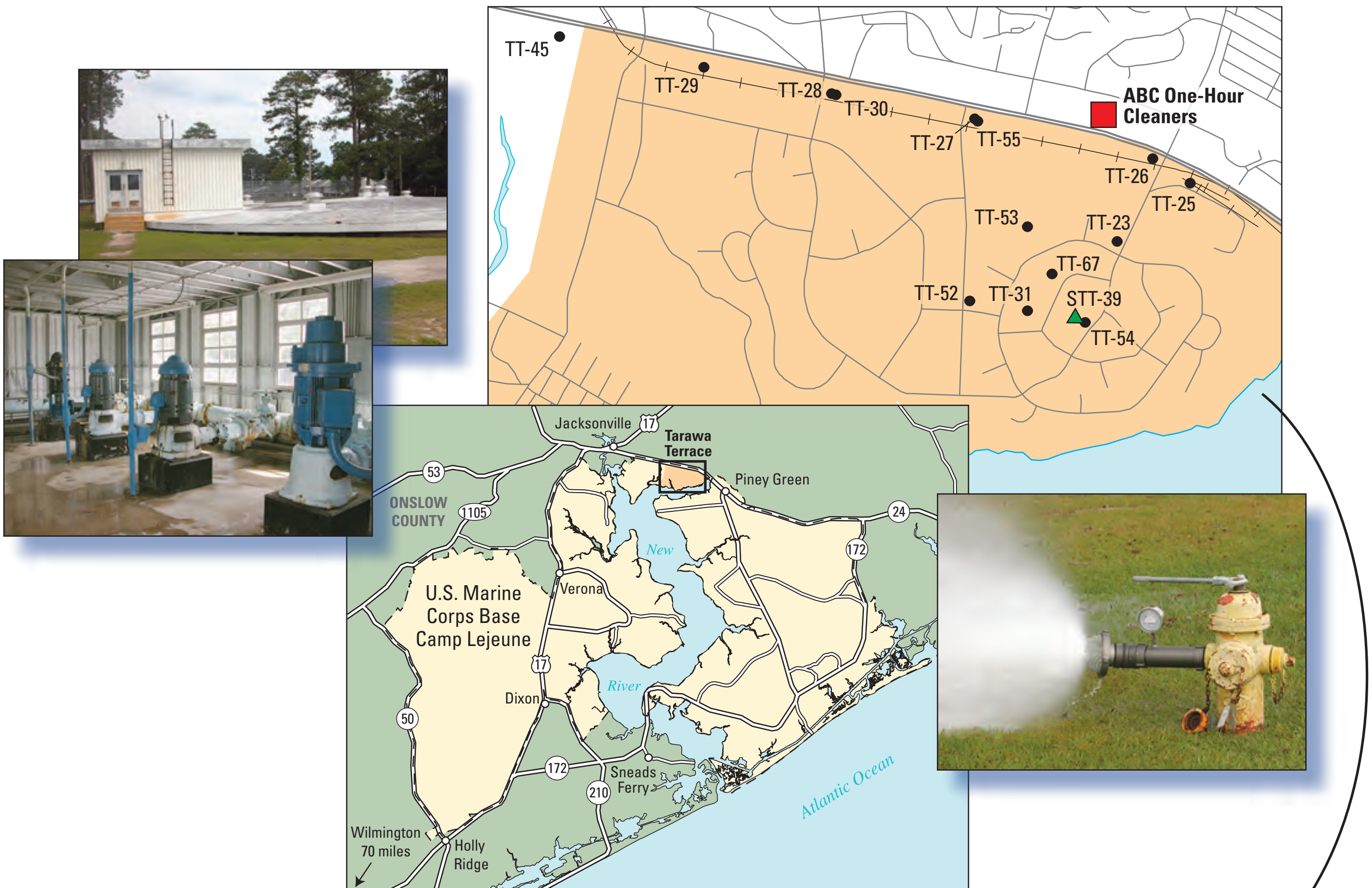
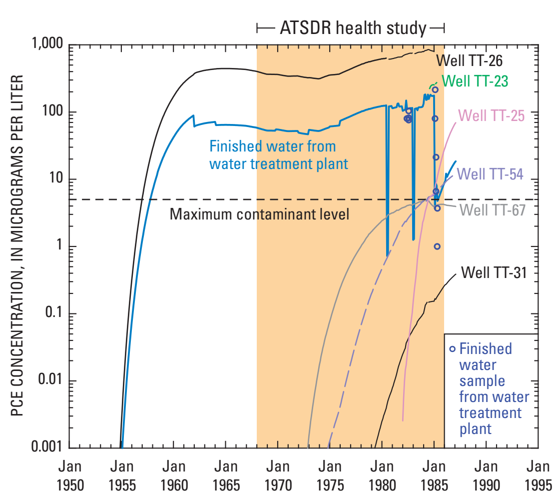
Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions

Chapter H: Effect of Groundwater Pumping Schedule Variation on Arrival of Tetrachloroethylene (PCE) at Water-Supply Wells and the Water Treatment Plant





DEPARTMENT OF HEALTH & HUMAN SERVICES · USA

ATSDR
AGENCY FOR TOXIC SUBSTANCES AND DISEASE REGISTRY

Atlanta, Georgia–February 2008

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

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

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

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

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

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Chapter H: Effect of Groundwater Pumping Schedule Variation on Arrival of Tetrachloroethylene (PCE) at Water-Supply Wells and the Water Treatment Plant

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U.S. Department of Health and Human Services
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February 2008

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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 H: Effect of Groundwater Pumping Schedule Variation on Arrival of Tetrachloroethylene (PCE) at Water-Supply Wells and the Water Treatment Plant*, 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.

Contents

Figures

Tables

Conversion Factors

Multiply	By	To obtain
	Length	
inch	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (MG)	3,785	cubic meter (m^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
million gallons per day (MGD)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
pound, avoirdupois (lb)	4.536×10^{-4}	gram (g)

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 ($\mu g/m^3$)	1,000
parts per billion by volume (ppbv)	parts per million by volume (ppmv)	1,000

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

Glossary and Abbreviations

ATSDR	Agency for Toxic Substances and Disease Registry
CEE	School of Civil and Environmental Engineering
CPU	central processing unit
DIS	MODFLOW discretization file
FTL	flow-transport link
GA	genetic algorithm
GB	gigabyte
GHz	gigahertz
Maximum Schedule	pumping schedule yielding the early arrival time
Minimum Schedule I	pumping schedule yielding the late arrival time with no conditions on well TT-26 schedules
Minimum Schedule II	pumping schedule yielding the late arrival time with conditions on well TT-26 schedules
MCL	maximum contaminant level
MESL	Multimedia Environmental Simulations Laboratory
OBS	concentration observation file for MT3DMS
Original Schedule	original pumping schedule used by ATSDR
PC	personal computer
PCE	tetrachloroethylene
PSOpS	Pumping Schedule Optimization System
S/O	simulation and optimization
USGS	U.S. Geological Survey
WEL	well package for MODFLOW
WTP	water treatment plant

Note: In this report, the maximum contaminant level (MCL) refers to the current MCL for tetrachloroethylene (PCE) that was set by the U.S. Environmental Protection Agency at 5 micrograms per liter, effective July 6, 1992 (40 CFR, Section 141.60, Effective Dates, July 1, 2002, ed.)

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Chapter H: Effect of Groundwater Pumping Schedule Variation on Arrival of Tetrachloroethylene (PCE) at Water-Supply Wells and the Water Treatment Plant

By Jinjun Wang[1] and Mustafa M. Aral[1]

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 H, describes the effect of groundwater pumping schedule variations on arrival times of PCE at water-supply wells and the Tarawa Terrace water treatment plant (WTP). 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.

During the historical reconstruction study—described in other chapters of this report series—groundwater flow and fate and transport of contaminants at Tarawa Terrace and vicinity were simulated to evaluate the contaminant concentration at the WTP. Due to uncertainty associated with reconstructed input data used in these simulations, uncertainty may be present in simulated contaminant concentrations at water-supply wells and the WTP. As a consequence, there also may be uncertainty associated with the arrival time of the maximum contaminant level (MCL) concentration at water-supply wells and the WTP. A major cause for and contribution to this uncertainty are the pumping schedules, which are discussed in other report chapters. The focus of this chapter report, therefore, is on the uncertainty associated with pumping schedules. The study discussed in this chapter includes the development of a simulation and optimization procedure identified as PSOpS (Pumping Schedule Optimization System), which combines simulation models and optimization techniques to optimize pumping schedules for maximum or minimum contaminant concentrations at the WTP. Based on optimized pumping schedules, variations of PCE concentration and the maximum contaminant level (MCL, 5 micrograms per liter for PCE) arrival time at water-supply wells and the WTP are evaluated. Results of this study indicate that variation of pumping schedules may cause significant changes in the contaminant concentration levels and MCL arrival times at the WTP.

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Introduction

The Agency for Toxic Substances and Disease Registry (ATSDR) is conducting an epidemiological study to evaluate whether exposures (in utero and during infancy—up to 1 year of age) to volatile organic compounds (VOCs) that contaminated drinking water at the U.S. Marine Corps Base Camp Lejeune, North Carolina, were associated with specific birth defects and childhood cancers. To provide the epidemiological study with quantitative estimates of exposure, characterization of environmental contamination and the frequency and duration of exposure to contaminated drinking water is being conducted using the historical reconstruction process (Maslia et al. 2001).

The site investigation at the base concluded that groundwater was the sole source of water to the Tarawa Terrace water treatment plant (WTP).[2] The contaminant source was ABC One-Hour Cleaners (Shiver 1985), located north of the Tarawa Terrace I family housing area (Figure H1). Major contaminants at the site included tetrachloroethylene (PCE) and its degradation by-products. Contaminants released from ABC One-Hour Cleaners migrated into the groundwater system and eventually were supplied to the WTP through several water-supply wells in the Tarawa Terrace area of the base.

Based on the study of hydrogeologic and historical data of Tarawa Terrace and vicinity, the ATSDR modeling team has reconstructed and simulated multilayer groundwater flow at the site using MODFLOW, a groundwater-flow simulation model (McDonald and Harbaugh 1988). The simulation model MT3DMS (Zheng and Wang 1999) was then used to evaluate the fate and transport of contaminants in the subsurface. Based on this analysis, concentration distribution and arrival time of contaminants at the WTP were determined historically.

Due to its nature, the historical reconstruction modeling process has uncertainties associated with it; these uncertainties could have a significant effect on the epidemiological study. One uncertainty is associated with pumping schedules used in groundwater-flow simulations because there are limited historical records of pumping rates at water-supply wells. In this study, the focus is on the evaluation of the uncertainty caused by pumping schedules and its effect on simulation results. For this purpose, a methodology was developed to yield the earliest/latest contaminant arrival times at water-supply wells and the WTP associated with allowable variations in groundwater pumping schedules throughout the historical operation of the site. As it was developed in this study, this methodology uses a combination of simulations and optimization methods to adjust pumping schedules while maintaining historical total pumping demands at the water-supply wells that were identified in other chapter reports. The study presented here includes the following assumptions:

1. Tetrachloroethylene (PCE) is the only contaminant of concern at the site, although other contaminants such as degradation by-products of PCE existed in the groundwater and at the WTP. In this study, the use of the term *contaminant* implies PCE, unless otherwise specified.
2. The pumping schedule is the only variable considered to be uncertain in this analysis. Some other factors, such as hydrogeologic variables, also may cause variations in the contaminant transport process and may affect contaminant concentration and arrival time at water-supply wells and the WTP. The uncertainties associated with these variables are discussed in Chapter A (Maslia et al. 2007) and Chapter I (Maslia et al. In press 2008) and, therefore, are not considered in this study.

This study used two simulation models:

1. *MODFLOW:* A modular three-dimensional groundwater simulation model. It can be used in the solution of governing equations of multilayer groundwater-flow systems. The model uses the finite-difference method in its process, was developed by the U.S. Geological Survey, and is an open source code (McDonald and Harbaugh 1984). MODFLOW-2000 (also identified as MF2K), a fourth generation of MODFLOW, is employed in this study. In this report, all MODFLOW-related information is adopted from the report authored by Harbaugh et al. (2000) unless otherwise identified. The executable file and the source codes of MODFLOW can be downloaded from *http://water.usgs.gov/nrp/gwsoftware/modflow2000/modflow2000.html*.
2. *MT3DMS:* A modular three-dimensional multispecies contaminant transport model. It can be used in the simulation of advective, diffusive, and reactive transport of contaminants in multilayer groundwater systems (Zheng and Wang 1999). All the MT3DMS-related information in this report is obtained from reports authored by Zheng and Wang (1999) and Zheng (2005) unless otherwise identified. The version of the MT3DMS model employed in this study is version 5.1. The executable file and the source codes of MT3DMS can be downloaded from *http://hydro.geo.ua.edu/mt3d/*.

In this study, all information regarding U.S. Marine Corps Base Camp Lejeune and input data used for the models previously described are the same as used in other report chapters. Thus, there is no discussion of details of the hydrogeologic framework and the bases of these data.

The organization of this report is as follows. In the next section, a review of the study conducted by the ATSDR modeling team is provided, including a background review and a review of the simulation models used in the historical reconstruction study. A groundwater simulation and optimization procedure—identified as PSOpS (Pumping Schedule Optimization System) and developed by the researchers at the Multimedia Environmental Simulations Laboratory, Georgia Institute of Technology—is introduced in the section "Optimization of Pumping Schedules." Simulation results and a discussion of these results are presented in the section "Simulation Results and Discussion," which is followed by a "Summary of Results" section.

[2]Throughout this report (Chapter H), the water treatment plant (WTP) refers solely to the Tarawa Terrace WTP.

A Review of ATSDR's Tarawa Terrace Study

Background

ATSDR, an agency of the U.S. Department of Health and Human Services, is currently (2007) conducting a historical reconstruction of contaminant occurrences in drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina. 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 H1). The purpose of the study is to determine if there is an association between exposure to contaminated drinking water and birth defects and childhood cancers in children born to women who were pregnant while living in base housing during the period 1968–1985.

Due to limited exposure data available for the period of interest (1968–1985), ATSDR has undertaken a reconstruction of historical conditions. In this series of chapter reports (A–K), ATSDR's investigation focuses solely on Tarawa Terrace and vicinity. (Future analyses and reports will present information and data about contamination of the Hadnot Point water-distribution system.) The Tarawa Terrace area is bounded on the east by Northeast Creek, and to the south by New River and Northeast Creek. On the west and north, it is bounded by the drainage boundaries of these streams. The historical reconstruction includes a groundwater system reconstruction, contaminant source characterization, and contaminant fate and transport simulation in the groundwater system and the water-distribution system serving the Tarawa Terrace area.

The ATSDR study concluded that groundwater was the sole source of water to the WTP and water-distribution system serving the Tarawa Terrace area. The source of contaminants in the groundwater was ABC One-Hour Cleaners (Shiver 1985), located to the north of several Tarawa Terrace water-supply wells (Figure H1). According to the ATSDR study, PCE was continuously released to the subsurface system at a rate of 1,200 grams per day during the period January 1953–December 1984 (Faye 2007b). PCE released from ABC One-Hour Cleaners migrated into the groundwater system and was then supplied to the WTP by water-supply wells pumping contaminated groundwater.

Using hydrogeologic data and contaminant source characterization (Faye 2007a), the ATSDR modeling team was able to simulate groundwater flow and contaminant fate and transport in the subsurface system at Tarawa Terrace and vicinity to reconstruct historical concentration levels of PCE (Faye and Valenzuela 2007; Faye 2007b). Due to the nature of historical reconstruction, uncertainties are associated with reconstructed information, which in turn cause uncertainties in resulting exposure analyses. Uncertainties in the exposure outcome can have a significant effect on the epidemiological study. In particular, the uncertainty caused by the groundwater pumping schedule used in the simulations has been pointed out to be important. Therefore, in this study, there is an evaluation of the variation in PCE concentrations and arrival times of the maximum contaminant level (MCL, 5 micrograms per liter [µg/L] for PCE) at water-supply wells and the WTP. The variation could be caused by changes in groundwater pumping rates at water-supply wells.

Introduction to Simulation Tools and Input Data

In the ATSDR study, the contaminant concentration at the WTP was evaluated by using the following steps:

1. The MODFLOW model was used to simulate groundwater flow at Tarawa Terrace area and vicinity. The MODFLOW simulation also generated a flow-transport link (FTL) file that was used in the MT3DMS simulation.
2. Using the FTL file, along with other input files, an MT3DMS simulation was conducted to obtain contaminant concentrations at water-supply wells.
3. The contaminant concentration distribution obtained from the MT3DMS simulation was used to calculate the PCE concentration at the WTP through a volumetric mixing model.

In the following sections, MODFLOW and MT3DMS models and their input files are briefly described.

MODFLOW Model and Input Data

MODFLOW is a computer program that was designed to solve the three-dimensional equation governing groundwater flow (Equation 1) by using the finite-difference method for both steady-state and transient-flow applications (McDonald and Harbaugh 1988):

$$\frac{\partial}{\partial x}(K_{xx}\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(K_{yy}\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(K_{zz}\frac{\partial h}{\partial z})+W=S_s\frac{\partial h}{\partial t}\ , \quad (1)$$

where

K_{xx}, K_{yy}, and K_{zz} are hydraulic conductivity values along the *x*-, *y*-, and *z*-coordinate axis directions (LT^{-1});
h is the piezometric head (L);
W is a volumetric flux per unit volume that represents sources and/or sinks at the site (T^{-1});
S_s is the specific storage of the porous medium (L^{-1});
t is time (T); and
x, y, z are the Cartesian coordinate directions (L).[3]

McDonald and Harbaugh (1984) developed MODFLOW. Since then it has been modified numerous times, and several versions exist in the literature. The second version is identified as MODFLOW-88 (McDonald and Harbaugh 1988). The third version is identified as MODFLOW-96 (Harbaugh and McDonald 1996a, 1996b). The latest version, which is used in this study, is identified as MODFLOW-2000 (Harbaugh et al. 2000). Also since its inception, Prudic (1989), Hill (1990), Leake and Prudic (1991), Goode and Appel (1992), Harbaugh (1992), McDonald et al. (1992), Hsieh and Freckleton (1993), Leake et al. (1994), Fenske et al. (1996),

[3]For equations in this report (Chapter H), L represents length units, T represents time units, and M represents mass units.

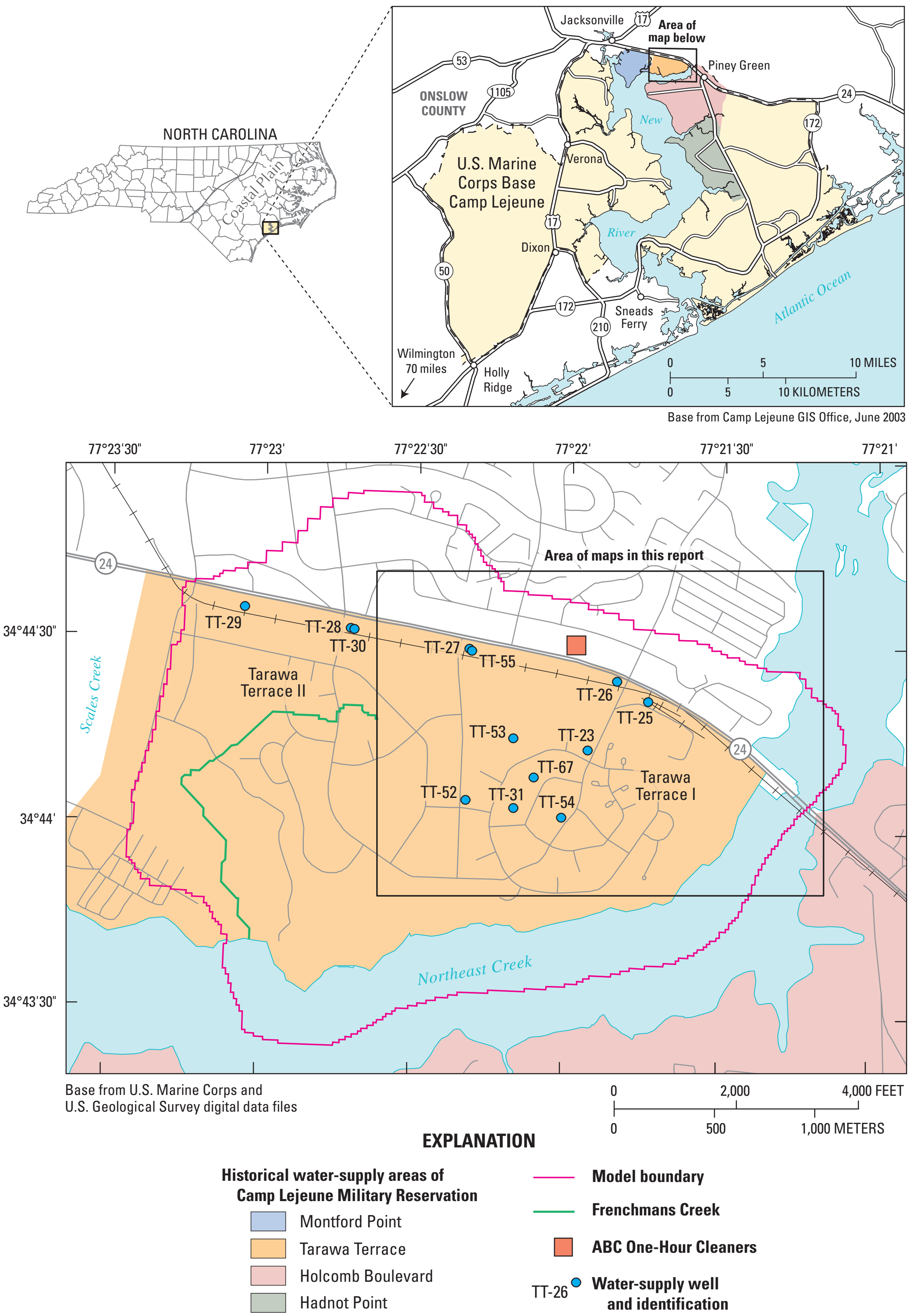


Figure H1. U.S. Marine Corps Base Camp Lejeune, water-supply wells, and ABC One-Hour Cleaners, Onslow County, North Carolina.

Leake and Lilly (1997), and Hill et al. (2000) have made several improvements to MODFLOW.

In this study, the MODFLOW model is applied to generate an FTL file for the MT3DMS simulation. In addition, MODFLOW also is a component of the newly developed PSOpS model.

In MODFLOW simulations, a fundamental component of time discretization data is the "time step." A group of time steps is identified as a "stress period" (Harbaugh et al. 2000). In this study, from the first month of year 1951 through the last month of year 1994, each month is identified as a stress period. There are a total of 528 stress periods during the overall simulation period. January 1951 is "stress period 1," February 1951 is "stress period 2," and so forth (Appendix H1). Within a stress period, time-dependent variables, such as groundwater pumping rates of water-supply wells, are constant. Therefore, the update of the pumping schedule, as reconstructed in this study, occurs monthly.

In MODFLOW, the basic spatial simulation unit used in finite-difference calculations is called a "finite-difference cell" or "cell." In the ATSDR study, the groundwater system at Tarawa Terrace and vicinity is modeled as a zone that contains 200 rows, 270 columns, and 7 layers of cells. Thus, a total of 378,000 cells are used to idealize the three-dimensional groundwater-flow region at the site.

Input data for the MODFLOW simulation can be divided into two categories: (1) "global process input" data files and (2) "groundwater-flow process input" data files. Global process input files contain basic information that is applied to the entire simulation. As for the groundwater-flow process input files, a group of related input data are put together into a file as the input for a specific "package." For example, a discretization (DIS) file is a global process input file. It contains data such as the number of rows, columns, and layers in the model, cell widths, and so forth. In comparison, a well (WEL) file is a file that contains input data for the "Well Package," including locations and pumping rates of water-supply wells assigned to each stress period. Based on these types of classifications, MODFLOW input files, as used in the ATSDR study, are listed and are summarized in Table H1.

Table H1. Input files used for the MODFLOW simulation code, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Process	File type	Package
Global	NAM	Not applicable
	DIS	Not applicable
Groundwater flow	BAS6	Basic
	BCF6	Block-Centered Flow
	DRN	Drain
	GHB	General-Head Boundary
	OC	Output Control Option
	PCG	Preconditioned Conjugate-Gradient
	RCH	Recharge
	LMT6	Link-MT3DMS
	WEL	Well

There are two global process files used in the study:

1. *File type:* NAM
   File contents: The name and Fortran unit of each file used in the simulation
2. *File type:* DIS
   File contents: Basic discretization information, including number of rows, columns, and layers of the model; number of stress periods; confining layers information; width of each cell along rows and columns; elevation of each cell; period length, number of time steps, and the state (steady or transient) of each stress period

The following nine groundwater-flow process files also are used in the study:

1. *File type:* BAS6
   Package: Basic Package
   File contents: Boundary conditions; piezometric head value in inactive cells; initial head distribution
2. *File type:* BCF6
   Package: Block-Centered Flow Package
   File contents: Wet-dry cell information; layer-type information (whether the layer is confined or not, and how the interblock transmissivity will be calculated); transmissivities or hydraulic conductivities; horizontal anisotropy factors; primary and secondary storage coefficients; vertical hydraulic conductivities divided by thickness of cells
3. *File type:* DRN
   Package: Drain Package
   File contents: Number of drain parameters; maximum number of drain cells used in any stress period; number of parameters used in each stress period; location and elevation of each drain cell, and factors used to calculate the drain conductance in that cell
4. *File type:* GHB
   Package: General-Head Boundary Package
   File contents: Number of general-head boundary parameters; maximum number of general-head-boundary cells used in any stress period; number of parameters used in each stress period; location of each constant head cell, and the heads in the cell at the beginning and end of each stress period
5. *File type:* OC
   Package: Output Control Option
   File contents: Information on whether the computed head, drawdown, and water budget will be saved for each stress period; where to save and in what format
6. *File type:* PCG
   Package: Preconditioned Conjugate-Gradient Package
   File contents: Maximum number of outer and inner iterations; matrix conditioning method; head change criterion and residual criterion for convergence; relaxation parameter; printout interval
7. *File type:* RCH
   Package: Recharge Package
   File contents: Recharge distribution type; recharge flux (if applicable)

8. *File type:* LMT6
   Package: Link-MT3DMS Package (Zheng et al. 2001)
   File contents: The name, unit, header, and format of the FTL file for MT3DMS simulation
9. *File type:* WEL
   Package: Well Package
   File contents: Maximum number of operating wells in each stress period; number, location, and pumping rate of each well in each stress period

MT3DMS Model and Input Data

MT3DMS is a modular three-dimensional multispecies transport model that can be used in the simulation of advective, dispersive, and reactive transport of contaminants in groundwater-flow systems (Zheng et al. 2001). In the MT3DMS model, three major classes of transport solution techniques are applied so that the best approach can be offered for various transport problems for efficiency and accuracy. These three techniques include the standard finite-difference method, the particle-tracking-based Eulerian-Lagrangian methods, and the higher-order finite-volume total-variation-diminishing (TVD) method.

The governing equation used in the MT3DMS simulation model can be given as:

$$\frac{\partial(\theta C^k)}{\partial t} = \frac{\partial}{\partial x_i}(\theta D_{ij}\frac{\partial C^k}{\partial x_j}) - \frac{\partial}{\partial x_i}(\theta \nu_i C^k) + q_s C_s^k + \sum R_n , \quad (2)$$

where

θ	is the porosity of subsurface system;
C^k	is the concentration of species k in aqueous phase (ML^{-3});
t	is time (T);
x_i and x_j	are the distances along the three-dimensional Cartesian coordinate axis directions (L);
D_{ij}	is the dispersion coefficient (L^2T^{-1});
v	is pore velocity (LT^{-1});
q_s	is the flow rate per unit volume of aquifer representing sinks and sources (T^{-1});
C_s^k	is the concentration of species k in sink or source flux (ML^{-3}); and
$\sum R_n$	is the chemical reaction term ($ML^{-3}T^{-1}$).

In this study, MT3DMS is used to simulate the fate and transport of PCE in the groundwater system at Tarawa Terrace and vicinity. The output of MT3DMS simulation provides PCE concentration at water-supply wells.

Similar to input files of MODFLOW, input files of MT3DMS include one name file and some other input files used for various packages. These input files are described below and listed in Table H2:

1. *File type:* NAM
   File contents: The name and Fortran unit of each file employed in the simulation
2. *File type:* BTN
   Package: Basic Transport Package
   File contents: Basic model information (number of rows, columns, layers, and stress periods); number of chemical species; transport and solution options; confining layer properties; cell width along rows and columns of each cell; porosity in each cell; boundary condition information; starting concentrations of each chemical species (initial conditions); printing options; output frequency; number of observation points and their locations; mass balance output options; and stress period information
3. *File type:* ADV
   Package: Advection Package
   File contents: Advection solution option and other advective transport simulation variables, if applicable
4. *File type:* DSP
   Package: Dispersion Package
   File contents: Longitudinal dispersivities; ratio of horizontal transverse dispersivity to longitudinal dispersivity; ratio of vertical transverse dispersivity to longitudinal dispersivity; effective molecular diffusion coefficients
5. *File type:* SSM
   Package: Sink and Source Mixing Package
   File contents: Sink and source term options; maximum number of sinks and sources; concentration read-in options; concentration of evapotranspiration flux (if applicable); concentration in specified cells
6. *File type:* RCT
   Package: Chemical Reaction Package
   File contents: Type of reaction; type of kinetic reaction; bulk densities of the aquifer medium for each cell; porosities of immobile domain (if applicable); initial concentration of the sorbed phase (if applicable); sorption parameters; reaction rates
7. *File type:* GCG
   Package: Generalized Conjugate-Gradient Solver Package
   File contents: Maximum numbers of inner and outer iterations; relaxation factor; convergence criterion
8. *File type:* FTL
   Package: Flow-Transport Link Package
   File contents: Groundwater-flow-related information

Table H2. Input files used for the MT3DMS simulation code, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

File type	Package
NAM	Not applicable
BTN	Basic Transport
ADV	Advection
DSP	Dispersion
SSM	Sink/Source Mixing
RCT	Chemical Reaction
GCG	Generalized Conjugate-Gradient Solver
FTL	Flow-Transport Link

Water-Supply Well Information

The purpose of this study is to examine the effect of updated pumping schedules on PCE concentration and the 5-µg/L arrival time at water-supply wells and the WTP. Among all input data used in this study, only groundwater pumping rates of water-supply wells are considered to be uncertain and are varied based on an optimization procedure developed in this study. Therefore, it is necessary to present detailed information about the water-supply system in the Tarawa Terrace area.

A total of 16 water-supply wells were used to supply groundwater to the WTP. Thirteen of these wells were located in the Tarawa Terrace area (Figure H1). The other three wells—identified as well #6, well #7, and well TT-45—were located outside of this area and, therefore, are not shown in Figure H1. In this study, it is assumed that well #6, well #7, and well TT-45 had zero contaminant concentration, which implies that these wells contributed only water but no contaminant mass to the WTP.

In MODFLOW and MT3DMS simulations, the location of a water-supply well is identified in terms of the coordinates of the cell (x, y, z) in which the well lies. In the simulation codes, the x, y, and z values correspond to the layer number, row number, and column number of the cells, respectively. According to well-construction logs, some wells penetrate more than one layer of aquifer. Therefore, in MODFLOW simulations, some well discharges are split into two "virtual" wells that extract water from different layers. For example, in MODFLOW input used by ATSDR, well TT-52 is split into TT-52A and TT-52B; wells TT-31 and TT-54 also are split this way. For this report chapter, wells TT-53 and TT-67 are split to satisfy their pumping capacities, with respect to dry- and wet-cell conditions observed at the cell. Locations and service periods of these 13 water-supply wells are listed in Table H3.

During the simulation period (1951–1994), pumping rates of water-supply wells varied, and some wells were out of service for some stress periods. Using historical records, pumping rates and pumping capacities of each water-supply well were generated for all stress periods.

Table H3. Locations and service periods of water-supply wells, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[See Figure H1 for well location; well name with A, model layer 1; well name with B, model layer 3]

Well	Layer	Row	Column	Start date	End date[1]
TT-23	3	84	175	08/1984	04/1985
TT-25	3	67	194	01/1982	02/1987
TT-26	3	61	184	01/1952	01/1985
TT-27	3	52	135	01/1952	12/1961
TT-28	3	47	96	01/1952	12/1971
TT-29	3	41	61	01/1952	06/1958
TT-30	3	47	97	01/1972	01/1985
TT-31A	1	104	152	01/1973	02/1987
TT-31B	3	104	152	01/1973	02/1987
TT-52A	1	101	136	01/1962	02/1987
TT-52B	3	101	136	01/1962	02/1987
TT-53A	1	81	151	01/1962	01/1984
TT-53B	3	81	151	01/1962	01/1984
TT-54A	1	106	167	01/1962	02/1987
TT-54B	3	106	167	01/1962	02/1987
TT-55	1	53	136	01/1962	12/1971
TT-67A	1	93	158	01/1972	02/1987
TT-67B	3	93	158	01/1972	02/1987

[1]End date indicates last month and year water-supply well was pumped for model simulation. Service was terminated the following month (see Table A6 in Chapter A report, Maslia et al 2007)

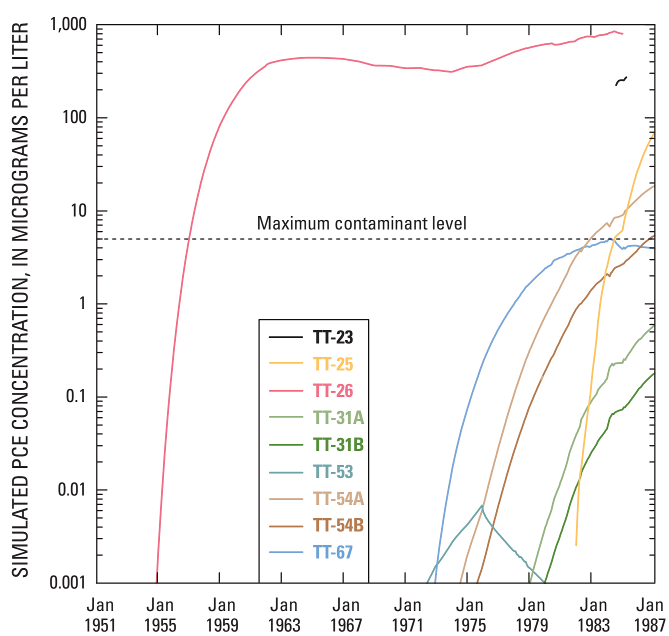


Figure H2. Simulated tetrachloroethylene (PCE) concentration at selected water-supply wells under the Original Schedule, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [TT-31A and TT-54A, model layer 1; TT-31B and TT-54B, model layer 3]

Simulation Results of ATSDR Modeling Study

Using input files listed in Table H1, a MODFLOW simulation was performed to generate an FTL file for the follow-up MT3DMS simulation. PCE concentration distribution at water-supply wells was then obtained from an output file of MT3DMS simulation—the concentration observation (OBS) file. These results are shown in Figure H2.

In Figure H2, PCE concentrations at water-supply wells are shown during their service periods as listed in Table H3. Although 16 pumping wells were operating in the Tarawa Terrace area in ATSDR's simulation, only wells TT-26, TT-23, TT-25, TT-67, TT-54A, and TT-54B had PCE concentrations that exceeded the MCL. Among them, well TT-26 had a much longer period of exposure to PCE concentrations of greater than 5 µg/L. The PCE MCL arrival time at well TT-26 is

January 1957, while the second-earliest PCE MCL arrival at a water-supply well occurred during January 1983 at well TT-54A. The PCE concentration at well TT-26 was always much greater than other water-supply wells, indicating that well TT-26 conveyed the majority of PCE mass introduced into the WTP. This is probably because of proximity of well TT-26 to the contaminant source and the well's long pumping history.

Using PCE concentration data at water-supply wells, along with their associated pumping rates, PCE concentration at the WTP is calculated by using the following mixing model:

$$C_i = \frac{\sum_{j=1}^{n} q_{ij} c_{ij}}{Q_{Ti}}, \qquad (3)$$

where

- C_i is the PCE concentration at the WTP for stress period i (ML^{-3});
- n is the total number of active water-supply wells for stress period i;
- q_{ij} is the pumping rate of well j for stress period i (L^3T^{-1});
- c_{ij} is the PCE concentration at water-supply well j for stress period i (ML^{-3}); and
- Q_{Ti} is the total water demand for stress period i (L^3T^{-1}).

PCE concentration at the WTP is shown in Figure H3. It is identified as the "Original Schedule" throughout the remainder of this chapter report to distinguish it from other updated pumping schedules that were developed and are discussed in later sections. The Orignial Schedule is the pumping schedule used in other Tarawa Terrace chapter reports (Faye 2007b, Faye and Valenzuela 2007).

As shown in Figure H3, PCE concentration at the WTP first exceeded the MCL during November 1957. When this outcome is compared to results presented in Figure H2, only well TT-26 had a PCE concentration exceeding 5 µg/L by November 1957. Therefore, well TT-26 is critical in assessing the PCE MCL arrival time at the WTP.

As shown in Figure H4 for the period of interest (January 1968–December 1985),[4] the maximum PCE concentration at the WTP is 183.04 µg/L and the minimum PCE concentration is 0.72 µg/L. During this period, however, there are only 15 months when the PCE concentration at the WTP is less than 46.69 µg/L. Therefore, for most of the period of interest (201 months out of 216 months), the PCE concentration at the WTP ranges between 46.69 µg/L and 183.04 µg/L, and the average PCE concentration is about 86.39 µg/L, which is much greater than the 5 µg/L MCL for PCE.

The time periods during which the PCE concentration at the WTP is lower than 46.69 µg/L are July 1980–August 1980, January 1983–February 1983, and February 1985–December 1985. These also are time periods during which well TT-26 was out of service. As can be seen in Figure H2, during these time periods, PCE concentrations at other water-supply wells were much less than those at well TT-26. Stopping well TT-26 from supplying water to the WTP,

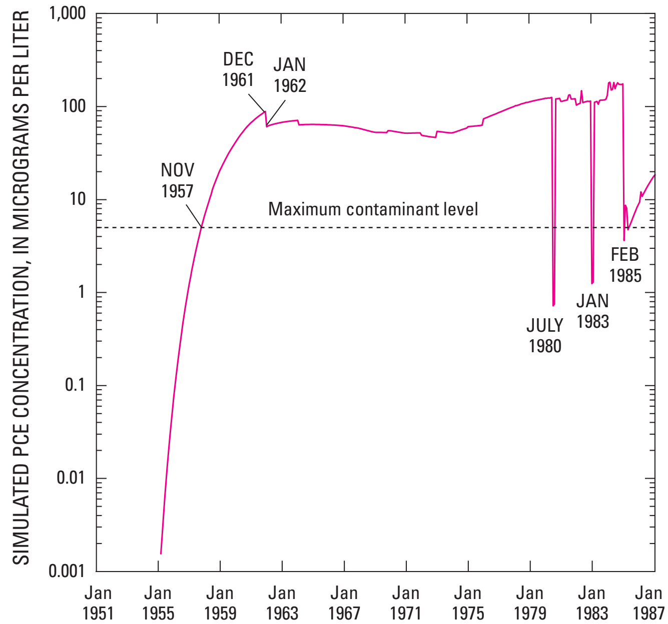


Figure H3. Simulated tetrachloroethylene (PCE) concentration at the water treatment plant under the Original Schedule, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

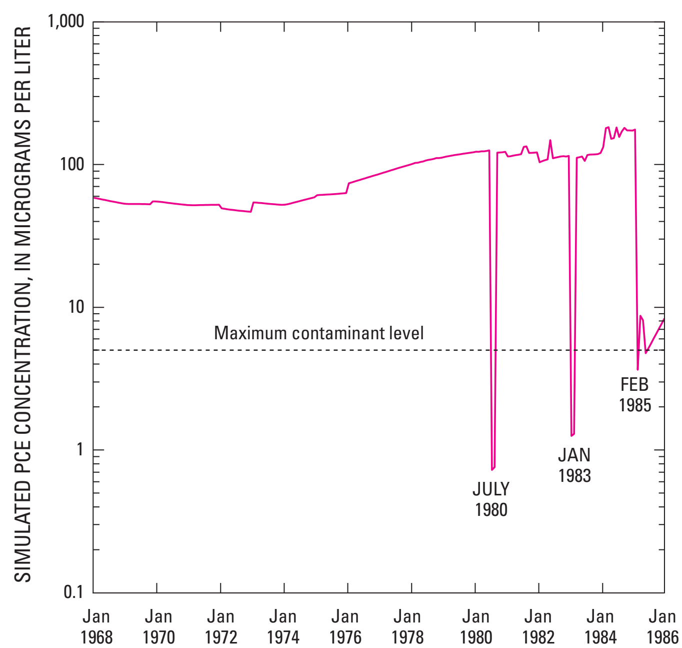


Figure H4. Simulated tetrachloroethylene (PCE) concentration at the water treatment plant under the Original Schedule, period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[4]Throughout this report (Chapter H), the "period of interest" is defined as January 1968–December 1985.

therefore, caused the sudden PCE concentration declines as shown in Figures H3 and H4.

The reason for the PCE concentration decline at the end of 1961 (Figure H3) is similar to the one described previously. At that time, the pumping rate of well TT-26 decreased from 28,715 cubic feet per day (ft^3/day) to 18,959 ft^3/day, while the total water supplied to the WTP was unchanged (116,199 ft^3/day). Because PCE concentrations at other water-supply wells were negligible (less than 0.001 µg/L) and well TT-26 was the only source of PCE to the WTP at that time, a decrease of PCE concentration was expected at the WTP.

Optimization of Pumping Schedules

As introduced in "A Review of ATSDR's Tarawa Terrace Study," PCE concentration at the WTP was obtained through consecutive application of the following three steps:

1. Simulation of groundwater flow using the MODFLOW model.
2. Simulation of PCE fate and transport using the MT3DMS model.
3. Calculation of PCE concentration at the WTP using the MT3DMS output, pumping schedules, and the WTP mixing model.

Throughout these steps, pumping schedules are used both in MODFLOW simulation and during the calculation of PCE concentration at the WTP when using the mixing model. Moreover, as stated earlier, pumping schedules are the only uncertain variable in this study. Therefore, to evaluate the change in PCE arrival time at water-supply wells and the WTP, pumping schedules that may cause that change must be obtained first according to certain criteria. In this study, a pumping schedule optimization system (PSOpS) was developed using the simulation and optimization (S/O) approach. In PSOpS, simulation models (MODFLOW and MT3DMS) were combined with optimization techniques to generate optimal pumping schedules that would yield the "earliest" or the "latest" PCE MCL arrival times at the WTP.

Formulation of the Optimization Model

To evaluate the change of PCE arrival time at the WTP caused by a variation of pumping schedules, models must be identified to link contaminant arrival time and pumping schedules. Currently, several simulation models (or a combination of simulation models), which may be used in this analysis, are available in the literature.

Among the models, one straightforward choice is the combination of MODFLOW and MODPATH (Pollock 1994). MODPATH is a particle-tracking model that computes three-dimensional pathlines and particle arrival times at pumping wells based on the advective flow output of MODFLOW. A combination of MODFLOW and MODPATH can provide the contaminant arrival time at water-supply wells. However, several limitations in the MODPATH model restrict its use in this study. First, MODPATH only simulates the advective transport of contaminants in the groundwater system. In a MODPATH simulation, the advection of water is considered to be the only driving force of contaminant movement, while other factors that also may affect the movement of contaminants, such as diffusion and dispersion, are not considered. Second, in a MODPATH simulation, the contaminant is treated as a tracer, which implies no chemical reaction or degradation can be accounted for that might be associated with the contaminant. Third, although a MODPATH simulation can provide contaminant arrival time at a pumping well, this time is only recorded for the first contaminant particle that arrives at the well. No concentration information is associated with this simulation output. In this study, however, a more precise simulation of contaminant fate and transport is required, and the time for contaminant concentration to reach a specific level is required for exposure evaluation purposes. Considering all these restrictions, a more sophisticated model with fewer limitations (MT3DMS) was chosen instead of MODPATH. Thus, the combination of MODFLOW and MT3DMS was selected for this study.

As introduced in previous sections, MT3DMS is a subsurface contaminant fate and transport simulation model. Using an FTL file obtained from MODFLOW, MT3DMS can be run on the same groundwater system used for MODFLOW simulation. MT3DMS does not have the restrictions associated with the MODPATH model. The output file of MT3DMS provides contaminant concentrations at specified times and locations. Using this information, certain concentration levels can be evaluated as to their arrival times at water-supply wells. Other benefits of the coupled simulation of MODFLOW and MT3DMS include:

1. The contaminant concentration at the WTP can be calculated and evaluated by using the output of MT3DMS.
2. Original input files obtained from the Tarawa Terrace study can be applied directly, and only a few complementary files need to be added within the PSOpS framework.

Using the coupled simulation of MODFLOW and MT3DMS, the following steps are used to evaluate the change of PCE arrival time caused by variation in pumping schedules:

1. Optimize pumping schedules for the "earliest" and the "latest" PCE arrival times using a combination of simulation models (MODFLOW and MT3DMS) and optimization techniques (S/O).
2. Simulate the groundwater flow and the contaminant fate and transport at the site using optimal pumping schedules obtained in step 1.
3. Calculate PCE concentration at the WTP using Equation 3 and optimal pumping schedules.
4. Evaluate the "earliest" and the "latest" PCE arrival times at the WTP.

In step 1, the optimization of pumping schedules for the "earliest" or the "latest" PCE arrival time is equivalent to optimizing the pumping schedule for the "maximum" or "minimum" PCE concentrations at the WTP because the observation of a higher concentration at the WTP implies an earlier contaminant arrival time, and vice versa. One approach to optimizing pumping at the WTP is to optimize pumping schedules for the maximum or minimum PCE concentrations for each stress period individually. After the maximum or minimum concentrations are obtained for each stress period, a relationship can be obtained between maximum or minimum concentration versus stress period (time). This approach, however, is associated with a substantial computational burden. The large scale of the simulation model—200 rows, 270 columns, 7 layers, and 528 stress periods—clearly indicates that this approach will require years of calculation time on a high-end personal computer (PC) to complete the simulations and, therefore, is unacceptable.

Another possible approach is to combine stress periods with the same characteristics (pumping rates, pumping capacities, pumping demands, recharge, and so forth) together to reduce the size of the overall model. This approach, however, would lose some detail during optimization, which implies that it would not be as precise as the original model and, thus, could affect optimization results.

Considering the computational power and memory of desktop workstations available for this study (64-bit dual-processor PCs), along with the need to obtain an acceptable result in a timely manner without losing any detail and accuracy, the optimization problem needs to be formulated in a more computationally cost-efficient manner. To create such a model, the following observations were made about the site data used in these simulations:

1. The contaminant was released continuously from the same source point (ABC One-Hour Cleaners, Figure H1).

2. Well TT-26 was the only major contaminant contributor to the WTP.

3. Well TT-26 was in operation during most of the period of interest (January 1968–December 1985).

With these observations in mind, the optimization problem is reformulated as follows: optimize each successive stress period i for a maximum or minimum PCE concentration at the WTP for stress period i while keeping all of the previously optimized pumping rates constant. In other words, in the reformulation, the pumping schedule of stress period 1 is first optimized for optimal (maximum or minimum) PCE concentration at the WTP for stress period 1. Then the pumping schedule of stress period 2 is optimized for optimal PCE concentration for stress period 2 keeping the optimization results from stress period 1 constant, and so on. In this manner, at the end of the simulation and optimization process, an optimal pumping schedule is obtained for all stress periods under which the PCE concentration at the WTP can be maximized or minimized.

The reformulated optimization problem for maximum PCE concentration at the WTP can be expressed mathematically as

$$\begin{aligned} &\underset{q_i \in R^n}{Max}\ C_i = f(q_1,...,q_i) \\ &s.t. \\ &0 \le q_i \le w_i \\ &\sum_{j=1}^{n} q_{ij} = Q_{Ti} \\ &q_k = q_k^*\ (k = 1,...,i-1), \end{aligned} \tag{4}$$

where

C_i is the PCE concentration at the WTP for stress period i (ML^{-3});

n is the number of active water-supply wells for stress period i;

q_i is an n-dimensional vector of pumping rates for stress period i (L^3T^{-1});

w_i is an n-dimensional vector of the upper bound of q_i for stress period i (pumping capacities) (L^3T^{-1});

q_{ij} is the pumping rate of well j for stress period i (L^3T^{-1});

Q_{Ti} is the total water demand for stress period i (L^3T^{-1}); and

q_k^* is the optimal pumping schedule for stress period k (L^3T^{-1}).

In the optimization problem given in Equation 4, $q_1, \ldots, q_{i-1}$ are known, and C_i is only a function of q_i. Thus, to obtain the maximum PCE concentration C_i, only the pumping schedule for stress period i needs to be optimized based on optimal pumping schedules for the previous stress periods. By formulating the problem in this way, the dimensions of the problem are reduced significantly, and the computational demand becomes manageable.

The optimization model for the minimum PCE concentration at the WTP is similar:

$$\begin{aligned} &\underset{q_i \in R^n}{Min}\ C_i = f(q_1,...,q_i) \\ &s.t. \\ &0 \le q_i \le w_i \\ &\sum_{j=1}^{n} q_{ij} = Q_{Ti} \\ &q_k = q_k^*\ (k = 1,...,i-1). \end{aligned} \tag{5}$$

Explanations used for this equation are the same as given for Equation 4.

Equation 5 can be easily solved by using the same method as used in the solution of the optimization problem given in Equation 4 because it can be rewritten as

$$
\begin{aligned}
&\underset{q_i \in R^n}{Max}\ C'_i = -C_i = -f(q_1, ..., q_i) \\
&s.t. \\
&0 \le q_i \le w_i \\
&\sum_{j=1}^{n} q_{ij} = Q_{Ti} \\
&q_k = q_k^* \ (k = 1, ..., i-1).
\end{aligned} \tag{6}
$$

Therefore, in this report only the “maximization” problem given in Equation 4 is used as an example when describing the optimization method.

Selection of the Optimization Method

For optimization problems given in Equations 4 and 5, PCE concentration at the WTP is calculated by using the following governing equations:

$$\frac{\partial}{\partial x}(K_{xx}\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_{yy}\frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_{zz}\frac{\partial h}{\partial z}) + W = S_s \frac{\partial h}{\partial t} \ ; \tag{7}$$

$$\frac{\partial(\theta C^k)}{\partial t} = \frac{\partial}{\partial x_i}(\theta D_{ij}\frac{\partial C^k}{\partial x_j}) - \frac{\partial}{\partial x_i}(\theta \nu_i C^k) + q_s C_s^k + \sum R_n \ ; \tag{8}$$

and

$$C_i = \frac{\sum_{j=1}^{n} q_{ij} c_{ij}}{Q_{Ti}} . \tag{9}$$

For the definition of the terms used in these equations, refer to the text following Equations 1, 2, and 3. Among Equations 7–9, Equation 7 is used in the MODFLOW simulation for obtaining piezometric head distribution and groundwater-flow velocity between adjacent nodes; Equation 8 is used in the MT3DMS simulation to obtain PCE concentration distribution; and Equation 9 is used to calculate PCE concentration at the WTP.

A study of Equations 7–9 shows that optimization problems given in Equations 4 and 5 are multidimensional, nonlinear optimization problems with linear constraints, which are much harder to solve and more computationally intensive than linear optimization problems. Moreover, objective functions are nonconcave or nonconvex, which imposes more difficulty in finding a global optimal solution. Significant literature exists on optimization methods for the solution of nonlinear optimization problems. Some of these methods are introduced briefly in the following sections.

Downhill Simplex Method

The downhill simplex method is an optimization method for multidimensional nonlinear problems that does not require evaluating the derivative of the objective function but uses only the objective function values (Press et al. 1989). For an N-dimensional minimization problem, the downhill simplex method starts with $N+1$ initial points (feasible solutions), which define an initial simplex, and then moves step by step toward the optimal solution. Each step is called a “reflection.” For a minimization problem, in each reflection the point of the simplex that has the largest value is found and moved through the opposite face of the simplex to a lower point, until the solution meets the termination criterion. In the downhill simplex method, although derivatives are not required, this approach is still not sufficiently efficient considering the number of objective function evaluations it requires.

Steepest Descent Method

The steepest descent method is a nonlinear optimization method that uses the derivative information of the objective function (Press et al. 1989). To solve a minimization problem by using this method, starting from an initial point, the downhill gradient is calculated at that point, and a minimization point is found along the gradient direction. The downhill gradient is calculated from that point, and another point is found along the gradient direction. By following the gradient directions on the objective function, an optimal solution can be found that meets the termination criterion.

The problem with the steepest gradient method is that iterated solutions may move in a direction of reversed gradient paths because the gradient at a new point can be perpendicular to the previous gradient. This increases the computational burden and may lead to an inefficient solution. Another problem for this method is that often the solution will be trapped in a local optimal solution.

Conjugate Gradient Method

Similar to the steepest descent method, the conjugate gradient method uses the derivative information to find the optimal solution for a nonlinear optimization problem (Press et al. 1989). This method differs from the steepest descent method in the following sense. The conjugate gradient method is improved in such a way that, for each movement toward the solution, the direction of movement is constructed to be conjugate to the old gradient. By doing this, an optimal solution can be achieved more efficiently.

Even though the conjugate gradient method is more efficient than the steepest descent method, calculation of derivatives of the objective function at each iteration step is still a heavy computational burden. Also, similar to the steepest descent method, the possibility for the solution of the conjugate gradient method to be a local optimum instead of a global optimum is very high.

Genetic Algorithms

A genetic algorithm (GA) refers to a method of optimization that attempts to find the most optimal solution by mimicking—in a computational sense—the mechanics of natural selection and genetics (Chinneck 2006). Its application requires the solution to be expressed as a string. Using a population of strings, an objective function value can be calculated for each string for its "fitness" evaluation.

During a GA process, first an initial population is generated, and the fitness of each string is evaluated. Then, a mating pool is generated from the current population using several GA operations. For example, crossover operation (two parent strings obtained from the mating pool exchange part of their strings to form two new child strings) and mutation operation (values at some points of some strings are changed randomly) are applied to generate the new population. After the generation of a new population, the fitness of each new string is evaluated again. This evolutionary process leads to the most fit strings to remain and accumulate in the population. If the termination criterion is met, the process is stopped. Otherwise, the process will start again based on the new generation of a population.

A good aspect of GAs is that the process can yield better and better solutions without reliance on gradients. Another advantage of GAs is that they search the optimal solution globally; thus, the solution is sometimes better than those obtained from other methods mentioned previously. However, considering the computation power required for the evaluation of fitness of each string, if the computation time of the simulation tools required to solve the problem is large and if the mating pool also is large, then GAs can be more computationally demanding than the other methods discussed previously.

Based on the review given previously, it can be concluded that for a complex nonlinear optimization problem, any of the methods discussed above can be quite computationally demanding. To reduce computational demand, a new optimization method—identified as "rank-and-assign method," which will be introduced in detail in the next section—was developed uniquely for the problem discussed in this study. The few cases that cannot be solved by the rank-and-assign method are optimized by the improved gradient method.

Introduction to the Pumping Schedule Optimization System (PSOpS)

Based on the two optimization techniques (rank-and-assign and improved gradient methods) and simulation models (MODFLOW and MT3DMS), a procedure identified as PSOpS has been developed to optimize the pumping schedule for the "earliest" or the "latest" PCE arrival time at the WTP using the S/O approach. In PSOpS, MODFLOW and MT3DMS are used to simulate the groundwater flow and contaminant fate and transport conditions for derivative calculations that are necessary in the solution of the optimization problem; optimization techniques are used within the same procedure to optimize pumping schedules.

Methodology of the Pumping Schedule Optimization System

The pumping schedule adjustment necessary to achieve the maximum PCE concentration level at the WTP, which is analogous to the earliest arrival time solution, is solved by the procedure shown in Figure H5. The variables and abbreviations used in Figure H5 are defined as

Q_{Ti} total pumping demand for stress period i;

$C_i^{(k)}$ PCE concentration at the WTP for stress period i after the k^{th} iteration;

q_{ij} pumping rate of water-supply well j for stress period i;

$(\frac{\partial C_i}{\partial q_{ij}})^{(k)}$ change of PCE concentration at the WTP for stress period i caused by the unit change of q_{ij} after the k^{th} iteration;

$q_i^{(k)}$ pumping schedule vector for stress period i after the k^{th} iteration which consists of q_{ij} of all water-supply wells for stress period i;

$\nabla C_i(q_i^{(k)})$ concentration gradient vector for $q_i^{(k)}$ which consists of $(\frac{\partial C_i}{\partial q_{ij}})^{(k)}$ of all active water-supply wells for stress period i;

$\left\|\nabla C_i(q_i^{(k)})\right\|$ norm of $\nabla C_i(q_i^{(k)})$, which is the maximum absolute value of $(\frac{\partial C_i}{\partial q_{ij}})^{(k)}$;

w_i pumping capacity vector for stress period i;

$SQ_i^{(k)}$ sequence of $(\frac{\partial C_i}{\partial q_{ij}})^{(k)}$; and

ε a predefined termination criterion. If $\left\|\nabla C_i(q_i^{(k)})\right\|$ is less than ε, the pumping schedule for stress period i is considered to be optimal.

The assumptions made in PSOpS are:

1. When $\left\|\nabla C_i(q_i^{(k)})\right\|$ is less than ε, the pumping schedule for the current stress period i is optimal, and no further update is required.
2. The total pumping rate of all water-supply wells for stress period i is equal to the total pumping demand for that stress period.
3. The pumping rate in a water-supply well is always less than or equal to its pumping capacity.
4. Water-supply wells outside of the simulated region (in this case, well #6, well #7, and well TT-45) are considered as one well with zero $\frac{\partial C_i}{\partial u_{ij}}$ value. In other words, pumping rates in these wells can be adjusted, but they do not provide contaminant mass to the WTP.

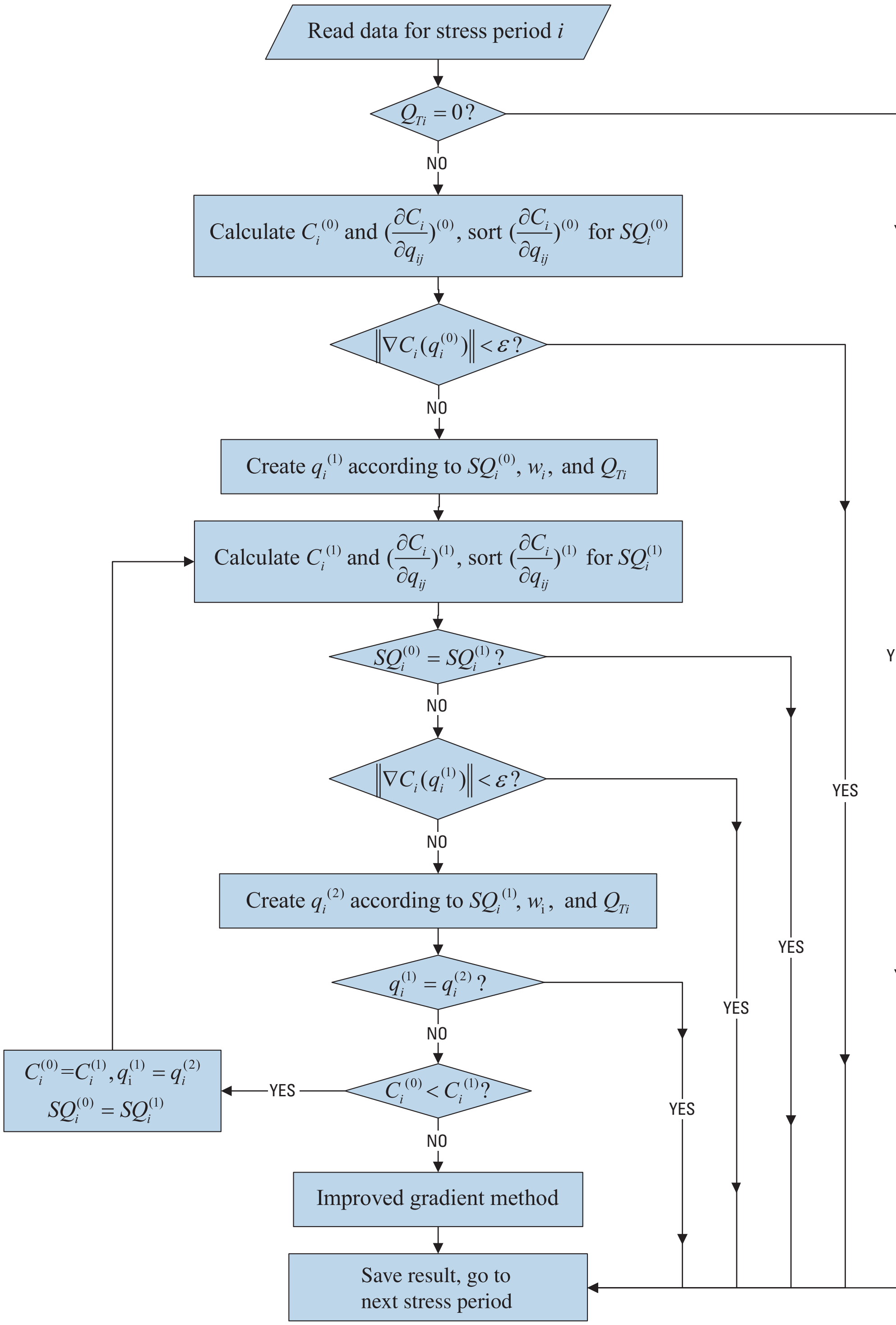


Figure H5. Flowchart of Pumping Schedule Optimization System (PSOpS).

Following the procedure shown in Figure H5, PSOpS optimizes pumping schedules for maximum PCE concentration levels at the WTP for stress period i as outlined in the step-by-step process given below:

1. Read input data for stress period i, such as the total pumping demand (Q_{Ti}), the pumping capacities (w_i), and the initial pumping schedule ($q_i^{(0)}$).

2. If Q_{Ti} is equal to zero, no pumping schedule update is required, go to step 13; otherwise go to step 3.

3. Run MODFLOW and MT3DMS for stress period i to obtain $C_i^{(0)}$, then run MODFLOW and MT3DMS for another n times, where n is the number of active wells for stress period i, with a unit change in pumping rate to calculate the gradients $(\frac{\partial C_i}{\partial q_{ij}})^{(0)}$ for each active well. After this computation, sort the $(\frac{\partial C_i}{\partial q_{ij}})^{(0)}$ values for $SQ_i^{(0)}$.

4. If $\left\|\nabla C_i(q_i^{(0)})\right\|$ is less than ε, no update for stress period i is required, then go to step 13; otherwise go to step 5.

5. Update the pumping schedule for stress period i to $q_i^{(1)}$ using rank-and-assign method according to $SQ_i^{(0)}$, w_i, and Q_{Ti} (refer to "Rank-and-Assign Method" section for detailed information on these variables).

6. Similar to step 3, update $C_i^{(1)}$ using $q_i^{(1)}$, calculate $(\frac{\partial C_i}{\partial q_{ij}})^{(1)}$ values and sort these values to obtain $SQ_i^{(1)}$.

7. Compare $SQ_i^{(0)}$ and $SQ_i^{(1)}$. If they are the same, $q_i^{(1)}$ is the optimal pumping schedule for stress period i, then go to step 13; otherwise go to step 8.

8. If $\left\|\nabla C_i(q_i^{(1)})\right\|$ is less than ε, $q_i^{(1)}$ is the optimum, then go to step 13; otherwise go to step 9.

9. Similar to step 5, update $q_i^{(1)}$ to $q_i^{(2)}$ using the rank-and-assign method according to $SQ_i^{(1)}$, w_i, and Q_{Ti}.

10. Compare $q_i^{(1)}$ and $q_i^{(2)}$. If they are the same, then go to step 13; otherwise go to step 11.

11. Compare $C_i^{(0)}$ and $C_i^{(1)}$. If $C_i^{(0)}$ is less than $C_i^{(1)}$, use $C_i^{(1)}$, $SQ_i^{(1)}$, and $q_i^{(2)}$ to replace $C_i^{(0)}$, $SQ_i^{(0)}$, and $q_i^{(1)}$, then go to step 6 and update again; otherwise go to step 12.

12. Optimize $q_i^{(2)}$ using the improved conjugate gradient method (refer to "Improved Gradient Method" section for detailed information).

13. Run MODFLOW and MT3DMS simulations using the optimal pumping schedule for stress period i again, and save piezometric head and concentration distribution information at the end of stress period i for optimization of pumping schedule of the next stress period.

Optimization of the pumping schedule to obtain the minimum PCE concentration at the WTP is equivalent to the optimization of the pumping schedule for the maximum PCE concentration at the WTP with the objective function multiplied by minus one.

Rank-and-Assign Method

The rank-and-assign method was specifically developed for PSOpS. This method updates the pumping schedule for maximum or minimum contaminant concentration levels at the WTP based on the derivative—pumping capacity—and the total pumping demand information available for the system. The name of this method reflects the steps it follows to update the pumping schedule—it first "ranks" the gradients and then "assigns" the pumping rates to each water-supply well according to this ranking.

Steps 3–11 shown in Figure H5 describe the rank-and-assign optimization technique. In step 5, by assuming an $SQ_i^{(0)}$ with the following ranking,

$$(\frac{\partial C_i}{\partial q_{i1}})^{(0)} \geq \ldots \geq (\frac{\partial C_i}{\partial q_{ik}})^{(0)} \geq \ldots \geq (\frac{\partial C_i}{\partial q_{in}})^{(0)} \quad , \qquad (10)$$

the procedure below is followed to assign the $q_i^{(1)}$ to yield the maximum PCE concentration at the WTP:

1. Assign the pumping capacity of the first well in $SQ_i^{(0)}$ as its pumping rate. If the total pumping demand is less than the pumping capacity of that well, assign the total pumping demand as its pumping rate, and go to step 4.

2. If the remaining pumping demand is greater than the pumping capacity of the next well in $SQ_i^{(0)}$, assign the pumping capacity of that well as its pumping rate, and repeat step 2; otherwise go to step 3.

3. Assign the remaining pumping demand as the pumping rate of the next well in $SQ_i^{(0)}$.

4. Assign zero pumping rates to all other wells that are left in the $SQ_i^{(0)}$ list.

In the rank-and-assign method, the optimized pumping schedule satisfying the condition "$SQ_i^{(0)} = SQ_i^{(1)}$" is at least a local optimum because it satisfies the Kuhn-Tucker condition (Kuhn and Tucker 1951). The Kuhn-Tucker condition is described below.

Consider the problem:

$$\begin{aligned} &\underset{x \in R^n}{Min}\, f(x) \\ &s.t. \\ &g_i(x) \leq 0 \\ &h_j(x) = 0, \end{aligned} \qquad (11)$$

where

$g_i(x)$ ($i = 1,\ldots,m$)	are the nonequality constraints;
$h_j(x)$ ($j = 1,\ldots,l$)	are the equality constraints;
m	is the number of nonequality constraints; and
l	is the number of equality constraints.

Suppose that the objective function $f: R^n \rightarrow R$ and the constraint functions $g_i : R^n \rightarrow R$ and $h_j : R^n \rightarrow R$ are continuously differentiable at a point $x^* \in S$. If x^* is a local minimum, then constants $\lambda_i \geq 0$ ($i = 1, \ldots, m$) and μ_j ($j = 1, \ldots, l$) exist such that

$$\nabla f(x^*) + \sum_{i=1}^{m} \lambda_i \nabla g_i(x^*) + \sum_{j=1}^{l} \mu_j \nabla h_j(x^*) = 0$$
$$\lambda_i g_i(x^*) = 0 \text{ for all } i = 1,...,m. \quad (12)$$

To prove that a solution from the rank-and-assign method satisfies the Kuhn-Tucker condition, the problem for one stress period is reformulated as:

$$\begin{aligned} &\underset{q \in R^n}{Min}\, C = -f(q) \\ &s.t. \\ &-q_i \leq 0 \;\; (i = 1,...,n) \\ &q_i - w_i \leq 0 \;\; (i = 1,...,n) \\ &\sum_{i=1}^{n} q_i - Q_T = 0, \end{aligned} \quad (13)$$

where

C	is the PCE concentration at the WTP;
n	is the number of active water-supply wells;
q	is an n-dimensional vector of pumping rates;
q_i	is the pumping rate of well i;
w_i	is the pumping capacity for well i; and
Q_T	is the total water demand.

The Kuhn-Tucker conditions for the problem given in Equation 13 are:

$$\begin{aligned} &-\frac{\partial f}{\partial q_i} - \lambda_i + \omega_i + \mu = 0 \;\; (i = 1,...,n) \\ &\lambda_i q_i = 0 \;\; (i = 1,...n) \\ &\omega_i (q_i - w_i) = 0 \;\; (i = 1,...,n) \\ &\lambda_i \geq 0 \;\; (i = 1,...n) \\ &\omega_i \geq 0 \;\; (i = 1,...,n). \end{aligned} \quad (14)$$

Suppose the optimal solution from the rank-and-assign method is

$$q_i \begin{cases} = w_i \;\; (i = 1,...,k-1) \\ \leq w_i \;\; (i = k) \\ = 0 \;\; (i = k+1,...,n) \end{cases}, \quad (15)$$

while the following condition is satisfied

$$\frac{\partial f}{\partial q_i} \geq ... \geq \frac{\partial f}{\partial q_k} \geq ... \geq \frac{\partial f}{\partial q_n} \quad . \quad (16)$$

For $i \leq k$, since $q_i > 0$, to satisfy $\lambda_\iota \theta_\iota = 0$, there is

$$\lambda_\iota = 0 \; (i = 1, \ldots, k). \quad (17)$$

According to equation: $-\frac{\partial f}{\partial q_i} - \lambda_\iota + \omega_i + \mu = 0$, there is

$$\omega_i = \frac{\partial f}{\partial q_i} - \mu \;\; (i = 1,...,k). \quad (18)$$

Let $\mu = \frac{\partial f}{\partial q_k}$, there is

$$\omega_\kappa = 0. \quad (19)$$

Since $\frac{\partial f}{\partial q_i} \geq \frac{\partial f}{\partial q_k}$ for $i < k$, there is

$$\omega_\iota = \frac{\partial f}{\partial q_i} - \frac{\partial f}{\partial q_k} \geq 0 \;\; (i = 1,...,k-1). \quad (20)$$

For $i > k$, since $q = 0$, to satisfy $\omega_\iota (q_i - w_i) = 0$, there must be

$$\omega_\iota = 0 \; (i = k + 1, \ldots, n). \quad (21)$$

According to equation $-\frac{\partial C}{\partial q_i} - \lambda_i + \omega_i + \mu = 0$, there is

$$\lambda_i = \mu - \frac{\partial C}{\partial q_i} = \frac{\partial C}{\partial q_k} - \frac{\partial C}{\partial q_i} (i = k+1,...,n). \quad (22)$$

Since $\frac{\partial C}{\partial q_k} \geq \frac{\partial C}{\partial q_i}$ for $i > k$, it is known that

$$\lambda_i = \frac{\partial C}{\partial q_k} - \frac{\partial C}{\partial q_i} \geq 0 \;\; (i = k+1,...,n). \quad (23)$$

Therefore, the Kuhn-Tucker conditions are satisfied.

The Kuhn-Tucker conditions are necessary for a solution to be optimal. For an optimization problem with a convex (minimization problem) or a concave (maximization problem) objective function, the Kuhn-Tucker conditions also are sufficient for the solution to be a global optimum. However, because the objective function in this problem is nonconvex (or nonconcave), the solution obtained from the rank-and-assign method is not guaranteed to be the global optimum, which is same as the situation associated with many other nonlinear optimization methods. In this sense, the rank-and-assign method trades computational efficiency with global optimality.

Improved Gradient Method

As shown in Figure H5, in PSOpS application, the rank-and-assign method is applied first to each stress period. If the optimal solution cannot be obtained from the rank-and-assign optimization process, an improved gradient method is used for the optimal solution. The improved gradient method is similar to the steepest descent method introduced previously. In PSOpS, the steepest descent method is further improved by two aspects: (1) reducing the dimension of the optimization problem and (2) projecting the gradient to satisfy the equality constraint.

In the improved gradient method, the ranking of active pumping wells in $SQ_i^{(0)}$ and $SQ_i^{(1)}$ obtained from the rank-and-assign method are compared, and wells with same rankings in both sequences are exempted from the optimization process. Thus, the dimension of the optimization problem can be reduced significantly along with the computational cost. For example, assume that there are five pumping wells with $SQ_i^{(0)}$ and $SQ_i^{(1)}$ as

$$SQ_i^{(0)}:(\frac{\partial C_i}{\partial q_{i1}})^{(0)} \geq (\frac{\partial C_i}{\partial q_{i2}})^{(0)} \geq (\frac{\partial C_i}{\partial q_{i3}})^{(0)} \geq (\frac{\partial C_i}{\partial q_{i4}})^{(0)} \geq (\frac{\partial C_i}{\partial q_{i5}})^{(0)} \qquad (24)$$

and

$$SQ_i^{(1)}:(\frac{\partial C_i}{\partial q_{i1}})^{(1)} \geq (\frac{\partial C_i}{\partial q_{i4}})^{(1)} \geq (\frac{\partial C_i}{\partial q_{i2}})^{(1)} \geq (\frac{\partial C_i}{\partial q_{i3}})^{(1)} \geq (\frac{\partial C_i}{\partial q_{i5}})^{(1)} . \qquad (25)$$

Between the two sequences given above, only wells 2, 3, and 4 have different rankings. Therefore, in the improved gradient method, only wells 2, 3, and 4 are considered as variables for optimization, and the dimension of the problem is reduced from 5 to 3, accordingly.

This variable-elimination step is logical. Using the maximization process as an example, after $SQ_i^{(0)}$ is obtained, the pumping schedule would be updated according to the procedure described in the rank-and-assign method. Then, according to Equation 25, $SQ_i^{(1)}$ indicates that well 1 still has the most potential to increase the contaminant concentration by increasing its pumping rate. However, the pumping rate in well 1 has reached its pumping capacity and cannot be increased any further. Therefore, it is exempted from optimization. The case for well 5 is similar—to increase the contaminant concentration its pumping rate is supposed to be decreased, while its pumping rate is already zero. (If the pumping rate of well 5 is not zero, then according to the description of the rank-and-assign method, we know that the pumping rates of wells 2, 3, and 4 are at their pumping capacities, respectively, and the pumping schedule cannot be updated any more.)

After eliminating water-supply wells with same rankings in both sequences, the gradient of the remaining wells is then projected to the feasible solution space by subtracting the same amount from all derivatives to make the summation of the resulting derivatives to be zero. The equality constraint of the optimization problem can be eliminated by applying this gradient projection because the process guarantees the summation of the resulting pumping rates to be constant.

The improved gradient method works through the steps shown in Figure H6. Some variables are the same as defined for Figure H5; the others are defined below.

$d^{(k)}$ The search direction of the optimal solution for the k^{th} iteration. Its dimension is the same as the dimension of the pumping rate vector.

λ_k The step size of the solution increment for the k^{th} iteration.

$\nabla^* C_i(q_i^{(k)})$ The projection of $\nabla C_i(q_i^{(k)})$ in the feasible solution space.

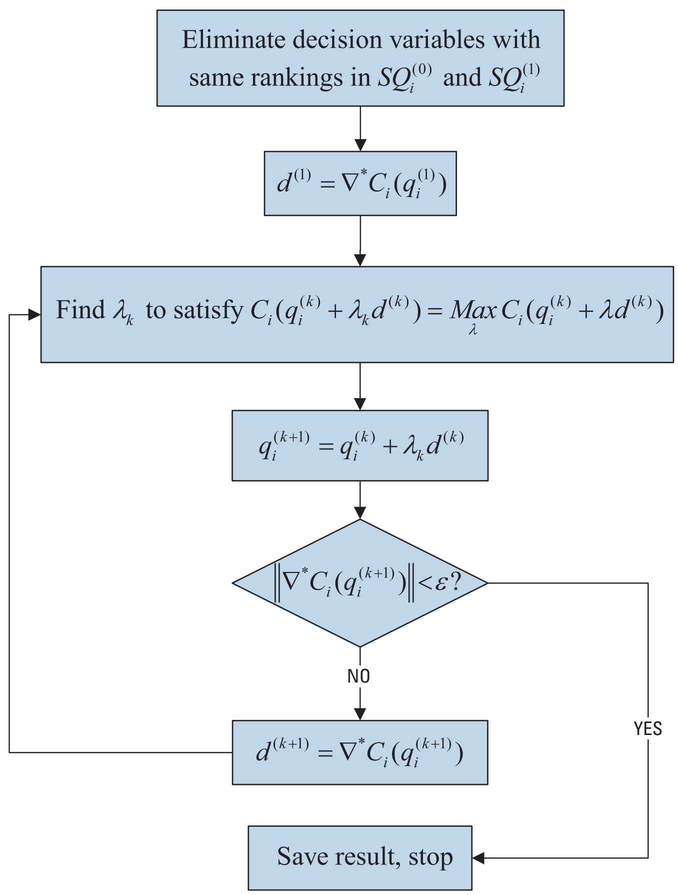


Figure H6. Flowchart of improved gradient method.

Computational steps of the improved gradient method in obtaining the maximum PCE concentration levels at the WTP for stress period *i* are:

1. Eliminate the decision variables with the same rankings in $SQ_i^{(0)}$ and $SQ_i^{(1)}$.
2. Set $d^{(1)}$ to be equal to $\nabla^* C_i(q_i^{(1)})$.
3. Find λ_k to maximize $C_i(q_i^{(k)} + \lambda d^{(k)})$ using the one-dimensional line search method.
4. Update $q_i^{(k)}$ to $q_i^{(k+1)}$.
5. If $\left\|\nabla^* C_i(q_i^{(k+1)})\right\|$ is less than ε, and $q_i^{(k+1)}$ is the optimum, then go to step 7; otherwise go to the next step.
6. Update $d^{(k)}$ to $d^{(k+1)}$, go to step 3 for another iteration.
7. Save the optimal solution.

Improvement of Computational Efficiency

PSOpS was developed to improve the computational efficiency of the pumping schedule optimization problem. Computational efficiency has been achieved through:

1. *The reduction of the dimensions of the problem:* By reformulating the problem, only the pumping schedule of the current stress period needs to be updated to obtain the optimal contaminant concentration at the WTP. A problem that cannot be solved by the rank-and-assign technique can be solved by the improved gradient method which further reduces the dimension of the problem.

2. *The reduction of the number of iterations for the optimization:* Simulation results for this study indicate that most rank-and-assign optimizations converge within two iterations.

3. *Elimination of repeated simulations:* At the end of optimization for each stress period, the piezometric head and concentration distributions are updated and saved as the starting point of the optimization for the next stress period.

By applying PSOpS, an optimal pumping schedule for the problem can be obtained within 4–5 days on a desktop workstation with a 2 gigahertz (GHz) central processing unit (CPU) and 1 gigabyte (GB) of memory. A summary of the optimization status for maximum PCE concentration levels at the WTP is listed in Table H4. For 106 of 528 stress periods, no water was supplied to the WTP (January 1951–December 1951 and March 1987–December 1994). Among the remaining 422 stress periods, pumping schedules in 417 stress periods were updated by the rank-and-assign method, which accounts for 98.8% of the solution. This percentage indicates that the rank-and-assign method works efficiently for this problem.

Table H4. Summary of the optimization status for maximum tetrachloroethylene concentration at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Optimization status	Number of cases	Percentage
$\left\|\nabla C_i(q_i^{(0)})\right\| < \varepsilon$, no update	3	0.6
$SQ_i^{(0)} = SQ_i^{(1)}$	369	69.9
$\left\|\nabla C_i(q_i^{(1)})\right\| < \varepsilon$, no second update	7	1.3
$q_i^{(1)} = q_i^{(2)}$	41	7.8
Optimization using improved gradient method	2	0.4
No pumping and no update	106	20.0
Total	**528**	**100**

Input Data for the Pumping Schedule Optimization System

As previously discussed, PSOpS was developed based on the S/O approach. In PSOpS, the groundwater simulation model MODFLOW and the contaminant fate and transport model MT3DMS are used as the simulators. Therefore, original input files of MODFLOW and MT3DMS obtained from ATSDR's Tarawa Terrace study can be used as input for PSOpS directly. Other than these files, only three files are required to provide simulation type, pumping capacities, and total pumping demand information as given below.

1. *File type:* INFO
   File contents: Optimization type ("1" for maximization of the contaminant concentration and "2" for minimization of the contaminant concentration)

2. *File type:* PCP
   File contents: Pumping capacities of each water-supply well for each stress period

3. *File type:* TPD
   File contents: Total pumping demand for each stress period

Direct application of input files for MODFLOW and MT3DMS as input for PSOpS makes the generation of input files very efficient and convenient.

Simulation Results and Discussion

In this study, PSOpS was run three times: the first run was to obtain the "early" PCE arrival time at the Tarawa Terrace WTP; the second run was to obtain the "late" PCE arrival time at the WTP; and the third run was to obtain the "late" PCE arrival time with a restriction that the assigned pumping rate in well TT-26 was not to be less than 25% of its pumping capacity. In all PSOpS applications, pumping rates in water-supply wells are considered to be the only unknown variables. In this report, optimal pumping schedules obtained from the three PSOpS runs are identified as "Maximum Schedule," "Minimum Schedule I," and "Minimum Schedule II." The original pumping schedule obtained from ATSDR's Tarawa Terrace analysis is identified as the "Original Schedule." In the following sections, results for these three optimized pumping schedules are discussed.

Optimization and Simulation Results for the Maximum Schedule

In the Maximum Schedule obtained from PSOpS, pumping rates are updated for 419 stress periods. Among them, pumping rates from 417 stress periods are updated by the rank-and-assign method, which reduces the computational time significantly.

According to ATSDR's Tarawa Terrace analysis, as previously discussed, water-supply wells started to pump during January 1952; ABC One-Hour Cleaners started operations during January 1953. The output of PSOpS indicates that the first 3 months of pumping during 1952 had a negligible effect on PCE concentration at the WTP after ABC One-Hour Cleaners started to release PCE into the groundwater system. Except for those three stress periods, supply well TT-26 always pumped at its maximum pumping rate (pumping capacity) in the Maximum Schedule solution. The higher (and maximum) pumping rate in well TT-26 generates a higher hydraulic gradient between the contaminant source and well TT-26. This results in faster movement of contaminants from the source to well TT-26 and, thus, an early contaminant arrival time at the pumping well and at the WTP. Pumping rates of well TT-26 under the Maximum Schedule are compared to its pumping capacities in Figure H7.

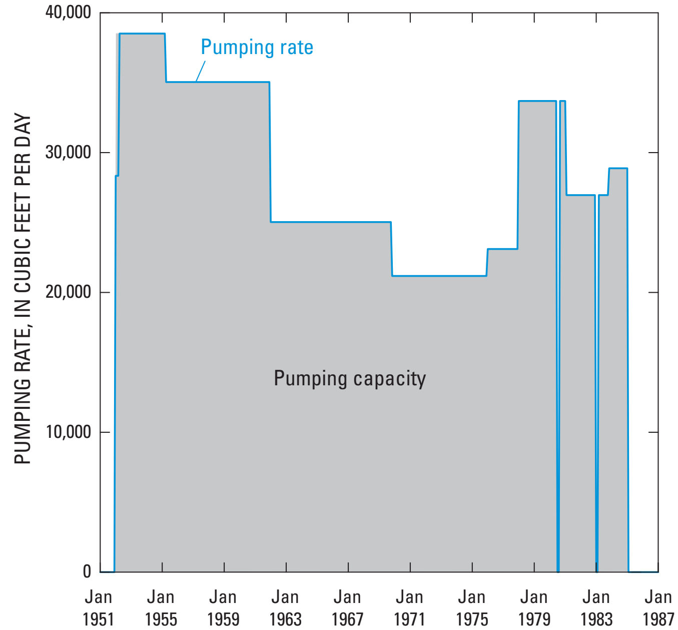


Figure H7. Pumping rate and capacity of water-supply well TT-26 under the Maximum Schedule, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

PCE Distribution in the Groundwater System

While keeping the other input data unchanged, and using the Maximum Schedule as input for the WEL package, MODFLOW and MT3DMS were used to simulate groundwater flow and PCE transport under the Maximum Schedule.

As expected, a variation in the pumping schedule changes the groundwater flow in the subsurface system. Thus, the PCE fate and transport in the aquifer domain also is changed. To illustrate this change, a comparison of the PCE distribution—for stress periods 100, 200, 300, and 400[5]—in the groundwater system at Tarawa Terrace and vicinity under the Original Schedule and the Maximum Schedule are shown in Figures H8–H10 for model layers 1, 3, and 5, respectively.

The results shown in Figures H8–H10 indicate that, when compared to the Original Schedule, the PCE contaminant plume under the Maximum Schedule is aggregated into a smaller domain and the front of the plume is directed more toward the location of water-supply well TT-26. This is because, under the Maximum Schedule, the higher pumping rate in well TT-26 creates a higher piezometric head gradient toward the location of well TT-26, which causes a faster groundwater flow toward and more contaminant mass entering into well TT-26. Therefore, a higher PCE concentration at well TT-26 is expected under the Maximum Schedule.

[5]Maps of PCE distribution always show results for stress periods 100, 200, 300, and 400. The corresponding month and year are labeled on the figures and also can be found in Appendix H1. Owing to brevity, only the stress period number will be used in the text.

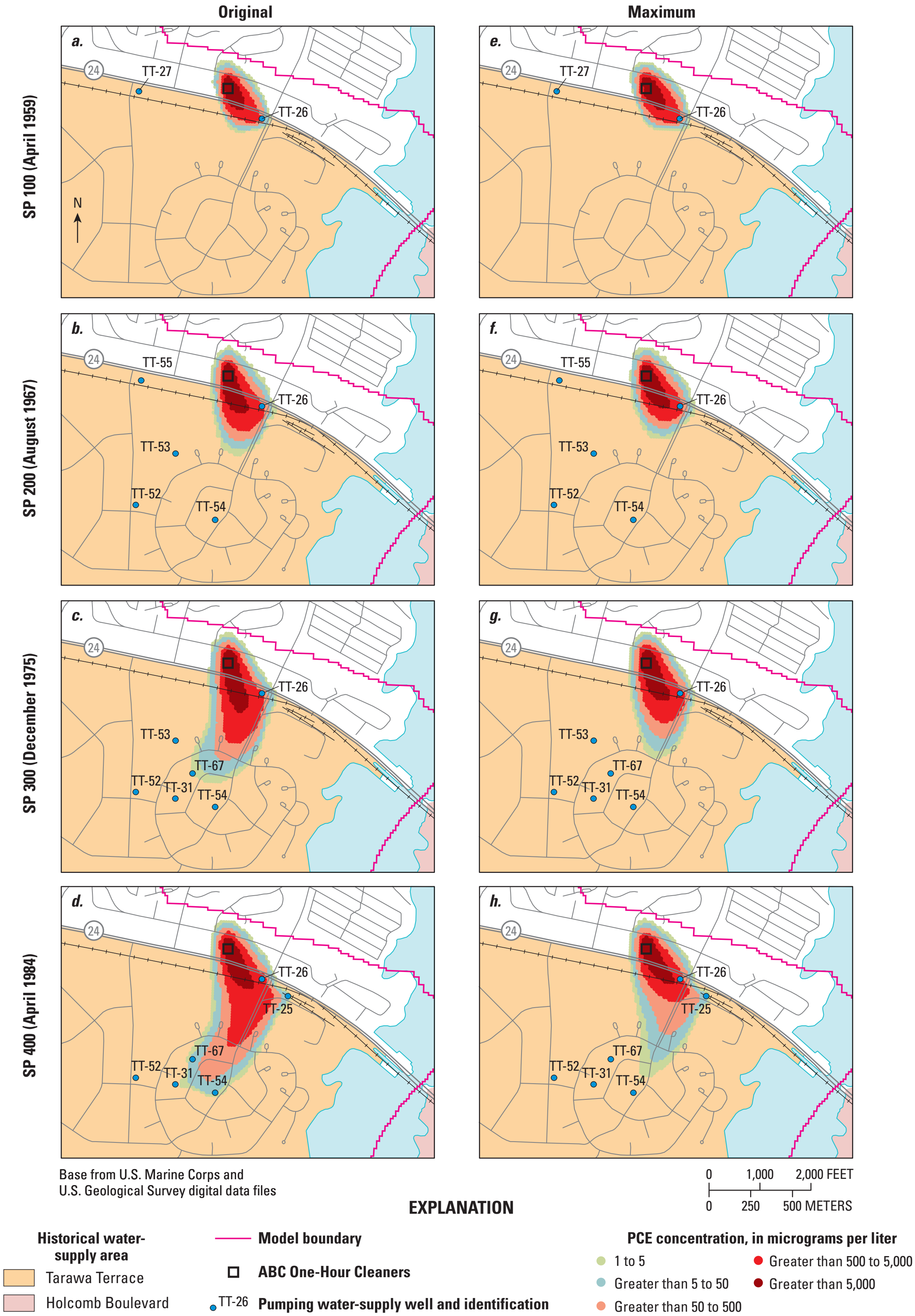


Figure H8. Comparison of tetrachloroethylene (PCE) distribution in model layer 1 under the Original Schedule for *(a)* SP 100, *(b)* SP 200, *(c)* SP 300, and *(d)* SP 400; and the Maximum Schedule for *(e)* SP 100, *(f)* SP 200, *(g)* SP 300, and *(h)* SP 400, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SP, stress period]

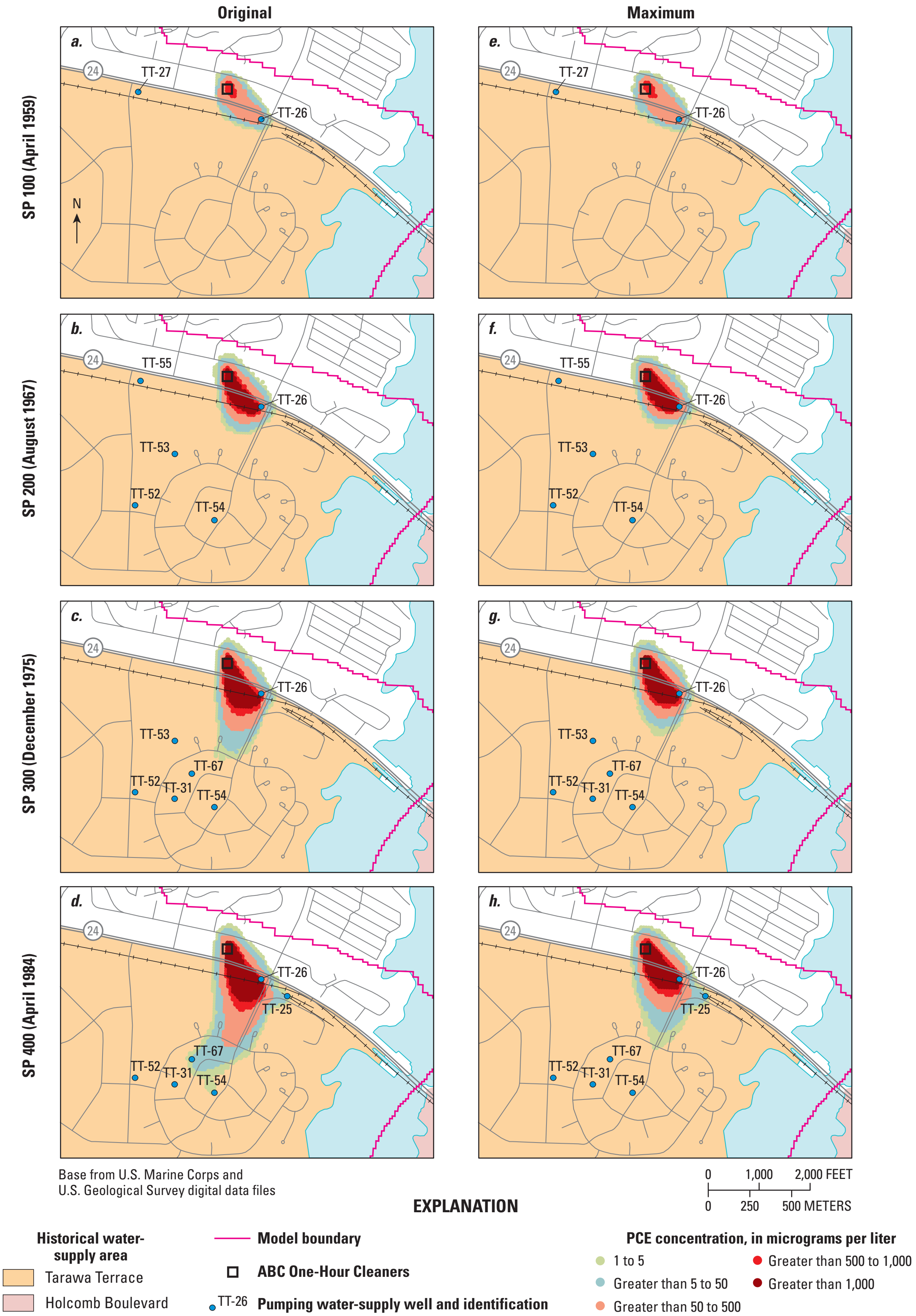


Figure H9. Comparison of tetrachloroethylene (PCE) distribution in model layer 3 under the Original Schedule for *(a)* SP 100, *(b)* SP 200, *(c)* SP 300, and *(d)* SP 400; and the Maximum Schedule for *(e)* SP 100, *(f)* SP 200, *(g)* SP 300, and *(h)* SP 400, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SP, stress period]

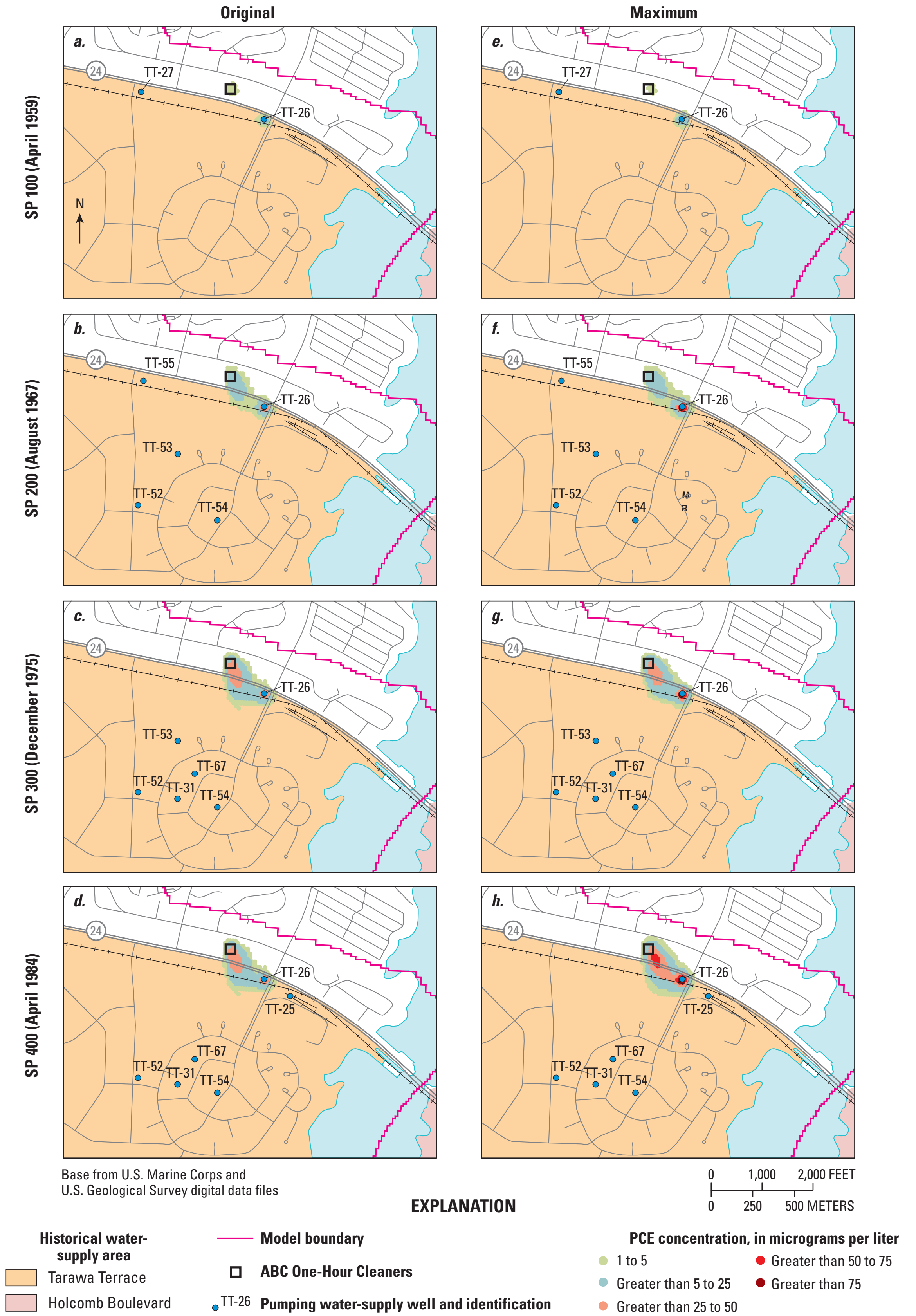


Figure H10. Comparison of tetrachloroethylene (PCE) distribution in model layer 5 under the Original Schedule for *(a)* SP 100, *(b)* SP 200, *(c)* SP 300, and *(d)* SP 400; and the Maximum Schedule for *(e)* SP 100, *(f)* SP 200, *(g)* SP 300, and *(h)* SP 400, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SP, stress period]

PCE Concentration at Water-Supply Wells

From a concentration observation file obtained from the MT3DMS simulation, PCE concentration is acquired at water-supply wells. The results are compared to the PCE concentration distribution under the Original Schedule as shown in Figure H11.

The results presented in Figure H11 lead to the following observations for PCE concentrations at water-supply wells under the Maximum Schedule:

1. Instead of nine water-supply wells (TT-23, TT-25, TT-26, TT-31A, TT-31B, TT-53, TT-54A, TT-54B, and TT-67) that had PCE concentrations greater than 0.001 µg/L under the Original Schedule, under the Maximum Schedule there are only five pumping wells (TT-23, TT-25, TT-26, TT-54A, and TT-54B) that had PCE concentrations greater than 0.001 µg/L.
2. Throughout the simulation period, PCE concentrations at well TT-26 are always higher under the Maximum Schedule when compared to concentrations obtained under the Original Schedule. More specifically, as shown in Figure H12, PCE concentrations at well TT-26 are much higher under the Maximum Schedule when compared with the Original Schedule results during the period of interest (1968–1985).
3. PCE concentration at well TT-25 is higher under the Maximum Schedule when compared with the Original Schedule results before October 1985 and is lower after that.
4. For wells TT-23, TT-54A, and TT-54B, PCE concentrations are lower under the Maximum Schedule when compared with concentrations obtained under the Original Schedule.
5. Under the Maximum Schedule, only three water-supply wells (TT-23, TT-25, and TT-26) have PCE concentrations greater than 5 µg/L. Among them, PCE concentration in well TT-26 is much greater than the MCL throughout the period of interest. The other two wells have PCE concentrations greater than the MCL only for a very short period of time.
6. PCE concentration at well TT-26 is much greater than those obtained in other wells throughout the simulation period. Since well TT-26 always pumped at its full capacity (except for the first 3 months of 1952), it is the major water-supply well that transported contaminants into the WTP under the Maximum Schedule.

Based on the observations listed above, the difference of PCE concentrations obtained in well TT-26 using different pumping schedules is further evaluated, and the following observations can be made:

1. PCE concentration at well TT-26 reaches 5 µg/L during May 1956 under the Maximum Schedule, which is 8 months earlier than the PCE MCL arrival time under the Original Schedule (January 1957). Since well TT-26 was the major contributor of PCE to the WTP, PCE concentration at the WTP also could reach the MCL earlier under the Maximum Schedule.
2. PCE concentration at well TT-26 is much higher under the Maximum Schedule when compared to the concentration obtained under the Original Schedule during the period of interest. Between these two pumping schedules, the minimum difference of PCE concentration at well TT-26 is 169.62 µg/L, the maximum difference is 304.84 µg/L, and the average difference is 247.13 µg/L (Table H5).

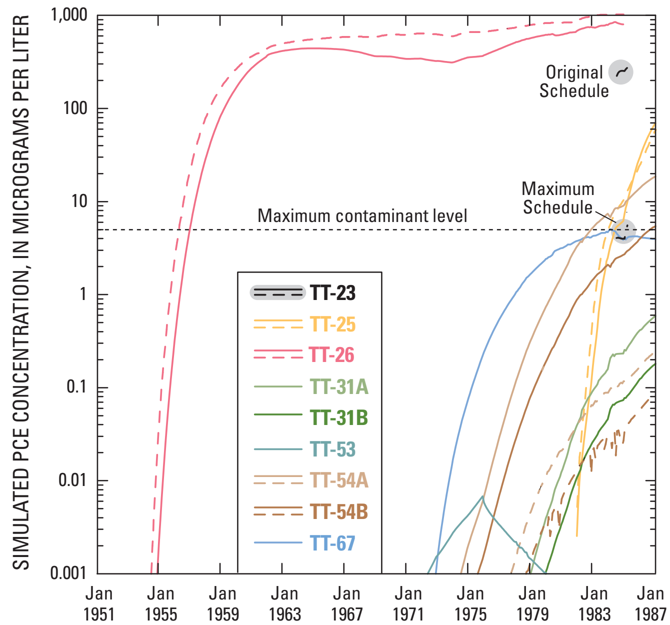


Figure H11. Simulated tetrachloroethylene (PCE) concentration at selected water-supply wells under the Original Schedule (solid line) and the Maximum Schedule (dashed line), Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [TT-31A and TT-54A, model layer 1; TT-31B and TT-54B, model layer 3]

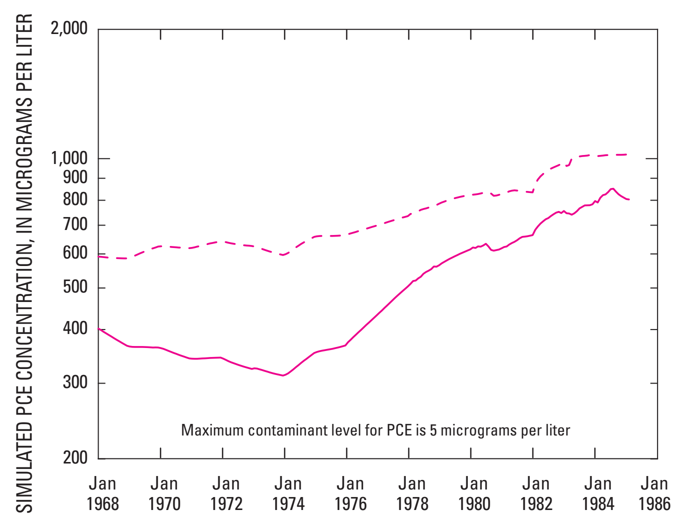


Figure H12. Simulated tetrachloroethylene (PCE) concentration at water-supply well TT-26 under the Original Schedule (solid line) and the Maximum Schedule (dashed line), period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Table H5. Tetrachloroethylene concentration at water-supply well TT-26 under the Original Schedule and the Maximum Schedule for the period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter]

	Maximum[1] (µg/L)	Minimum[1] (µg/L)	Average (µg/L)
Original Schedule	312.62	851.19	494.36
Maximum Schedule	585.98	1,023.31	741.49
Difference	304.84	169.62	247.13

[1]Values for Original Schedule and Maximum Schedule occur during different stress periods

PCE Concentration at the Water Treatment Plant

Using the mixing model described in Equation 3, PCE concentration at the WTP under the Maximum Schedule was calculated and compared to that obtained under the Original Schedule. These comparisons are shown in Figure H13 for the entire simulation period and in Figure H14 for the period of interest (January 1968–December 1985).

Results shown in Figures H13 and H14 lead to the following observations:

1. PCE concentration at the WTP under the Maximum Schedule is significantly higher than that obtained from the Original Schedule, except for the time period after February 1985, when well TT-26 was out of service. The higher PCE concentration at the WTP is caused by the higher pumping rate and the higher PCE concentration at well TT-26 under the Maximum Schedule.
2. The higher PCE concentration at the WTP is equivalent to the earlier contaminant arrival time—PCE concentration at the WTP reached 5 µg/L during December 1956, which is 11 months earlier than the Original Schedule (November 1957).
3. There are three sudden declines in PCE concentration at the WTP under the Maximum Schedule: July 1980–August 1980, January 1983–February 1983, and February 1985–December 1985. This is similar to what was observed under the Original Schedule and also is caused by well TT-26 being out of service during these periods.

Results shown in Figures H13 and H14 also indicate that after well TT-26 was shut down during February 1985, PCE concentration at the WTP is lower than that obtained under the Original Schedule, although the absolute difference is small (less than 4 µg/L). This phenomenon is caused by the presence of lower PCE concentrations in other water-supply wells. Ten water-supply wells (TT-23, TT-25, TT-31A, TT-31B, TT-52A, TT-52B, TT-54A, TT-54B, TT-67A, and TT-67B) are still in service after February 1985 under the Maximum Schedule. Results shown in Figure H11 indicate that, besides water-supply wells with PCE concentrations lower than 0.001 µg/L and not shown in the figure, PCE concentrations in all remaining wells are lower under the Maximum Schedule when compared with results obtained under the Original Schedule for this period.

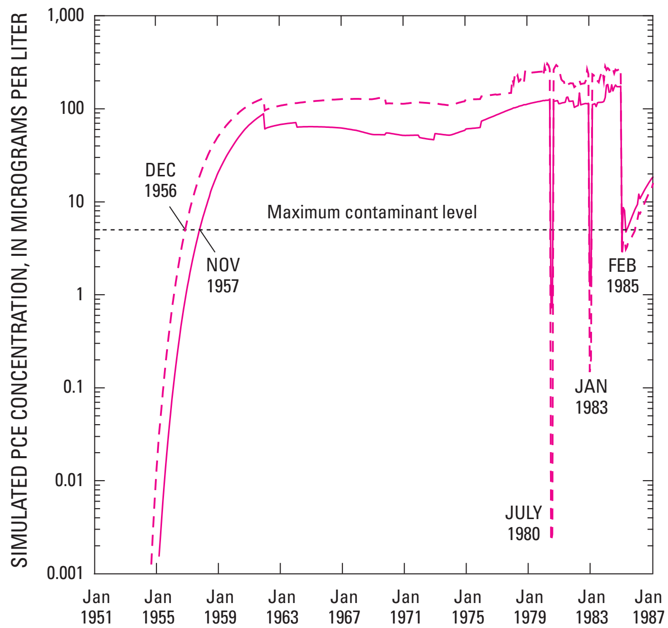


Figure H13. Simulated tetrachloroethylene (PCE) concentration at the water treatment plant under the Original Schedule (solid line) and the Maximum Schedule (dashed line), Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

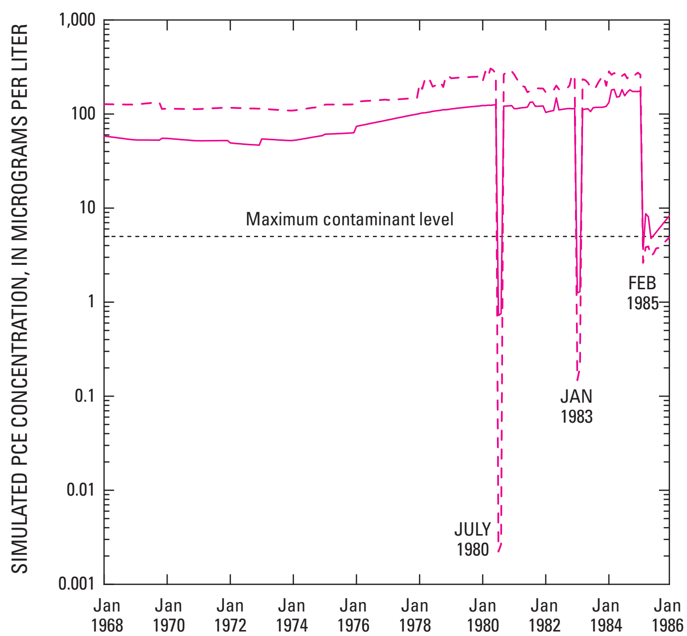


Figure H14. Simulated tetrachloroethylene (PCE) concentration at the water treatment plant under the Original Schedule (solid line) and the Maximum Schedule (dashed line), period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Lower PCE concentrations in these 10 water-supply wells may be attributed to the following:

1. According to results shown in Figures H8–H10, the higher pumping rate in well TT-26 under the Maximum Schedule causes the PCE plume to aggregate into a smaller region, which in turn causes lower PCE concentrations at water-supply wells other than TT-26.
2. More contaminant mass is withdrawn and less mass is left in the groundwater system under the Maximum Schedule. According to the original model, 1.40×10^7 gr of PCE were released into the groundwater system January 1953–December 1984. By the time all pumping operations were terminated (February 1987), 2.45×10^6 gr of PCE were discharged through water-supply wells under the Original Schedule, while 4.59×10^6 gr of PCE were discharged under the Maximum Schedule as indicated in Table H6.

As discussed previously, there were 15 months during the period of interest when well TT-26 was out of service and PCE concentration at the WTP was less than 5 μg/L. In the other 201 months, PCE concentration at the WTP was greater than the MCL under both the Original Schedule and the Maximum Schedule. A comparison of PCE concentrations at the WTP during those 201 months is summarized in Table H7.

Table H6. Tetrachloroethylene mass withdrawn under the Original Schedule and the Maximum Schedule, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

	Total mass released (gram)	Mass withdrawn (gram)	Percentage[1]
Original Schedule	1.40×10^7	2.45×10^6	17.50
Maximum Schedule	1.40×10^7	4.59×10^6	32.78

[1]Percentage of mass withdrawn relative to total mass released

Table H7. Tetrachloroethylene concentration at the water treatment plant under the Original Schedule and the Maximum Schedule for the period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[μg/L, microgram per liter]

	Maximum[1] (μg/L)	Minimum[1] (μg/L)	Average (μg/L)
Original Schedule	183.04	46.69	86.39
Maximum Schedule	304.66	108.76	166.07
Difference	180.75	42.67	79.68

[1]Values for Original Schedule and Maximum Schedule occur during different stress periods

Optimization and Simulation Results for Minimum Schedule I

Similar to the Maximum Schedule, PSOpS was run using Minimum Schedule I to obtain the "latest" PCE MCL arrival time at the WTP. The results obtained under Minimum Schedule I indicate that well TT-26 pumped at the lowest possible rate for most of the time period (Figure H15), which implies that well TT-26 was not put into operation unless there was no other water-supply well available to provide the required total demand. The reason for this is evident because PCE concentration at well TT-26 is significantly higher than PCE concentration in other pumping wells. For most of the simulation period, lower PCE concentration at the WTP can be realized by reducing the pumping rate of well TT-26. However, there are exceptions to this during the period of late 1970s and early 1980s, which will be discussed in the following section.

PCE Distribution in the Groundwater System

Similar to the maximum schedule results presented in Figures H8–H10, PCE distributions in the subsurface system around Tarawa Terrace and vicinity under the Original Schedule and Minimum Schedule I are compared in Figures H16–H18. The notation used in these figures is the same as used for Figures H8–H10.

Results presented in Figures H16–H18 indicate that Minimum Schedule I also causes a change of PCE distribution in the groundwater system. The contaminant plume under Minimum Schedule I is dispersed to a larger area, and the front of the plume is away from well TT-26, which is opposite to what has been observed under the Maximum Schedule. Therefore, PCE concentrations at some wells other than well TT-26 are expected to be higher, and PCE concentration at TT-26 is expected to be lower.

According to results presented in Figures H16–H18, PCE concentration near well TT-26 is still relatively high due to its closeness to the contaminant source, which causes a greater PCE concentration at well TT-26 when compared to other wells. Therefore, as discussed in previous sections, well TT-26 was pumped at the lowest possible rates for most of the time under Minimum Schedule I to lower the PCE concentration at the WTP.

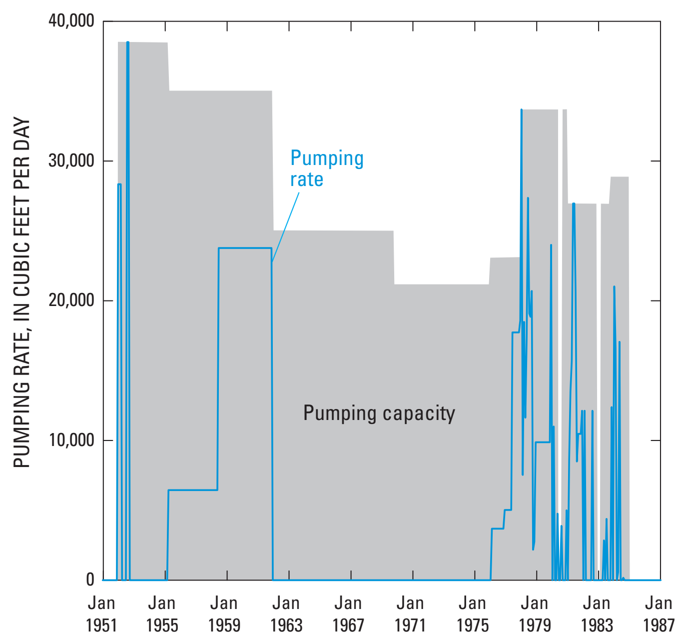


Figure H15. Pumping rate and capacity of water-supply well TT-26 under Minimum Schedule I, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

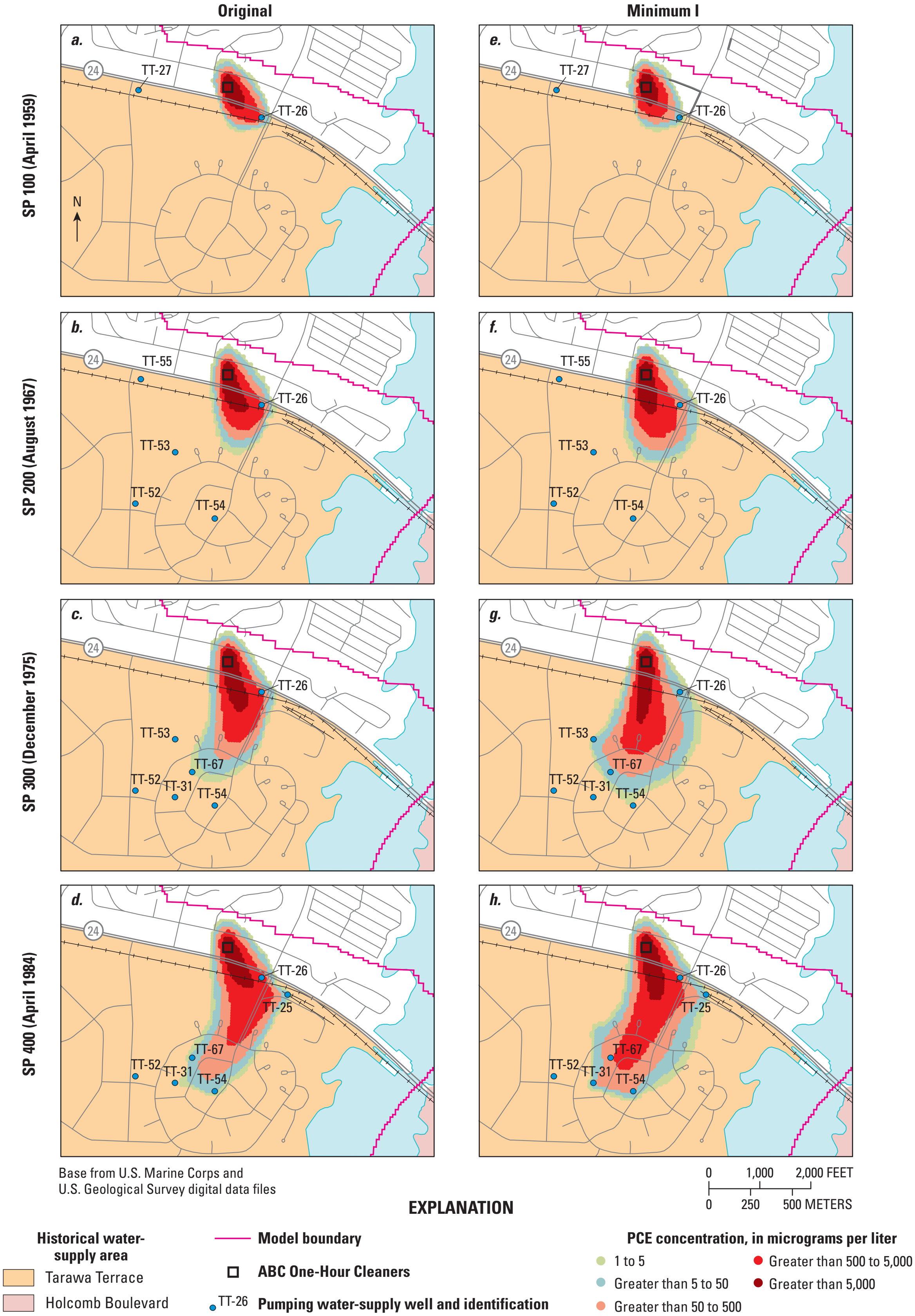


Figure H16. Comparison of tetrachloroethylene (PCE) distribution in model layer 1 under the Original Schedule for *(a)* SP 100, *(b)* SP 200, *(c)* SP 300, and *(d)* SP 400; and Minimum Schedule I for *(e)* SP 100, *(f)* SP 200, *(g)* SP 300, and *(h)* SP 400, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SP, stress period]

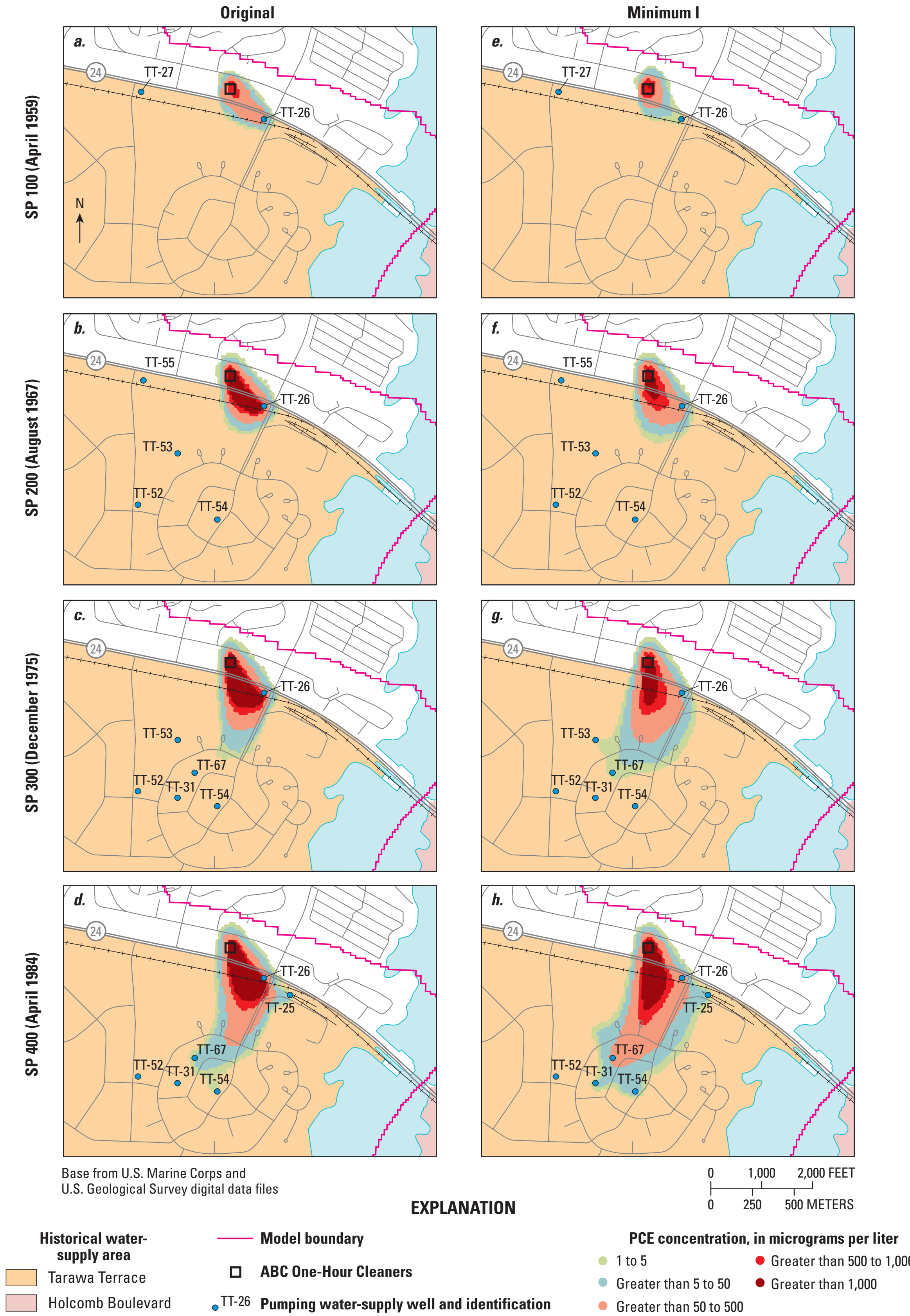


Figure H17. Comparison of tetrachloroethylene (PCE) distribution in model layer 3 under the Original Schedule for *(a)* SP 100, *(b)* SP 200, *(c)* SP 300, and *(d)* SP 400; and Minimum Schedule I for *(e)* SP 100, *(f)* SP 200, *(g)* SP 300, and *(h)* SP 400, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SP, stress period]

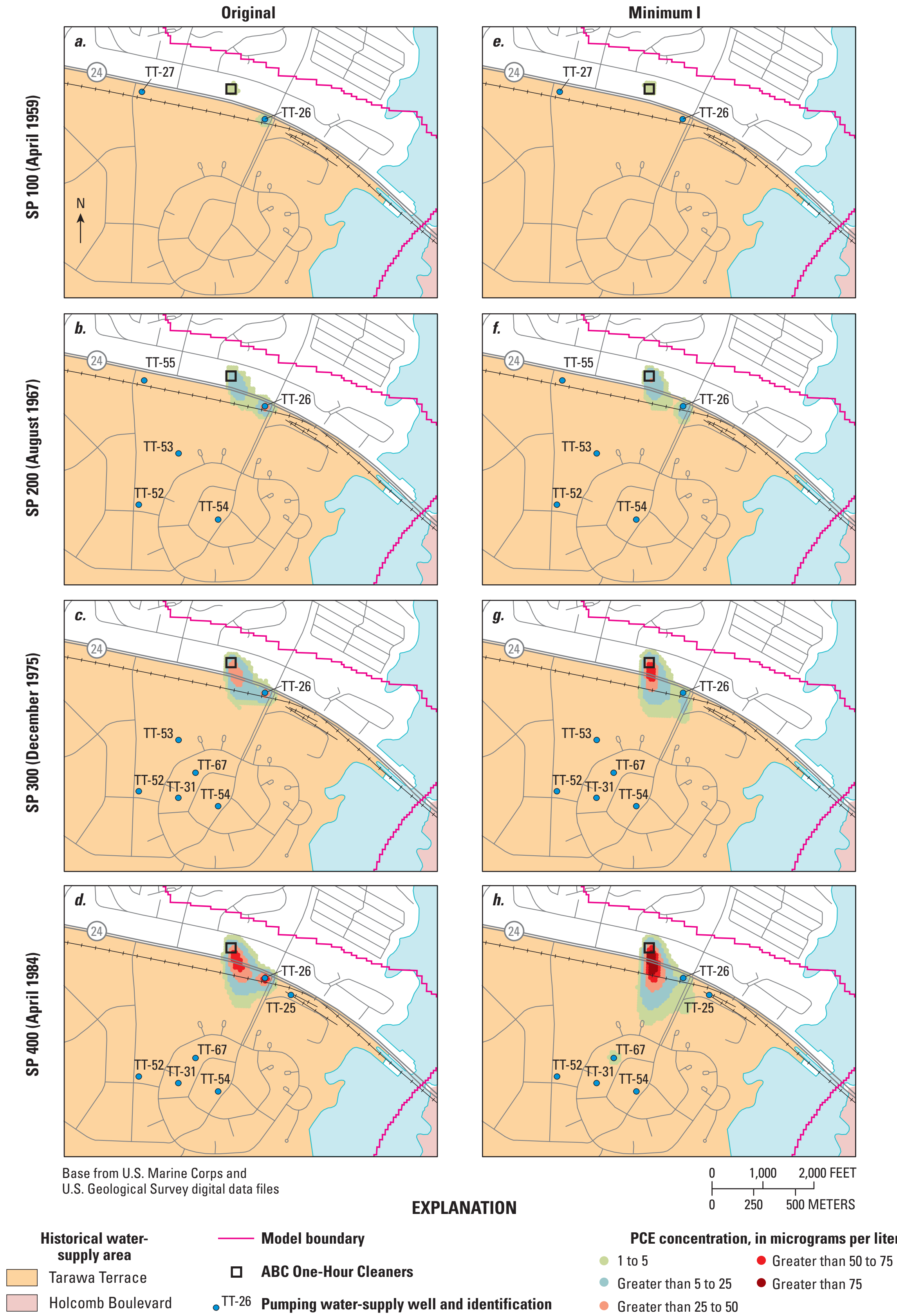


Figure H18. Comparison of tetrachloroethylene (PCE) distribution in model layer 5 under the Original Schedule for *(a)* SP 100, *(b)* SP 200, *(c)* SP 300, and *(d)* SP 400; and Minimum Schedule I for *(e)* SP 100, *(f)* SP 200, *(g)* SP 300, and *(h)* SP 400, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SP, stress period]

PCE Concentration at Water-Supply Wells

The output of the MT3DMS simulation under Minimum Schedule I provides PCE concentrations at water-supply wells. These results show higher PCE concentrations in some pumping wells other than well TT-26 (Figure H19). Only wells with PCE concentrations exceeding 0.001 µg/L are shown in Figure H19. Another version of Figure H19, emphasizing the period of interest, is shown in Figure H20.

From the results shown in Figures H19 and H20, the following may be observed:

1. Instead of six water-supply wells (TT-23, TT-25, TT-26, TT-54A, TT-54B, and TT-67) having PCE concentrations exceeding 5 µg/L, as seen with the Original Schedule, nine pumping wells have PCE concentrations exceeding 5 µg/L under Minimum Schedule I. These wells are TT-23, TT-25, TT-26, TT-31A, TT-31B, TT-54A, TT-54B, TT-67A, and TT-67B. As discussed in the previous section, this is caused by the generation of a more dispersed contaminant plume under Minimum Schedule I.

2. PCE concentration at well TT-26 is always less under Minimum Schedule I than under the Original Schedule throughout the simulation period.

3. Well TT-26 is the first well to have a PCE concentration exceeding the PCE MCL. During the first half of the simulation period, well TT-26 is the only well with a PCE concentration greater than 5 µg/L. Therefore, well TT-26 is still critical to the PCE MCL arrival time at the WTP.

4. PCE concentration at well TT-26 exceeds 5 µg/L during August 1959 under Minimum Schedule I, which is 31 months later than the case for the Original Schedule (January 1957). This delay also would cause a "late" PCE MCL arrival time at the WTP.

5. Under Minimum Schedule I, PCE concentration in well TT-26 is no longer dominant during the second half of the simulation period. PCE concentrations at wells TT-23, TT-67A, and TT-67B are sometimes greater than the concentration at well TT-26. Higher PCE concentrations at these pumping wells also explain why well TT-26 is not always pumping at the lowest possible rates toward the end of the simulation period; with several pumping wells having high PCE concentration, Minimum Schedule I is managed in such a way that the plume front does not migrate to any particular water-supply well.

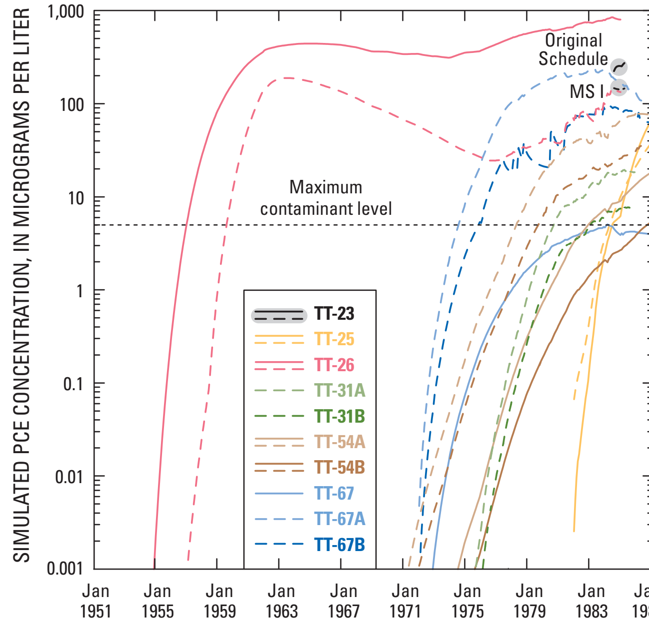


Figure H19. Simulated tetrachloroethylene (PCE) concentration at selected water-supply wells under the Original Schedule (solid line) and Minimum Schedule I (MS I, dashed line), Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [TT31A, TT-54A, and TT-67A, model layer 1; TT31B, TT-54B, and TT-67B, model layer 3]

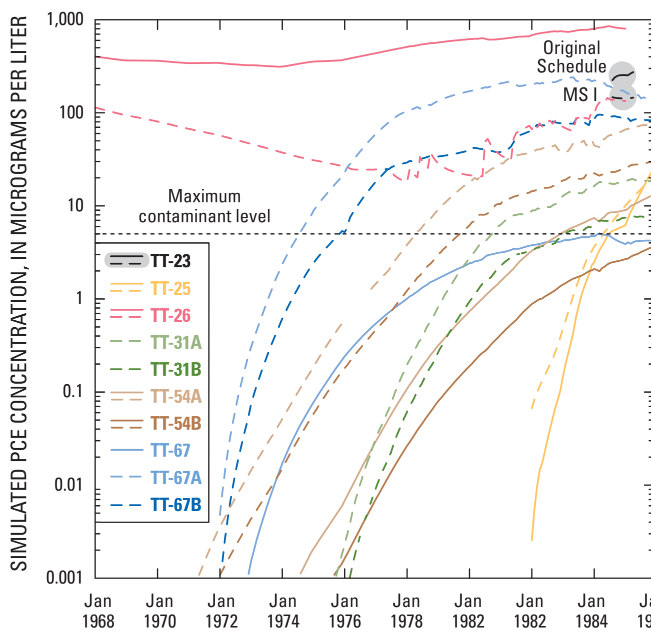


Figure H20. Simulated tetrachloroethylene (PCE) concentration at selected water-supply wells under the Original Schedule (solid line) and Minimum Schedule I (MS I, dashed line), period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [TT31A, TT-54A, and TT-67A, model layer 1; TT31B, TT-54B, and TT-67B, model layer 3]

PCE Concentration at the Water Treatment Plant

PCE concentration at the WTP under Minimum Schedule I is calculated using Equation 3 and is shown in Figures H21 and H22.

The results shown in Figures H21 and H22 lead to the following observations:

1. PCE concentration at the WTP under Minimum Schedule I is lower than PCE concentration obtained under the Original Schedule except for the period after February 1985.

2. PCE concentration at the WTP reaches 5 µg/L during June 1960 under Minimum Schedule I, which is 31 months later than the arrival time of the Original Schedule. This is due to lower PCE concentration and lower pumping rate at well TT-26 under Minimum Schedule I. By the time the PCE concentration at the WTP reaches 5 µg/L, PCE concentrations at water-supply wells other than TT-26 are still negligible (Figure H19). Therefore, well TT-26 is the critical well affecting the PCE MCL arrival time at the WTP.

3. Under Minimum Schedule I, PCE concentration at the WTP increases steadily until December 1961, when PCE concentration declines below trace levels because of no pumping in well TT-26. PCE concentration again reaches 5 µg/L during November 1977. Between January 1962 and December 1971, PCE concentration at the WTP is less than 0.001 µg/L and, therefore, is not shown in these figures.

4. Sudden declines in PCE concentration that were observed during periods of July 1980–August 1980, January 1983–February 1983, and February 1985–December 1985 under the Original Schedule are not obvious under Minimum Schedule I for two reasons. First, overall PCE concentration level at the WTP is very low under Minimum Schedule I. Second, PCE concentration at well TT-26 is no longer dominant as shown in Figure H20.

Another observation that can be made from results presented in Figures H21 and H22 is that during the last 11 months of the period of interest, PCE concentrations at the WTP under Minimum Schedule I are slightly higher than those obtained under the Original Schedule, which is in contrast to the results obtained under the Maximum Schedule. The reason for this is the higher PCE concentrations in some water-supply wells other than well TT-26 (that is, wells TT-67A and TT-67B). The higher PCE concentrations in these two water-supply wells may be caused by the following factors:

1. By the end of the period of interest, less contaminant mass is extracted from the groundwater system under Minimum Schedule I, and more mass is left in the aquifer, which causes higher PCE concentrations in water-supply wells (Table H8).

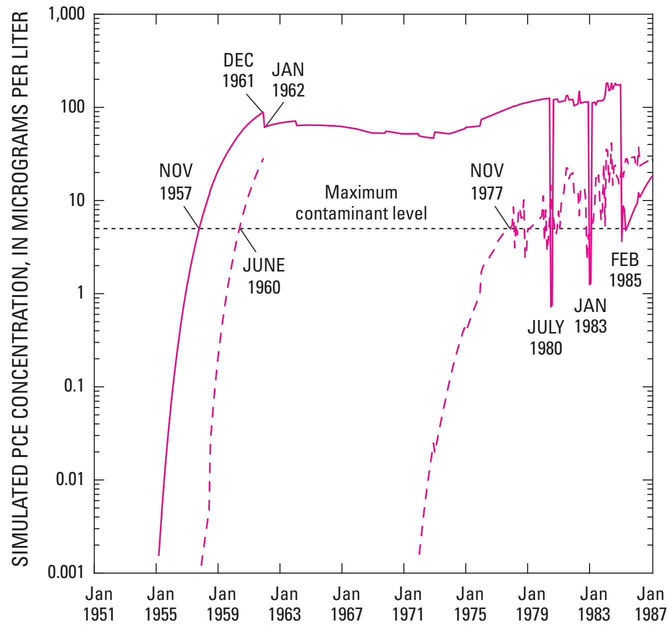


Figure H21. Simulated tetrachloroethylene (PCE) concentration at the water treatment plant under the Original Schedule (solid line) and Minimum Schedule I (dashed line), Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

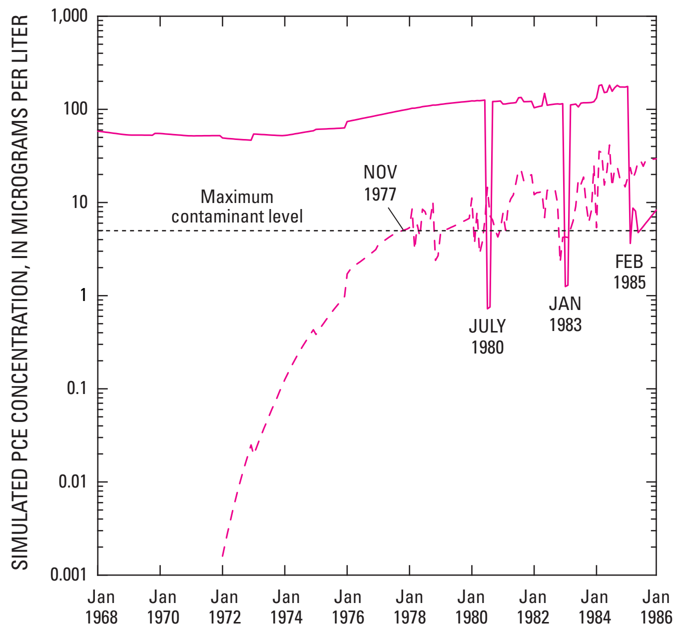


Figure H22. Simulated tetrachloroethylene (PCE) concentration at the water treatment plant under the Original Schedule (solid line) and Minimum Schedule I (dashed line), period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

2. Minimum Schedule I causes a more dispersed contaminant plume than the Original Schedule in the groundwater system (Figure H17). While PCE concentration at well TT-26 decreases, the PCE concentrations at some other wells increase.

Minimum Schedule I yields lower PCE concentrations at the WTP for the period of interest (Table H9). To keep this comparison consistent with the previous comparison made for the Maximum Schedule, the concentration distribution obtained from the 15 months when well TT-26 was out of service is not included in this analysis. The results shown in Table H9 indicate that the average PCE concentration at the WTP under Minimum Schedule I is 5.01 µg/L, which is close to the 5 µg/L MCL of PCE.

Table H8. Tetrachloroethylene mass withdrawn under the Original Schedule and Minimum Schedule I, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

	Total mass released (gram)	Mass withdrawn (gram)	Percentage[1]
Original Schedule	1.40×10^{7}	2.45×10^{6}	17.50
Minimum Schedule I	1.40×10^{7}	1.98×10^{5}	1.41

[1]Percentage of mass withdrawn relative to total mass released

Table H9. Tetrachloroethylene concentration at the water treatment plant under the Original Schedule and Minimum Schedule I for the period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter]

	Maximum[1] (µg/L)	Minimum[1] (µg/L)	Average (µg/L)
Original Schedule	183.04	46.69	86.39
Minimum Schedule I	41.36	7.84×10^{-8}	5.01
Difference	158.48	46.69	81.39

[1]Values for Original Schedule and Maximum Schedule occur during different stress periods

Optimization and Simulation Results for Minimum Schedule II

Results obtained under Minimum Schedule I indicate that water-supply well TT-26 was out of service for a long period of time, which is unrealistic based on historical records and considering that well TT-26 was one of the major water-supply wells for the Tarawa Terrace area. Therefore, a third PSOpS simulation was conducted to obtain a pumping schedule that could yield the "latest" arrival time but at the same time honor historical data on the schedule of well operations at the site. To achieve this, one more constraint was added to the optimization model—the pumping rate in well TT-26 is restricted to never being less than 25 percent of its pumping capacity at any time when in service. The pumping rate of well TT-26 obtained for this case is shown in Figure H23. Similar to Minimum Schedule I, the pumping rate for well TT-26 for Minimum Schedule II also is the minimum possible during the first half of the simulation period.

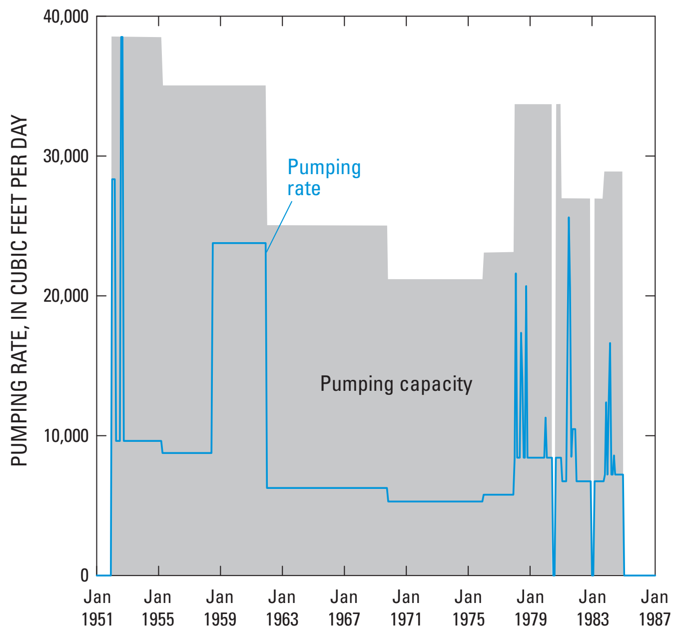


Figure H23. Pumping rate and capacity of water-supply well TT-26 under Minimum Schedule II, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

PCE Distribution in the Groundwater System

PCE distribution in the subsurface system at Tarawa Terrace and vicinity under the Original Schedule and Minimum Schedule II are shown in Figures H24–H26 for different stress periods for model layers 1, 3, and 5, respectively. A comparison of PCE distributions obtained under Minimum Schedule I and Minimum Schedule II are shown in Figures H27–H29 for different stress periods for model layers 1, 3, and 5, respectively.

A comparison of Figures H16–H18 and Figures H24–H29 indicates that Minimum Schedule II also causes the PCE plume to be more dispersed than the Original Schedule, but not as much as Minimum Schedule I. This is because the average pumping rate in well TT-26 under Minimum Schedule II is less than that obtained under the Original Schedule, but greater than the average pumping rate obtained under Minimum Schedule I. Therefore, PCE concentrations at well TT-26 and the WTP under Minimum Schedule II are expected to be between those obtained under the Original Schedule and Minimum Schedule I.

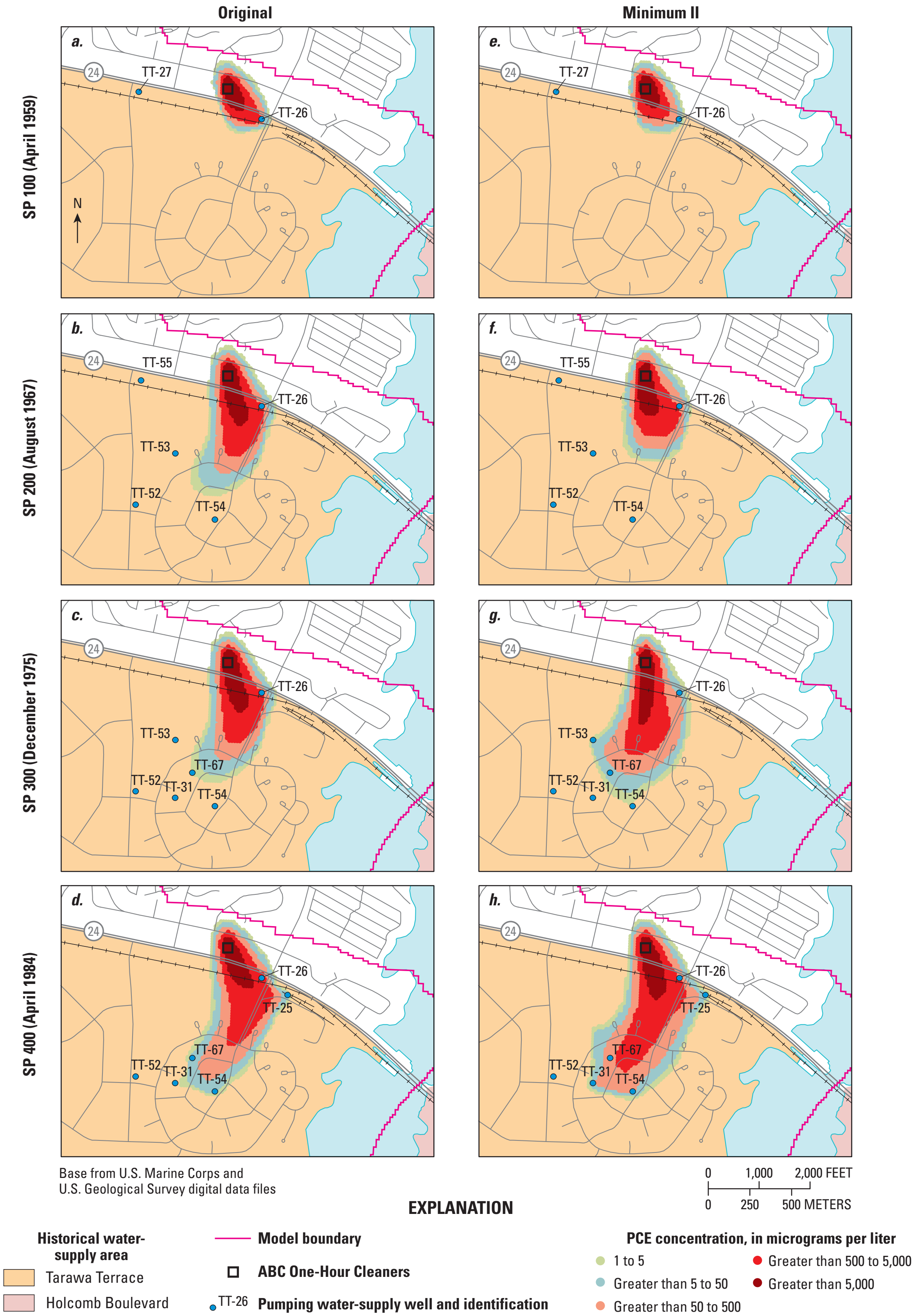


Figure H24. Comparison of tetrachloroethylene (PCE) distribution in model layer 1 under the Original Schedule for *(a)* SP 100, *(b)* SP 200, *(c)* SP 300, and *(d)* SP 400; and Minimum Schedule II for *(e)* SP 100, *(f)* SP 200, *(g)* SP 300, and *(h)* SP 400, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SP, stress period]

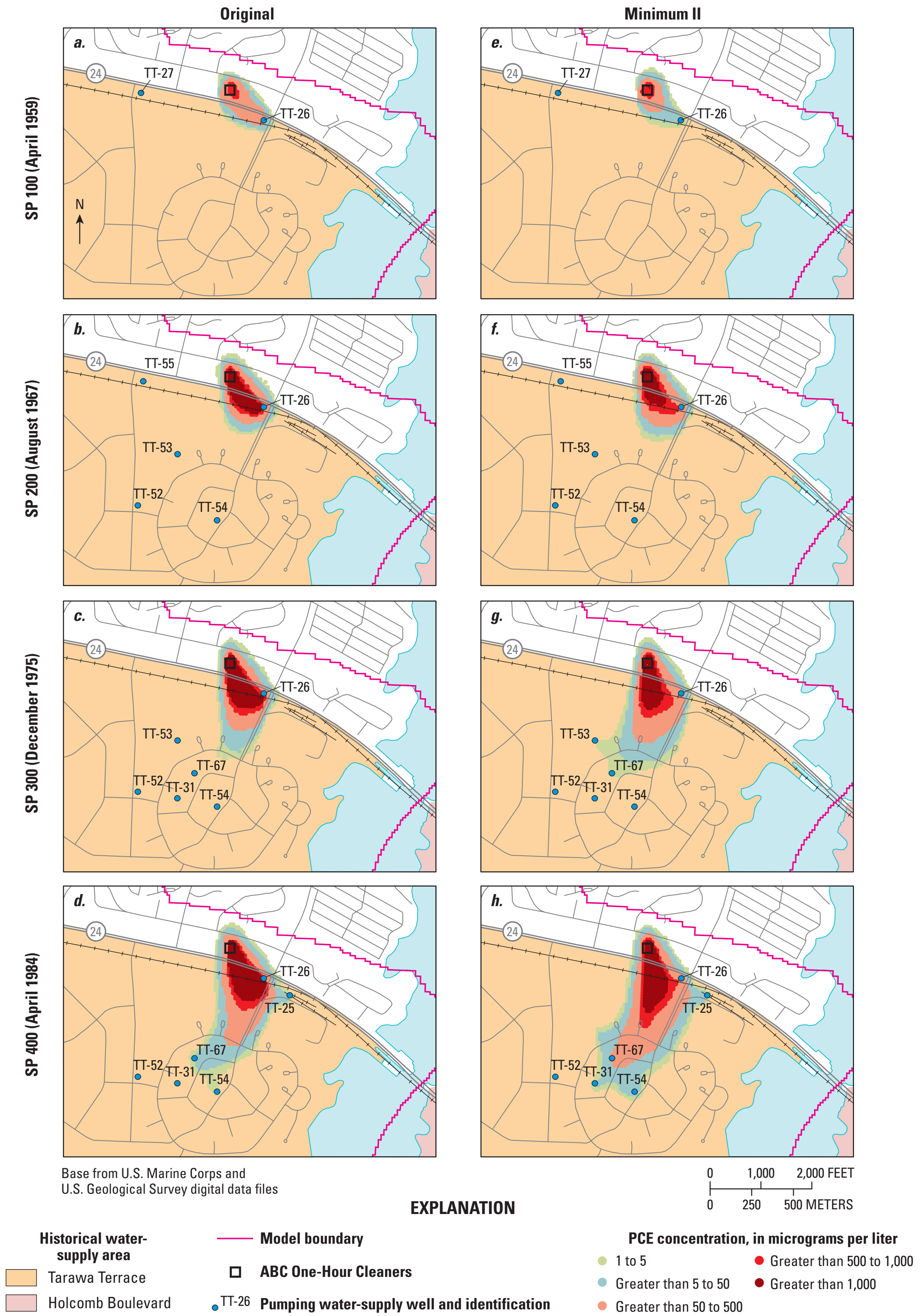


Figure H25. Comparison of tetrachloroethylene (PCE) distribution in model layer 3 under the Original Schedule for *(a)* SP 100, *(b)* SP 200, *(c)* SP 300, and *(d)* SP 400; and Minimum Schedule II for *(e)* SP 100, *(f)* SP 200, *(g)* SP 300, and *(h)* SP 400, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SP, stress period]

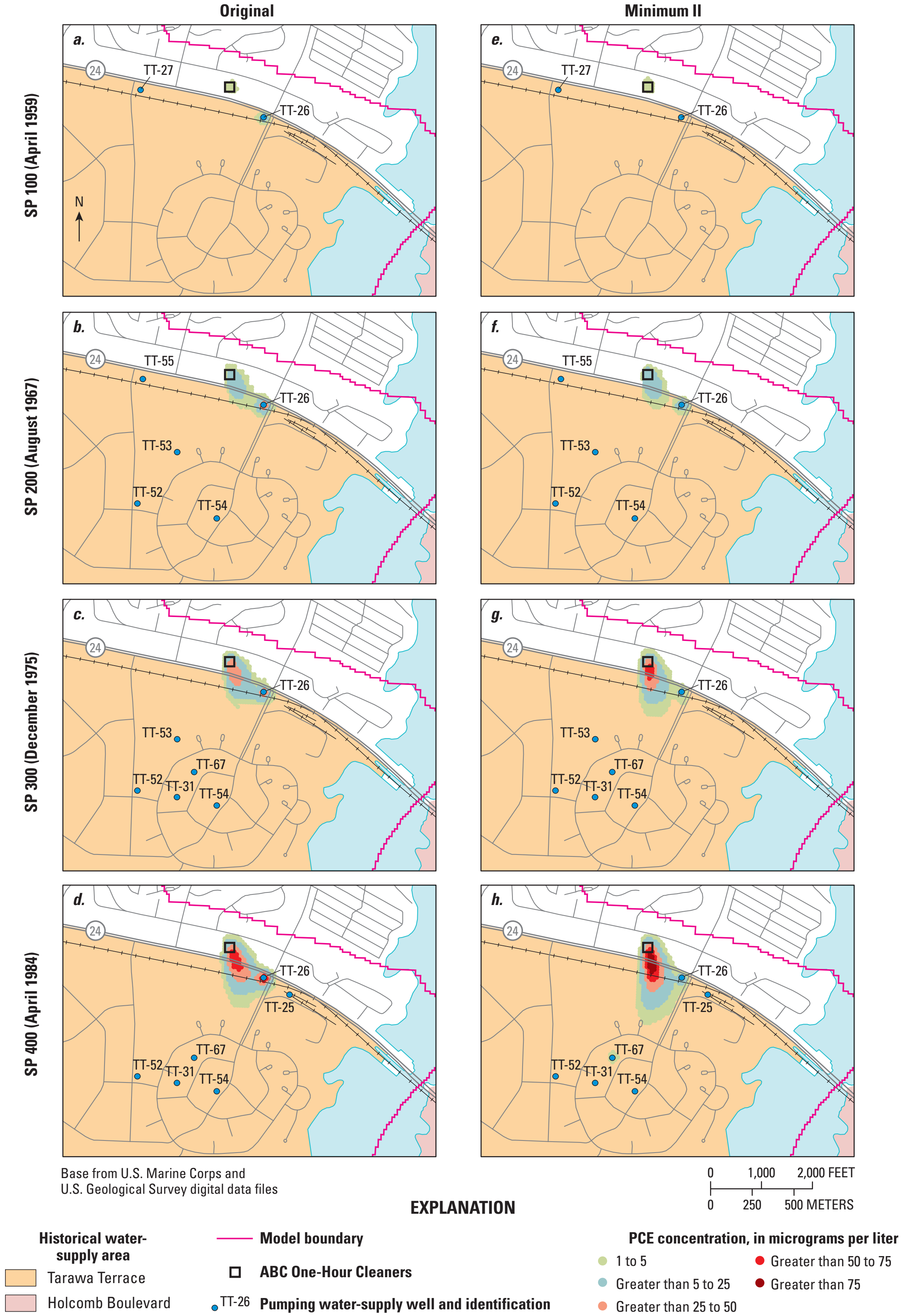


Figure H26. Comparison of tetrachloroethylene (PCE) distribution in model layer 5 under the Original Schedule for *(a)* SP 100, *(b)* SP 200, *(c)* SP 300, and *(d)* SP 400; and Minimum Schedule II for *(e)* SP 100, *(f)* SP 200, *(g)* SP 300, and *h)* SP 400, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SP, stress period]

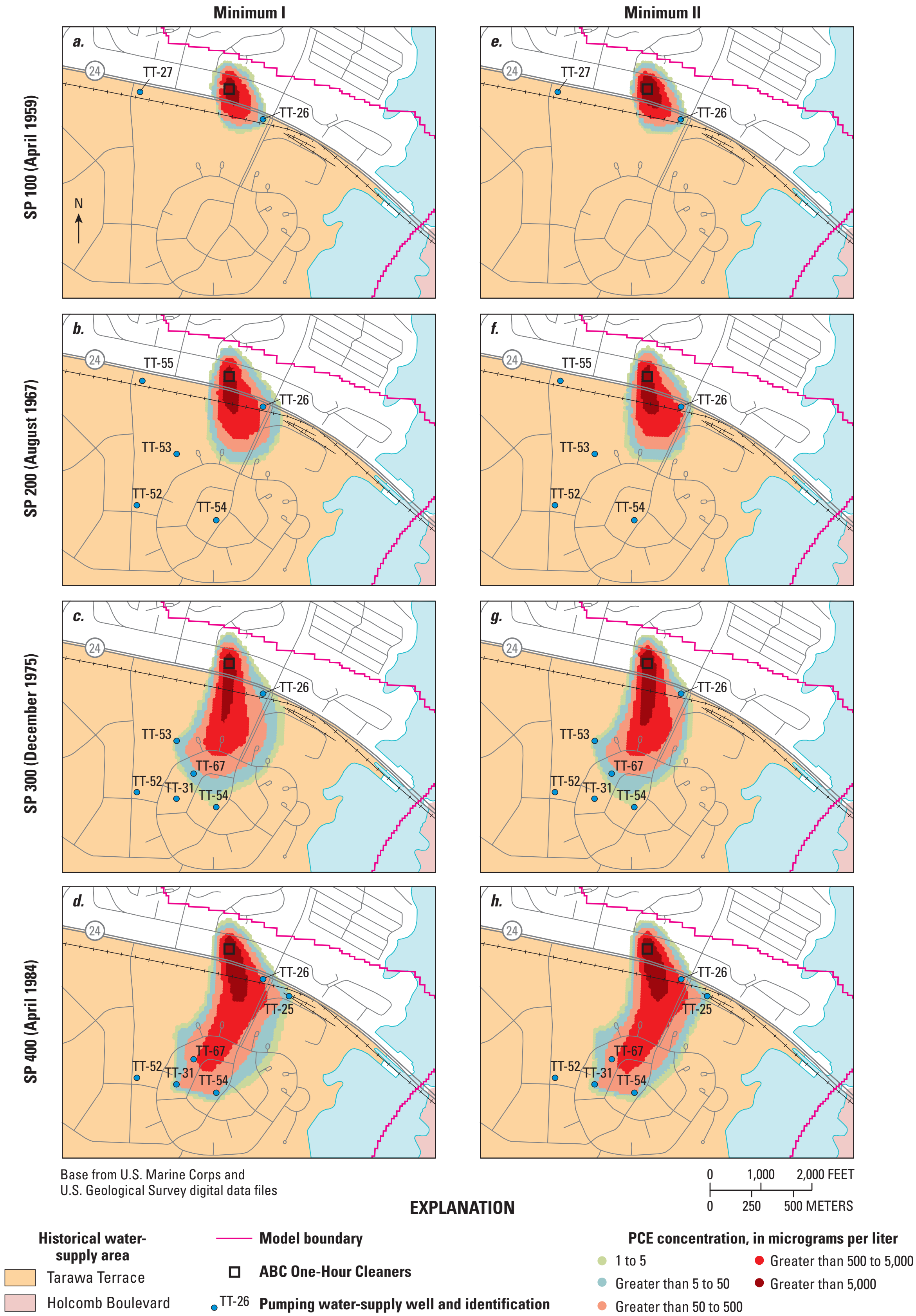


Figure H27. Comparison of tetrachloroethylene (PCE) distribution in model layer 1 under Minimum Schedule I for *(a)* SP 100, *(b)* SP 200, *(c)* SP 300, and *(d)* SP 400; and Minimum Schedule II for *(e)* SP 100, *(f)* SP 200, *(g)* SP 300, and *(h)* SP 400, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SP, stress period]

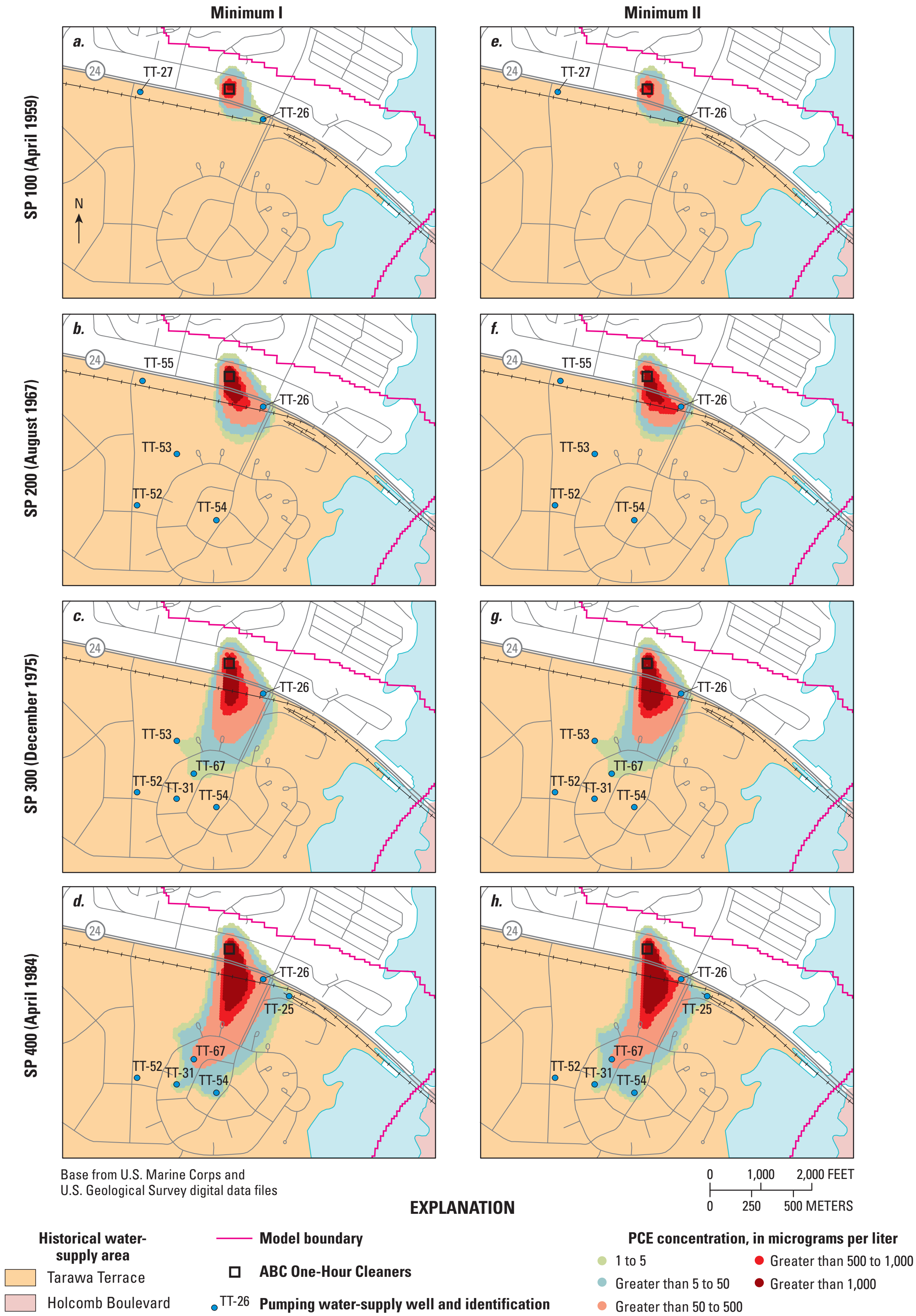


Figure H28. Comparison of tetrachloroethylene (PCE) distribution in model layer 3 under Minimum Schedule I for *(a)* SP 100, *(b)* SP 200, *(c)* SP 300, and *(d)* SP 400; and Minimum Schedule II for *(e)* SP 100, *(f)* SP 200, *(g)* SP 300, and *(h)* SP 400, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SP, stress period]

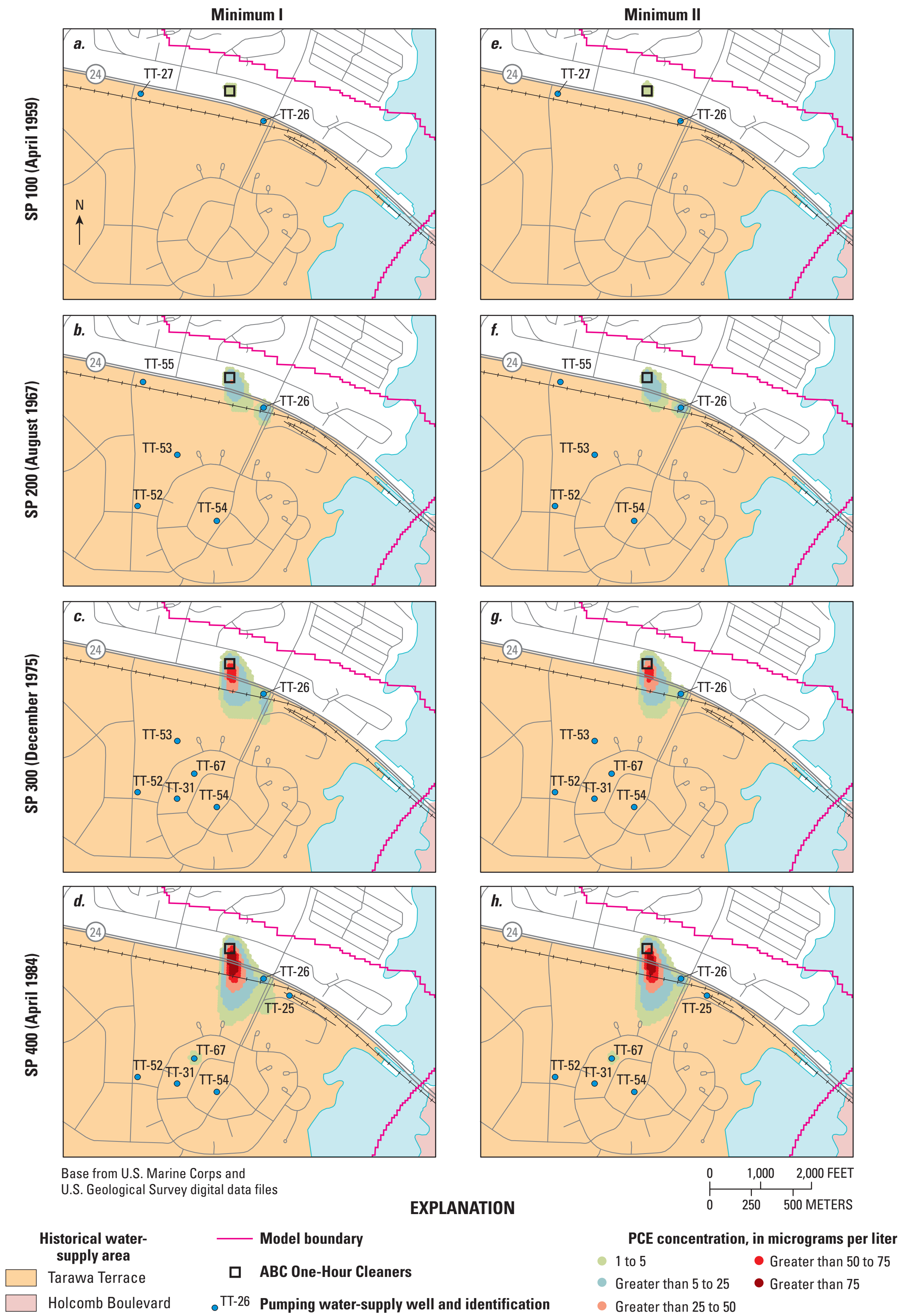


Figure H29. Comparison of tetrachloroethylene (PCE) distribution in model layer 5 under Minimum Schedule I for *(a)* SP 100, *(b)* SP 200, *(c)* SP 300, and *(d)* SP 400; and Minimum Schedule II for *(e)* SP 100, *(f)* SP 200, *(g)* SP 300, and *(h)* SP 400, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [SP, stress period]

PCE Concentration at Water-Supply Wells

Similar to results presented in Figures H19 and H20, PCE concentrations at water-supply wells which have PCE concentrations exceeding 5 µg/L are plotted in Figures H30 and H31 for Minimum Schedule II. A comparison of PCE concentrations at higher producing water-supply wells is shown in Figure H32.

Results summarized in Figures H30–H32 show that PCE concentration distribution at water-supply wells under Minimum Schedule II is similar to the distribution obtained under Minimum Schedule I. The differences for this case are: (1) PCE concentration at well TT-26 under Minimum Schedule II always exceeds PCE concentration obtained under Minimum Schedule I for most of the period of interest, and (2) PCE concentrations at wells TT-54A, TT-54B, TT-67A, and TT-67B are slightly lower than those obtained under Minimum Schedule I (Figure H32). This is because, as discussed in the previous section, continuous operation of well TT-26 yields a less dispersed PCE plume in the groundwater system and the contaminant plume is more directed toward well TT-26.

Higher PCE concentrations at well TT-26 cause a relatively early PCE MCL arrival time at this location. According to simulation results, PCE concentration at well TT-26 reached MCL during March 1959 under Minimum Schedule II, which is 5 months earlier than under Minimum Schedule I (August 1959). Thus, an earlier PCE MCL arrival time at the WTP is expected for Minimum Schedule II.

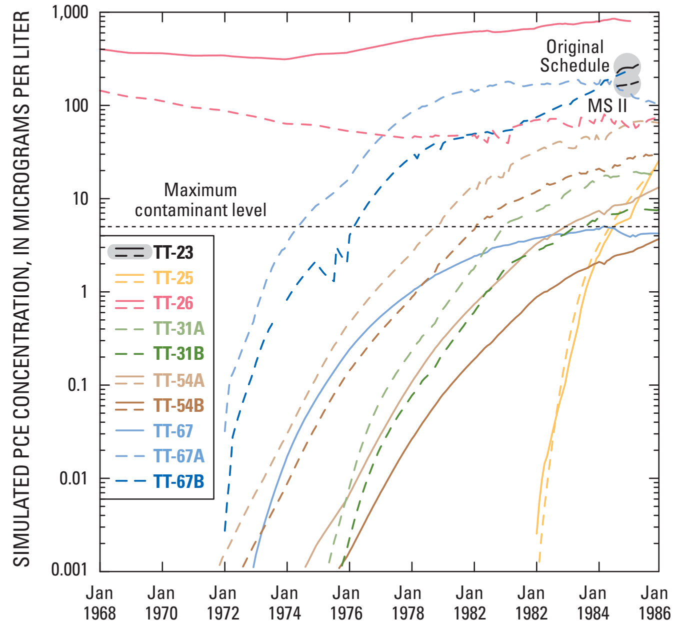


Figure H31. Simulated tetrachloroethylene (PCE) concentration at selected water-supply wells under the Original Schedule (solid line) and Minimum Schedule II (MS II, dashed line), period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [TT31A, TT-54A, and TT-67A, model layer 1; TT-31B, TT-54B, and TT-67B, model layer 3]

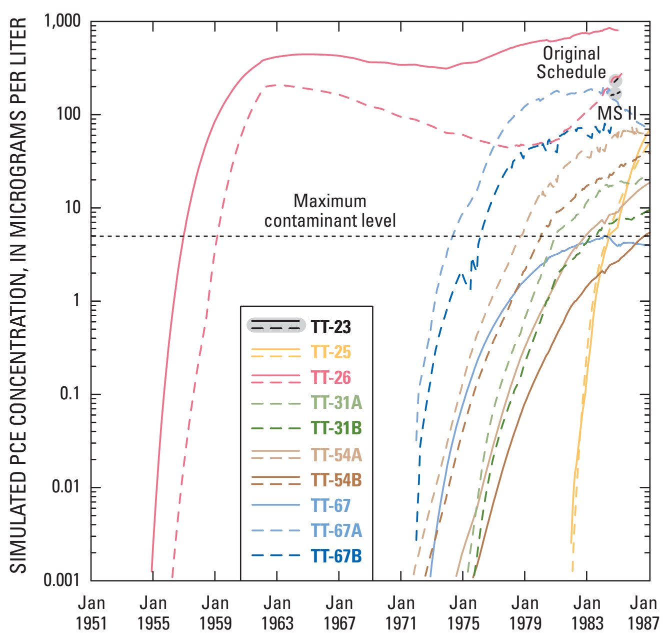


Figure H30. Simulated tetrachloroethylene (PCE) concentration at selected water-supply wells under the Original Schedule (solid line) and Minimum Schedule II (MS II, dashed line), Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [TT31A, TT-54A, and TT-67A, model layer 1; TT31B, TT-54B, and TT-67B, model layer 3]

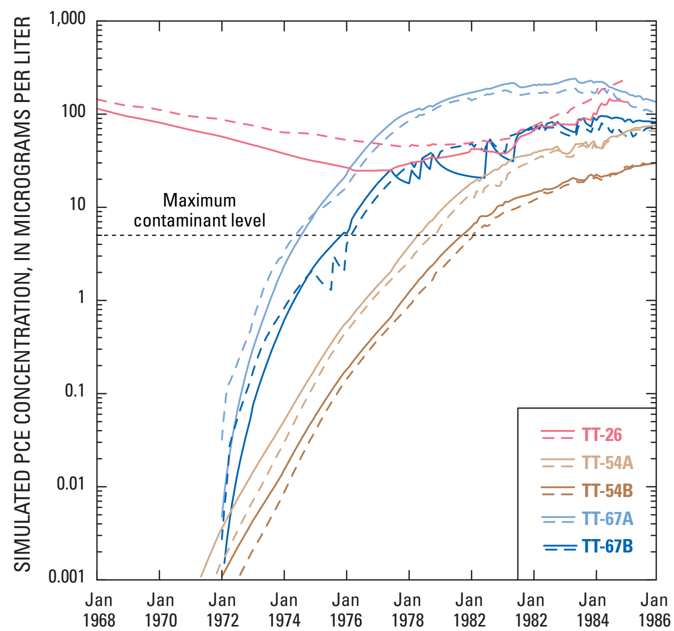


Figure H32. Simulated tetrachloroethylene (PCE) concentration at selected water-supply wells under Minimum Schedule I (solid line) and Minimum Schedule II (dashed line), period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [TT-54A and TT-67A, model layer 1; TT-54B and TT-67B, model layer 3]

PCE Concentration at the Water Treatment Plant

PCE concentration at the WTP under Minimum Schedule II is shown in Figures H33 and H34. To illustrate the difference in PCE concentration between the two minimum schedules, PCE concentration obtained at the WTP under Minimum Schedule I also is shown in these figures.

Based on results presented in Figures H33 and H34, the following observations can be made:

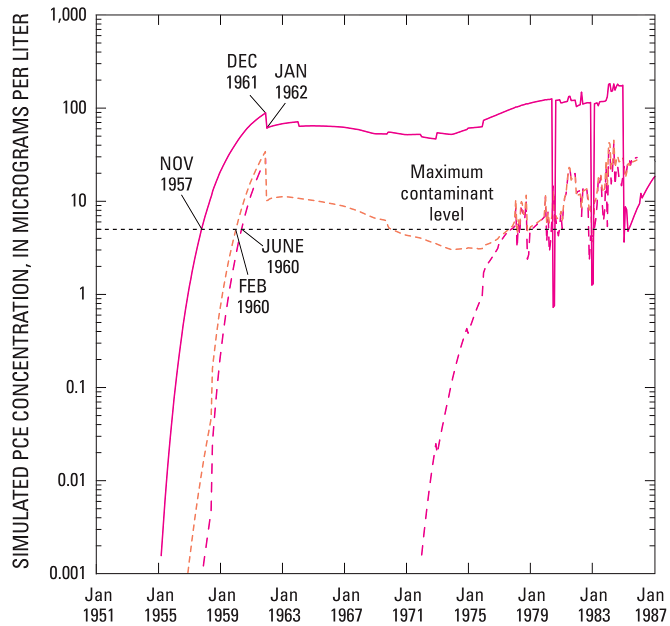
1. PCE concentration at the WTP under Minimum Schedule II is lower than PCE concentration obtained under the Original Schedule except for the period after February 1985, which is similar to the Minimum Schedule I results.

2. PCE concentration at the WTP reaches 5 µg/L during February 1960 under Minimum Schedule II, which is 4 months earlier than obtained under Minimum Schedule I and a delay of 27 months when compared to the Original Schedule (November 1957).

3. Before January 1978, PCE concentration at the WTP under Minimum Schedule II is greater than PCE concentration obtained under Minimum Schedule I, but the difference is minimal after that time. This is because the pumping rate of well TT-26 under Minimum Schedule II after January 1978 is similar to that of Minimum Schedule I.

4. Due to the continuous pumping schedule of well TT-26 under Minimum Schedule II, PCE concentration at the WTP does not decrease below 1 µg/L; this also is observed under Minimum Schedule I. In fact, PCE concentrations at the WTP are greater than 5 µg/L most of the time after exceeding the MCL during February 1960, except for the period March 1970–September 1977.

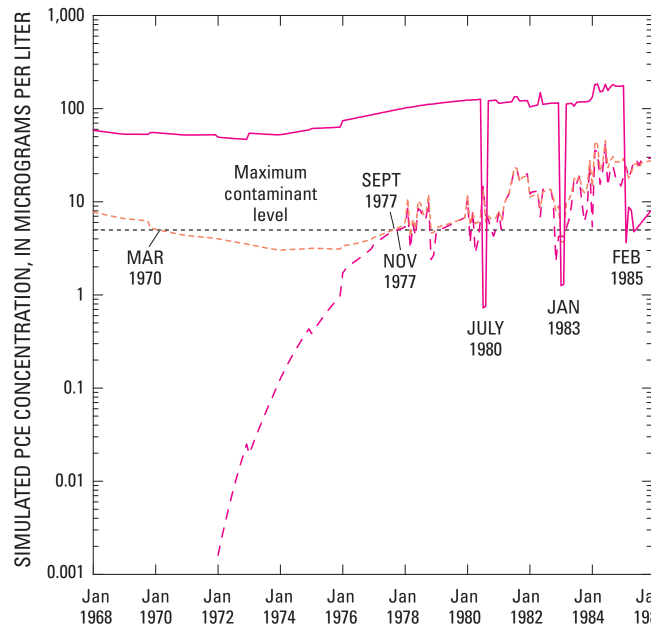
The total mass of contaminant withdrawn from the groundwater system by water-supply wells under the three pumping schedules is listed in Table H10. PCE concentrations at the WTP for the three pumping schedules are listed in Table H11. Based on the results listed in Tables H10 and H11, it may be concluded that by forcing the pumping rate of well TT-26 to be at least 25 percent of its pumping capacity throughout the simulation period, when compared to Minimum Schedule I, about 72 percent more PCE mass is withdrawn by pumping wells under Minimum Schedule II. Furthermore, the average PCE concentration at the WTP for the period of interest is approximately 60 percent higher.



EXPLANATION

Original Schedule
Minimum Schedule I
Minimum Schedule II

Figure H33. Simulated tetrachloroethylene (PCE) concentration at the water treatment plant under the Original Schedule (solid line), Minimum Schedule I, and Minimum Schedule II (dashed lines), Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.



EXPLANATION

Original Schedule
Minimum Schedule I
Minimum Schedule II

Figure H34. Simulated tetrachloroethylene (PCE) concentration at the water treatment plant under the Original Schedule (solid line), Minimum Schedule I, and Minimum Schedule II (dashed lines), period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Table H10. Tetrachloroethylene mass withdrawn under the Original Schedule, Minimum Schedule I, and Minimum Schedule II, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

	Total mass released (gram)	Mass withdrawn (gram)	Percentage[1]
Original Schedule	1.40×10^{7}	2.45×10^{6}	17.50
Minimum Schedule I	1.40×10^{7}	1.98×10^{5}	1.41
Minimum Schedule II	1.40×10^{7}	3.41×10^{5}	2.44

[1]Percentage of mass withdrawn relative to total mass released

Table H11. Tetrachloroethylene concentration at the water treatment plant under the Original Schedule, Minimum Schedule I, and Minimum Schedule II for the period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter]

	Maximum[1] (µg/L)	Minimum[1] (µg/L)	Average
Original Schedule	183.04	46.69	86.39
Minimum Schedule I	41.36	7.84×10^{-8}	5.01
Minimum Schedule II	45.31	3.04	8.04

[1]Values for Original Schedule and Maximum Schedule occur during different stress periods

Summary of Simulation Results

Pumping Rate in Water-Supply Well TT-26

Based on results discussed in previous sections, it may be concluded that the pumping schedule variation causes significant changes in contaminant concentrations and MCL arrival times at water-supply wells and the WTP. In this case, the pumping rate in well TT-26 is critical to the PCE MCL arrival time because of its proximity to the contaminant source. The change of pumping rate in well TT-26 can cause PCE concentrations at the WTP to change from trace levels to amounts several orders higher than the MCL. The pumping rate percentage in well TT-26 relative to its pumping capacity under different pumping schedules is summarized in Figure H35. Figure H36 is plotted to give a clear view of the variation of the pumping rate in well TT-26 between 1976 and 1985.

Based on the results shown in Figures H35 and H36, the period January 1962–February 1976 is when the pumping rate in well TT-26 could have varied the most. This period also is consistent with the most variation of PCE concentrations that is observed at water-supply wells and the WTP under different pumping schedules. The periods when well TT-26 is out of service are consistent with the sudden declines of PCE concentration observed at the WTP under the Original Schedule and the Maximum Schedule.

From results presented in Figures H35 and H36, except for the first few months when pumping schedule has no significant effect on PCE concentration, well TT-26 is always being operated at its full capacity for early arrival simulations.

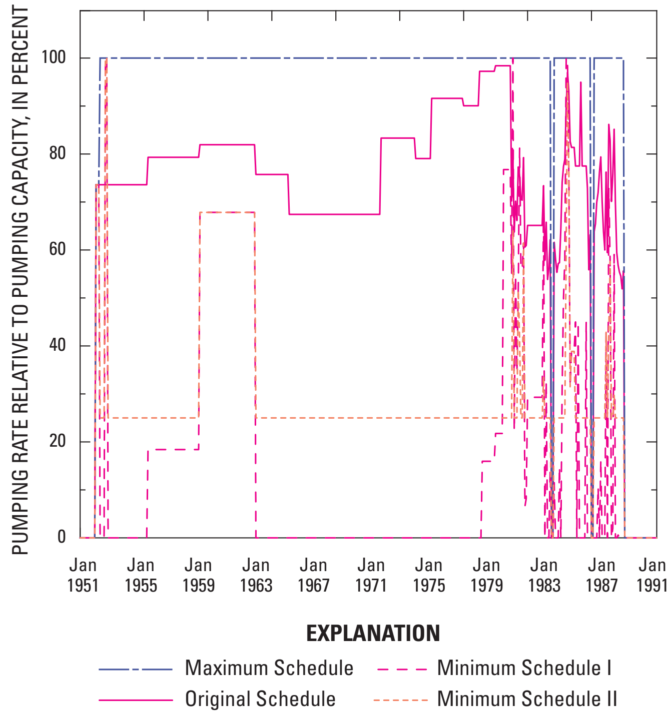


Figure H35. Percentage of pumping rate relative to its pumping capacity in water-supply well TT-26 under the Original Schedule (solid line) and updated pumping schedules (dashed lines), Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

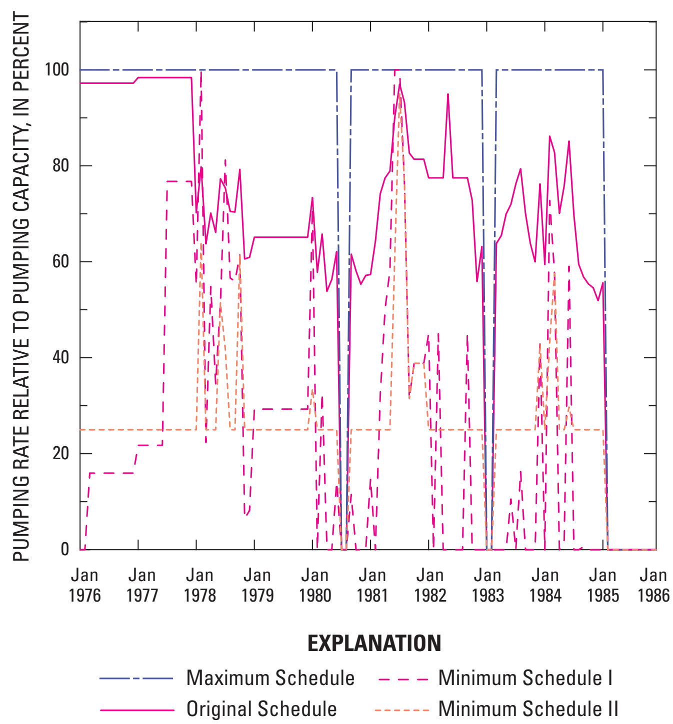


Figure H36. Percentage of pumping rate relative to its pumping capacity in water-supply well TT-26 under the Original Schedule (solid line) and updated pumping schedules (dashed lines), for the period 1976–1985, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Under the Maximum Schedule, PCE concentration at well TT-26 is always much greater than other water-supply wells. Therefore, operation of well TT-26 at 100% capacity is required to obtain the maximum PCE concentration and the earliest arrival of PCE at the WTP. Under the two "late" arrival schedules, however, TT-26 is not pumping at the least possible rates for some stress periods near the end of the simulation. This occurs because in the second half of the simulation period for the "late arrival" cases, PCE concentration at well TT-26 is no longer the dominant source of contaminants.

All simulation results discussed here are based on pumping capacities used for this study, which limits maximum allowances for changes in pumping rates. If this limiting factor is not considered, pumping rates in water-supply wells may be changed without restriction, thus significantly affecting PCE concentrations and MCL arrival times. However, this would not be a realistic solution.

PCE Concentration at Water Supply Well TT-26

Simulation results for all three pumping schedules show that these schedules can cause changes in PCE distribution in the groundwater system, in PCE concentrations at water-supply wells and the WTP, and in PCE MCL arrival times. The comparison of PCE concentrations at water-supply well TT-26 under different pumping schedules is shown in Figure H37.

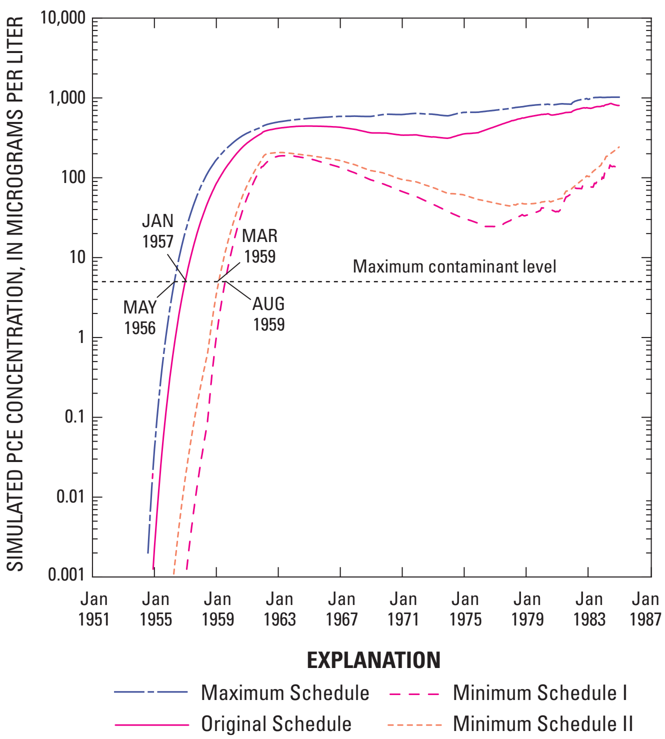


Figure H37. Simulated tetrachloroethylene (PCE) concentration at water-supply well TT-26 under the Original Schedule (solid line) and updated pumping schedules (dashed lines), Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

From results shown in Figure H37, it can be concluded that the earliest time for PCE concentration at well TT-26 to reach the 5 µg/L MCL is May 1956; the latest date is August 1959. This indicates that given hydrogeologic data—together with, and only with—a change of pumping schedules, the 5 µg/L arrival time of PCE at well TT-26 can vary from May 1956 to August 1959. This shows a 39-month variability between the "early" and "late" arrival dates. In this figure, the difference observed in the PCE MCL arrival time under Minimum Schedule I is greater than the one observed under the Maximum Schedule relative to the Original Schedule results. The reason for this is, as shown in Figure H35, the change of pumping rate in well TT-26 during the first half of the simulation period under Minimum Schedule I is greater than the change under the Maximum Schedule. Furthermore, the greater difference yields a more dispersed contaminant plume and a much lower PCE concentration at well TT-26. A summary of PCE concentrations and MCL arrival time at well TT-26 under different pumping schedules is listed in Table H12.

Table H12. Tetrachloroethylene concentration and maximum contaminant level arrival time at water-supply well TT-26 under the Original Schedule and updated pumping schedules for the period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter]

Pumping schedule	Maximum (µg/L)	Minimum (µg/L)	Average (µg/L)	Month and year
Original Schedule	851.19	312.62	490.62	January 1957
Maximum Schedule	1,023.32	585.98	738.40	May 1956
Minimum Schedule I	144.74	24.49	58.28	August 1959
Minimum Schedule II	243.00	44.32	85.49	March 1959

PCE Concentration at the Water Treatment Plant

PCE concentrations at the WTP calculated from different pumping schedules are shown in Figures H38 and H39. Figure H38 shows PCE concentrations at the WTP during the period January 1951–February 1987, while Figure H39 shows PCE concentrations at the WTP during the period of interest only.

Results shown in Figure H38 indicate that PCE concentration at the WTP could reach the 5 µg/L MCL as early as December 1956 or as late as June 1960. Compared to the PCE MCL arrival time at the WTP under the Original Schedule (November 1957), PCE concentration at the WTP could reach the MCL 11 months earlier or 31 months later.

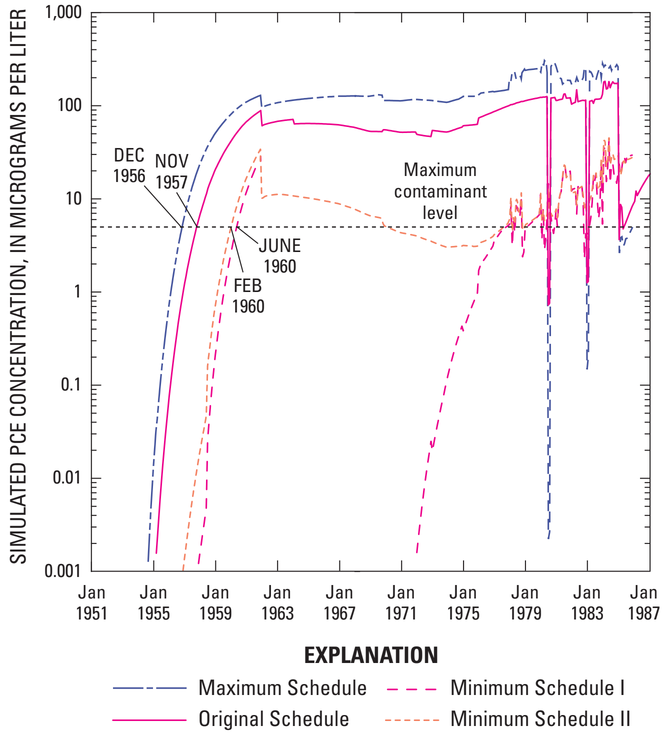


Figure H38. Simulated tetrachloroethylene (PCE) concentration at the water treatment plant under the Original Schedule (solid line) and updated pumping schedules (dashed lines), Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

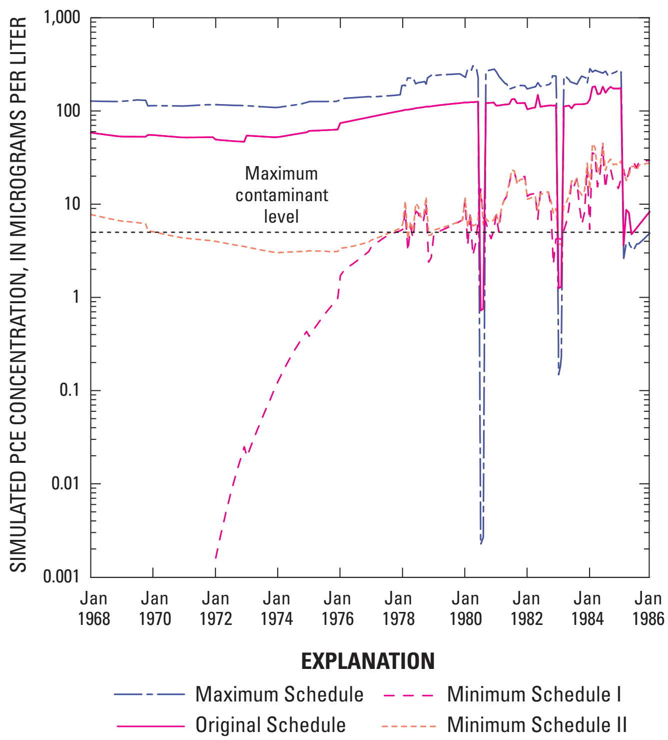


Figure H39. Simulated tetrachloroethylene (PCE) concentration in at water treatment plant under the Original Schedule (solid line) and updated pumping schedules (dashed lines), period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

These results are obtained without changing other calibrated model parameters that could affect the fate and transport of PCE in the subsurface and, thus, the 5-µg/L PCE MCL arrival time at the WTP. Therefore, the variation of pumping schedule has an important effect on PCE concentration at the WTP and on the MCL arrival time. A summary of maximum, minimum, and average PCE concentrations and MCL arrival times at the WTP under different pumping schedules is listed in Table H13.

Variation of pumping schedules also changes the amount of contaminant mass withdrawn from the groundwater system. A summary of PCE masses withdrawn under different schedules is listed in Table H14. In this table, the change of mass withdrawn from the groundwater system is quite significant.

Table H13. Tetrachloroethylene concentration and maximum contaminant level arrival time at the water treatment plant under the Original Schedule and the updated pumping schedules for the period of interest, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter]

Pumping schedule	Maximum (µg/L)	Minimum (µg/L)	Average (µg/L)	Arrival time
Original Schedule	183.04	46.69	86.39	November 1957
Maximum Schedule	304.66	108.76	166.07	December 1956
Minimum Schedule I	41.36	7.84×10^{-8}	5.01	June 1960
Minimum Schedule II	45.31	3.04	8.04	February 1960

Table H14. Tetrachloroethylene mass withdrawn under the Original Schedule and the updated pumping schedules, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Pumping schedule	Total mass released (gram)	Mass withdrawn (gram)	Percentage[1]
Original Schedule	1.40×10^{7}	2.45×10^{6}	17.50
Maximum Schedule	1.40×10^{7}	4.59×10^{6}	32.78
Minimum Schedule I	1.40×10^{7}	1.98×10^{5}	1.41
Minimum Schedule II	1.40×10^{7}	3.41×10^{5}	2.44

[1]Percentage of mass withdrawn relative to total mass released

Summary and Conclusions

In this chapter of the Tarawa Terrace report series, the effect of pumping schedule variations on tetrachloroethylene (PCE) arrival times at water-supply wells and the Tarawa Terrace water treatment plant (WTP) is evaluated. Because of the large scale and complexity of the problem, a procedure was developed—identified as the Pumping Schedule Optimization System (PSOpS). This procedure is based on the simulation and optimization (S/O) approach. PSOpS was applied to optimize pumping schedules for evaluation of PCE maximum contaminant level (MCL) arrival time at the WTP. Final results indicate that PSOpS works well for this study and is computationally cost-efficient.

Simulation results presented in this study lead to the following conclusions:

1. Variation of pumping schedule has an effect on contaminant arrival time at water-supply wells. According to study results, a change in pumping schedules can cause changes in the contaminant plume distribution and the orientation of the plume front in the groundwater system. Changes in the contaminant transport characteristics lead to a variation of contaminant concentrations at water-supply wells. This is equivalent to the variation of contaminant arrival time at water-supply wells. For example, according to results presented herein, the arrival time of a 5-μg/L PCE concentration at well TT-26 varies from May 1956 to August 1959.
2. Variation of pumping schedule has an impact on the contaminant arrival time at the WTP, and this impact is twofold. The mixing-model equation indicates that PCE concentration at the WTP is calculated using PCE concentrations and pumping rates at water-supply wells. Therefore, a variation of pumping schedule changes the contaminant arrival time at the WTP by affecting both quantities of the mixing-model equation. Simulation results reported in this study indicate that the PCE MCL arrival time at the WTP varies from December 1956 to June 1960. This outcome is based on allowable changes to pumping schedules within the pumping capacity of each well.
3. Water-supply well TT-26 is critical for assessing the contaminant arrival time at the WTP. All simulation results show that by the time PCE concentrations at the WTP reach 5 μg/L, PCE concentrations at all water-supply wells, except well TT-26, are still negligible. This is due to some unique characteristics of well TT-26. First, well TT-26 is the closest water-supply well to the contaminant source, ABC One-Hour Cleaners. Second, well TT-26 is located in the downgradient groundwater-flow direction relative to the contaminant source. Third, well TT-26 has the longest pumping history among all water-supply wells. Therefore, increasing the pumping rate in well TT-26 can cause earlier contaminant arrival time at the WTP; conversely, reducing the pumping rate in well TT-26 can cause later contaminant arrival time at the WTP.
4. Variation of pumping schedule can cause a significant change in the amount of contaminant mass withdrawn from the groundwater system. Considering the total amount of water supplied to the WTP, a change in PCE concentration at the WTP caused by a variation in pumping schedule leads to a change in contaminant mass withdrawn. Given different pumping schedules derived in this study, the total PCE mass that was supplied to the WTP could vary from 1.41 to 32.78 percent of the total contaminant mass released from the contaminant source into the groundwater system at the site.

Based on optimal pumping schedules obtained from PSOpS, simulations have been conducted to demonstrate the effect of the pumping schedule variation on PCE arrival times at water-supply wells and the WTP. Analyses of simulation results indicate that a variation in pumping schedules can affect PCE arrival time. Considering this uncertainty factor, a change in pumping schedules yields the following outcomes according to simulation results: (1) PCE MCL arrival time at well TT-26 varies from May 1956 to August 1959, and (2) PCE MCL arrival time at the WTP varies from December 1956 to June 1960.

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Appendix H1. 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 H1. 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

Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—Chapter H: Effect of Groundwater Pumping Schedule Variation on Arrival of Tetrachloroethylene (PCE) at Water-Supply Wells and the Water Treatment Plant

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