	18.62	
60	Dec 1955	0.35	0.02	0.34	0.41							

Table G2.4. Simulated tetrachloroethylene (PCE) and PCE degradation by-products in groundwater at water-supply well TT-26, January 1951–December 1994,¹ Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[TCE, trichloroethylene; 1,2-tDCE, trans-1,2-dichloroethylene; VC, vinyl chloride; all values are in micrograms per liter and were obtained using the TechFlowMP model]

Stress period	Month and year	PCE	TCE	1,2-tDCE	VC	Stress period	Month and year	PCE	TCE	1,2-tDCE	VC
109	Jan 1960	120.06	5.65	27.84	19.17	157	Jan 1964	373.16	15.88	53.12	29.57
110	Feb 1960	126.11	5.92	28.79	19.67	158	Feb 1964	374.43	15.90	52.90	29.36
111	Mar 1960	131.84	6.17	29.66	20.13	159	Mar 1964	374.59	15.85	52.18	28.70
112	Apr 1960	138.22	6.45	30.64	20.64	160	Apr 1964	374.66	15.79	51.61	28.24
113	May 1960	144.32	6.72	31.51	21.06	161	May 1964	374.19	15.74	51.08	27.82
114	June 1960	150.70	7.00	32.48	21.57	162	June 1964	373.70	15.68	50.59	27.43
115	July 1960	156.97	7.27	33.41	22.06	163	July 1964	373.15	15.63	50.12	27.07
116	Aug 1960	163.65	7.56	34.42	22.60	164	Aug 1964	372.65	15.58	49.69	26.73
117	Sept 1960	170.47	7.86	35.46	23.17	165	Sept 1964	372.13	15.53	49.27	26.41
118	Oct 1960	177.22	8.16	36.48	23.73	166	Oct 1964	371.61	15.48	48.87	26.12
119	Nov 1960	184.39	8.47	37.56	24.32	167	Nov 1964	371.14	15.44	48.51	25.84
120	Dec 1960	191.42	8.78	38.61	24.90	168	Dec 1964	370.65	15.39	48.16	25.58
121	Jan 1961	198.86	9.11	39.72	25.50	169	Jan 1965	370.21	15.36	47.82	25.33
122	Feb 1961	206.47	9.44	40.86	26.15	170	Feb 1965	369.76	15.32	47.51	25.09
123	Mar 1961	213.37	9.74	41.89	26.73	171	Mar 1965	369.24	15.28	47.20	24.86
124	Apr 1961	221.29	10.09	43.07	27.39	172	Apr 1965	368.91	15.25	46.93	24.66
125	May 1961	228.88	10.43	44.17	27.99	173	May 1965	368.44	15.21	46.65	24.45
126	June 1961	236.84	10.77	45.31	28.61	174	June 1965	368.03	15.18	46.38	24.26
127	July 1961	244.53	11.11	46.39	29.19	175	July 1965	367.56	15.14	46.12	24.07
128	Aug 1961	252.56	11.46	47.51	29.79	176	Aug 1965	367.15	15.11	45.87	23.89
129	Sept 1961	260.60	11.81	48.61	30.37	177	Sept 1965	366.68	15.07	45.62	23.71
130	Oct 1961	268.36	12.14	49.66	30.92	178	Oct 1965	366.21	15.04	45.39	23.54
131	Nov 1961	276.49	12.50	50.76	31.50	179	Nov 1965	365.77	15.01	45.16	23.38
132	Dec 1961	284.36	12.83	51.81	32.04	180	Dec 1965	365.28	14.98	44.94	23.22
133	Jan 1962	292.56	13.19	52.89	32.60	181	Jan 1966	364.82	14.94	44.73	23.07
134	Feb 1962	305.55	13.80	55.18	34.07	182	Feb 1966	364.32	14.91	44.52	22.92
135	Mar 1962	314.27	14.18	56.17	34.56	183	Mar 1966	363.74	14.88	44.30	22.77
136	Apr 1962	320.95	14.45	56.66	34.71	184	Apr 1966	363.33	14.85	44.12	22.64
137	May 1962	325.87	14.62	56.84	34.66	185	May 1966	362.77	14.82	43.92	22.50
138	June 1962	330.19	14.77	56.89	34.52	186	June 1966	362.25	14.78	43.74	22.37
139	July 1962	333.87	14.88	56.85	34.31	187	July 1966	361.67	14.75	43.54	22.24
140	Aug 1962	337.40	14.99	56.76	34.07	188	Aug 1966	361.12	14.72	43.36	22.12
141	Sept 1962	340.65	15.09	56.63	33.81	189	Sept 1966	360.53	14.68	43.17	21.99
142	Oct 1962	343.58	15.17	56.47	33.54	190	Oct 1966	359.90	14.65	42.99	21.87
143	Nov 1962	346.48	15.26	56.31	33.23	191	Nov 1966	359.32	14.62	42.82	21.75
144	Dec 1962	349.11	15.33	56.13	32.94	192	Dec 1966	358.67	14.58	42.64	21.63
145	Jan 1963	351.74	15.41	55.96	32.65	193	Jan 1967	358.05	14.55	42.47	21.52
146	Feb 1963	354.08	15.47	55.73	32.36	194	Feb 1967	357.27	14.51	42.27	21.40
147	Mar 1963	356.12	15.52	55.50	32.10	195	Mar 1967	356.31	14.46	42.06	21.27
148	Apr 1963	358.42	15.59	55.28	31.85	196	Apr 1967	355.27	14.41	41.84	21.15
149	May 1963	360.40	15.64	55.04	31.58	197	May 1967	354.00	14.35	41.58	20.99
150	June 1963	362.39	15.69	54.81	31.31	198	June 1967	352.64	14.28	41.30	20.83
151	July 1963	364.12	15.72	54.55	31.04	199	July 1967	351.17	14.21	41.02	20.66
152	Aug 1963	365.86	15.75	54.31	30.77	200	Aug 1967	349.65	14.14	40.73	20.48
153	Sept 1963	367.49	15.78	54.05	30.51	201	Sept 1967	348.07	14.06	40.42	20.30
154	Oct 1963	368.98	15.80	53.80	30.26	202	Oct 1967	346.49	13.99	40.13	20.13
155	Nov 1963	370.47	15.83	53.57	30.02	203	Nov 1967	344.94	13.91	39.85	19.96
156	Dec 1963	371.80	15.85	53.34	29.79	204	Dec 1967	343.40	13.84	39.56	19.78

Table G2.4. Simulated tetrachloroethylene (PCE) and PCE degradation by-products in groundwater at water-supply well TT-26, January 1951–December 1994,¹ Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[TCE, trichloroethylene; 1,2-tDCE, trans-1,2-dichloroethylene; VC, vinyl chloride; all values are in micrograms per liter and were obtained using the TechFlowMP model]

Stress period	Month and year	PCE	TCE	1,2-tDCE	VC	Stress period	Month and year	PCE	TCE	1,2-tDCE	VC
205	Jan 1968	341.82	13.77	39.27	19.60	253	Jan 1972	284.56	11.32	31.43	15.42
206	Feb 1968	340.01	13.68	38.93	19.41	254	Feb 1972	280.87	11.13	30.81	15.06
207	Mar 1968	337.95	13.59	38.57	19.21	255	Mar 1972	277.56	10.98	30.34	14.80
208	Apr 1968	335.74	13.49	38.20	19.00	256	Apr 1972	274.10	10.82	29.86	14.53
209	May 1968	333.34	13.37	37.80	18.78	257	May 1972	270.75	10.67	29.39	14.25
210	June 1968	330.90	13.26	37.39	18.55	258	June 1972	267.44	10.53	28.93	13.99
211	July 1968	328.16	13.14	36.92	18.26	259	July 1972	264.36	10.39	28.50	13.75
212	Aug 1968	325.32	13.01	36.44	17.98	260	Aug 1972	261.38	10.26	28.09	13.52
213	Sept 1968	322.42	12.88	35.98	17.71	261	Sept 1972	258.51	10.14	27.70	13.31
214	Oct 1968	319.60	12.76	35.53	17.46	262	Oct 1972	255.85	10.03	27.34	13.11
215	Nov 1968	316.83	12.63	35.10	17.21	263	Nov 1972	253.27	9.92	27.00	12.93
216	Dec 1968	314.09	12.51	34.67	16.96	264	Dec 1972	250.80	9.82	26.68	12.76
217	Jan 1969	311.41	12.40	34.26	16.72	265	Jan 1973	248.38	9.72	26.37	12.59
218	Feb 1969	309.11	12.30	33.90	16.50	266	Feb 1973	253.41	10.01	27.39	13.23
219	Mar 1969	307.25	12.22	33.60	16.30	267	Mar 1973	254.45	10.06	27.55	13.36
220	Apr 1969	306.11	12.17	33.43	16.19	268	Apr 1973	254.04	10.05	27.56	13.42
221	May 1969	305.09	12.13	33.25	16.07	269	May 1973	253.01	10.01	27.50	13.44
222	June 1969	304.29	12.01	33.12	15.98	270	June 1973	251.78	9.96	27.43	13.44
223	July 1969	303.52	12.07	33.00	15.90	271	July 1973	250.19	9.89	27.28	13.40
224	Aug 1969	302.98	12.05	32.91	15.84	272	Aug 1973	248.70	9.83	27.15	13.36
225	Sept 1969	302.36	12.03	32.82	15.78	273	Sept 1973	247.16	9.77	27.00	13.30
226	Oct 1969	301.74	12.00	32.75	15.73	274	Oct 1973	245.56	9.70	26.82	13.23
227	Nov 1969	301.18	11.98	32.69	15.70	275	Nov 1973	244.01	9.64	26.66	13.17
228	Dec 1969	302.59	12.07	33.01	15.90	276	Dec 1973	242.42	9.57	26.49	13.09
229	Jan 1970	303.17	12.01	33.12	15.97	277	Jan 1974	240.86	9.51	26.32	13.02
230	Feb 1970	303.04	12.09	33.14	16.01	278	Feb 1974	240.32	9.49	26.29	12.98
231	Mar 1970	302.46	12.07	33.11	16.02	279	Mar 1974	240.13	9.48	26.25	12.93
232	Apr 1970	301.80	12.05	33.09	16.05	280	Apr 1974	240.74	9.51	26.36	12.98
233	May 1970	300.85	12.01	33.01	16.04	281	May 1974	241.61	9.55	26.53	13.08
234	June 1970	299.82	11.96	32.91	16.02	282	June 1974	243.08	9.62	26.80	13.25
235	July 1970	298.71	11.91	32.80	15.98	283	July 1974	244.45	9.68	27.06	13.41
236	Aug 1970	297.56	11.86	32.67	15.93	284	Aug 1974	245.99	9.75	27.36	13.60
237	Sept 1970	296.25	11.81	32.52	15.86	285	Sept 1974	247.59	9.82	27.68	13.81
238	Oct 1970	294.87	11.75	32.35	15.78	286	Oct 1974	249.17	9.90	28.02	14.03
239	Nov 1970	293.47	11.69	32.19	15.72	287	Nov 1974	250.95	9.98	28.40	14.29
240	Dec 1970	292.13	11.63	32.04	15.65	288	Dec 1974	252.67	10.05	28.78	14.55
241	Jan 1971	290.78	11.57	31.88	15.57	289	Jan 1975	254.57	10.14	29.20	14.85
242	Feb 1971	289.64	11.52	31.74	15.50	290	Feb 1975	255.36	10.17	29.45	15.07
243	Mar 1971	288.75	11.48	31.62	15.43	291	Mar 1975	256.12	10.20	29.72	15.31
244	Apr 1971	288.13	11.46	31.55	15.39	292	Apr 1975	257.02	10.24	30.03	15.57
245	May 1971	287.44	11.43	31.47	15.34	293	May 1975	257.62	10.27	30.27	15.78
246	June 1971	287.05	11.42	31.45	15.34	294	June 1975	258.18	10.30	30.50	15.98
247	July 1971	286.58	11.40	31.42	15.33	295	July 1975	258.58	10.32	30.69	16.15
248	Aug 1971	286.19	11.38	31.40	15.32	296	Aug 1975	258.98	10.33	30.88	16.32
249	Sept 1971	285.80	11.37	31.39	15.33	297	Sept 1975	259.27	10.34	31.03	16.45
250	Oct 1971	285.42	11.35	31.38	15.34	298	Oct 1975	259.56	10.35	31.18	16.59
251	Nov 1971	285.13	11.34	31.40	15.37	299	Nov 1975	259.98	10.37	31.34	16.71
252	Dec 1971	284.81	11.33	31.41	15.39	300	Dec 1975	260.27	10.38	31.45	16.81

Table G2.4. Simulated tetrachloroethylene (PCE) and PCE degradation by-products in groundwater at water-supply well TT-26, January 1951–December 1994,¹ Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[TCE, trichloroethylene; 1,2-tDCE, trans-1,2-dichloroethylene; VC, vinyl chloride; all values are in micrograms per liter and were obtained using the TechFlowMP model]

Stress period	Month and year	PCE	TCE	1,2-tDCE	VC	Stress period	Month and year	PCE	TCE	1,2-tDCE	VC
301	Jan 1976	260.61	10.39	31.57	16.90	349	Jan 1980	483.25	19.81	65.91	36.77
302	Feb 1976	270.19	10.87	33.47	18.18	350	Feb 1980	496.51	20.45	68.21	38.19
303	Mar 1976	275.28	11.10	34.38	18.80	351	Mar 1980	487.29	19.90	65.66	36.38
304	Apr 1976	280.04	11.32	35.35	19.48	352	Apr 1980	494.96	20.28	67.17	37.35
305	May 1976	284.23	11.51	36.23	20.11	353	May 1980	485.48	19.73	64.60	35.51
306	June 1976	288.58	11.71	37.13	20.74	354	June 1980	486.61	19.78	64.73	35.55
307	July 1976	292.61	11.88	37.98	21.34	355–	July 1980–	No pumping			
308	Aug 1976	296.98	12.08	38.88	21.96	356	Aug 1980	No pumping			
309	Sept 1976	301.31	12.27	39.75	22.55	357	Sept 1980	480.70	19.82	62.82	34.52
310	Oct 1976	305.47	12.45	40.58	23.11	358	Oct 1980	462.18	18.34	56.82	29.50
311	Nov 1976	309.87	12.64	41.44	23.67	359	Nov 1980	460.29	18.35	56.50	29.41
312	Dec 1976	314.04	12.82	42.24	24.20	360	Dec 1980	458.36	18.29	56.30	29.38
313	Jan 1977	318.46	13.01	43.09	24.74	361	Jan 1981	461.78	18.50	57.01	29.94
314	Feb 1977	323.55	13.23	44.04	25.35	362	Feb 1981	465.50	18.69	57.78	30.41
315	Mar 1977	327.76	13.41	44.80	25.82	363	Mar 1981	461.69	18.47	56.88	29.85
316	Apr 1977	332.92	13.64	45.74	26.41	364	Apr 1981	471.48	18.99	58.91	31.19
317	May 1977	337.62	13.84	46.57	26.91	365	May 1981	480.37	19.42	60.46	32.18
318	June 1977	342.68	14.05	47.45	27.45	366	June 1981	487.90	19.77	61.78	33.04
319	July 1977	347.43	14.25	48.27	27.94	367	July 1981	502.82	20.51	64.62	34.88
320	Aug 1977	352.49	14.47	49.13	28.45	368	Aug 1981	519.37	21.30	67.69	36.90
321	Sept 1977	357.52	14.68	49.96	28.94	369	Sept 1981	528.76	21.73	69.37	37.99
322	Oct 1977	362.36	14.88	50.76	29.40	370	Oct 1981	528.46	21.66	69.15	37.82
323	Nov 1977	367.71	15.11	51.65	29.93	371	Nov 1981	530.66	21.73	69.49	37.99
324	Dec 1977	372.60	15.31	52.41	30.36	372	Dec 1981	533.83	21.85	69.91	38.19
325	Jan 1978	377.90	15.54	53.26	30.84	373	Jan 1982	537.72	22.00	70.40	38.40
326	Feb 1978	385.61	15.89	54.59	31.66	374	Feb 1982	552.23	22.66	73.12	40.22
327	Mar 1978	398.01	16.48	56.95	33.18	375	Mar 1982	565.08	23.24	75.39	41.72
328	Apr 1978	394.34	16.23	55.73	32.23	376	Apr 1982	577.64	23.82	77.66	43.25
329	May 1978	400.90	16.53	57.01	33.03	377	May 1982	588.05	24.29	79.58	44.54
330	June 1978	403.12	16.59	57.06	32.92	378	June 1982	612.87	25.55	84.69	47.95
331	July 1978	416.22	17.22	59.55	34.52	379	July 1982	614.98	25.53	84.44	47.64
332	Aug 1978	423.89	17.56	60.71	35.17	380	Aug 1982	622.32	25.83	85.75	48.45
333	Sept 1978	425.63	17.59	60.67	35.02	381	Sept 1982	630.45	26.17	87.09	49.23
334	Oct 1978	429.43	17.74	61.15	35.22	382	Oct 1982	638.15	26.50	88.28	49.90
335	Nov 1978	442.43	18.36	63.46	36.64	383	Nov 1982	638.94	26.45	87.90	49.47
336	Dec 1978	433.30	17.81	60.90	34.74	384	Dec 1982	615.82	25.11	82.08	45.29
337	Jan 1979	431.96	17.71	60.42	34.33	385–	Jan 1983–	No pumping			
338	Feb 1979	438.77	18.02	61.51	34.95	386	Feb 1983	No pumping			
339	Mar 1979	442.82	18.18	61.84	35.05	387	Mar 1983	590.87	24.36	76.91	42.17
340	Apr 1979	447.26	18.36	62.31	35.26	388	Apr 1983	577.14	22.93	72.21	38.06
341	May 1979	451.18	18.52	62.69	35.41	389	May 1983	585.64	23.49	73.41	38.73
342	June 1979	455.63	18.70	63.18	35.63	390	June 1983	599.09	24.22	76.23	40.72
343	July 1979	459.34	18.84	63.51	35.75	391	July 1983	614.39	24.99	79.22	42.73
344	Aug 1979	463.62	19.02	63.98	35.97	392	Aug 1983	630.43	25.80	82.43	44.94
345	Sept 1979	467.50	19.17	64.34	36.11	393	Sept 1983	646.51	26.59	85.59	47.06
346	Oct 1979	471.48	19.34	64.76	36.30	394	Oct 1983	644.01	26.39	84.70	46.40
347	Nov 1979	475.40	19.49	65.13	36.44	395	Nov 1983	636.44	25.93	82.99	45.22
348	Dec 1979	479.36	19.65	65.54	36.63	396	Dec 1983	636.43	25.91	83.06	45.24

Table G2.4. Simulated tetrachloroethylene (PCE) and PCE degradation by-products in groundwater at water-supply well TT-26, January 1951–December 1994,¹ Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.—
Continued

[TCE, trichloroethylene; 1,2-tDCE, trans-1,2-dichloroethylene; VC, vinyl chloride; all values are in micrograms per liter and were obtained using the TechFlowMP model]

Stress period	Month and year	PCE	TCE	1,2-tDCE	VC
397	Jan 1984	669.53	27.63	89.80	49.60
398	Feb 1984	656.15	26.79	85.89	46.77
399	Mar 1984	701.41	29.17	95.46	53.06
400	Apr 1984	726.87	30.34	99.48	55.47
401	May 1984	727.18	30.20	98.66	54.72
402	June 1984	744.85	31.04	102.01	56.79
403	July 1984	774.99	32.51	107.46	60.14
404	Aug 1984	772.30	32.19	105.73	58.71
405	Sept 1984	741.09	30.44	98.48	53.69
406	Oct 1984	710.58	28.86	92.41	49.67
407	Nov 1984	684.55	27.56	87.48	46.46
408	Dec 1984	664.78	26.60	83.72	44.01
409	Jan 1985	644.30	25.58	79.64	41.36
410– 528	Feb 1985– Dec 1994	No pumping			

¹ Current maximum contaminant levels (MCLs) are as follows: tetrachloroethylene (PCE) and trichloroethylene (TCE), 5 micrograms per liter ($\mu\text{g/L}$); *trans*-1,2-dichloroethylene (1,2-tDCE), 100 $\mu\text{g/L}$; and vinyl chloride (VC), 2 $\mu\text{g/L}$ (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.)

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