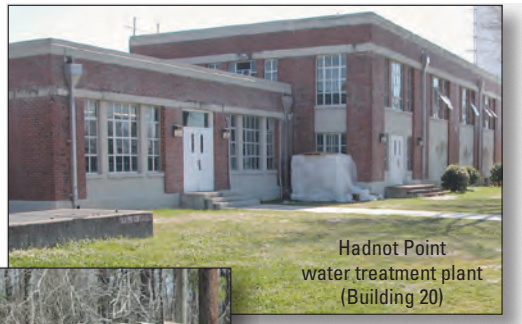
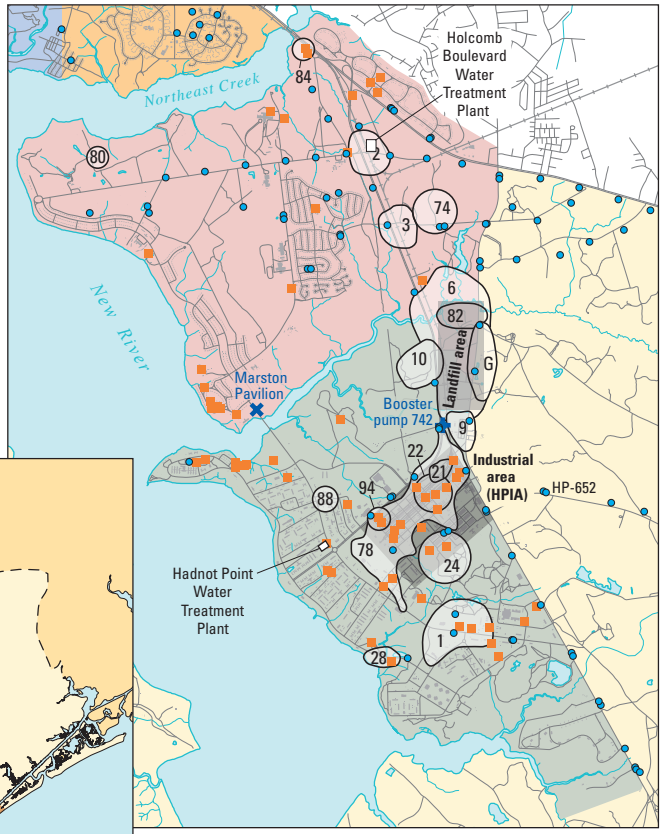
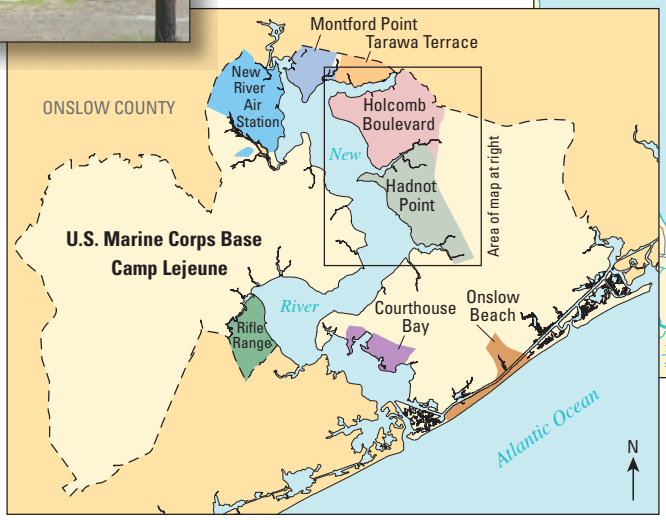
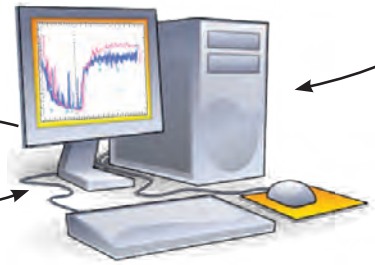
Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina

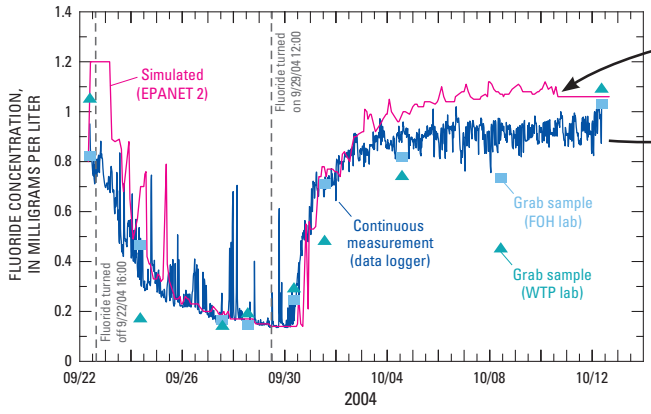
Chapter A: Summary and Findings











DEPARTMENT OF HEALTH & HUMAN SERVICES · USA

ATSDR
AGENCY FOR TOXIC SUBSTANCES AND DISEASE REGISTRY

Atlanta, Georgia – March 2013

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

Maps: U.S. Marine Corps Base Camp Lejeune, North Carolina; Holcomb Boulevard and Hadnot Point areas showing extent of sampling at Installation Restoration Program sites (white numbered areas), above-ground and underground storage tank sites (orange squares), and water-supply wells (blue circles).

Photograph (upper): Hadnot Point water treatment plant (Building 20).

Photograph (lower): Well house building for water-supply well HP-652.

Graph: Measured fluoride data and simulation results for Paradise Point elevated storage tank (S-2323) for tracer test of the Holcomb Boulevard water-distribution system, September 22–October 12, 2004; simulation results obtained using EPANET 2 water-distribution system model assuming last-in first-out plug flow (LIFO) storage tank mixing model. [WTP lab, water treatment plant water-quality laboratory; FOH lab, Federal Occupational Health Laboratory]

Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina

Chapter A: Summary and Findings

By Morris L. Maslia, René J. Suárez-Soto, Jason B. Sautner, Barbara A. Anderson, L. Elliot Jones, Robert E. Faye, Mustafa M. Aral, Jiabao Guan, Wonyong Jang, Ilker T. Telci, Walter M. Grayman, Frank J. Bove, Perri Z. Ruckart, and Susan M. Moore

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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 epidemiological studies to evaluate the potential for health effects from exposures to volatile organic compounds (such as tetrachloroethylene, trichloroethylene, and benzene) in drinking (finished) water at U.S. Marine Corps Base Camp Lejeune, North Carolina. Historical exposure data needed for the epidemiological studies are limited. To obtain estimates of historical exposures, ATSDR is using water-modeling techniques and the process of historical reconstruction to quantify concentrations of particular contaminants in finished water and to compute the level and duration of human exposure to contaminated drinking water.

Eight water-distribution systems have supplied or currently (2013) are supplying finished water to family housing and other facilities at U.S. Marine Corps Base Camp Lejeune, North Carolina. The three distribution systems of interest to this study—Tarawa Terrace, Hadnot Point, and Holcomb Boulevard—have historically supplied finished water to the majority of family housing units at the Base. During 2007–2009, ATSDR published historical reconstruction results for the Tarawa Terrace housing areas and vicinity. Results for Hadnot Point and Holcomb Boulevard family housing areas and vicinities—based on information gathering, data interpretations, and water-modeling analyses—are now presented as another series of reports supporting ATSDR's health studies at Camp Lejeune. These reports provide comprehensive descriptions of information, data analyses and interpretations, and modeling results used to reconstruct historical contaminant levels in finished water within the service areas of the Hadnot Point and Holcomb Boulevard water treatment plants and vicinities. Each topical subject within the historical reconstruction process is assigned a chapter letter (e.g., Chapters A, B, C, and D) or presented as supplemental information as part of Chapter A.

- **Chapter A**: Summary and Findings
  - **Supplement 1**: Descriptions and Characterizations of Data Pertinent to Water-Supply Well Capacities, Histories, and Operations
  - **Supplement 2**: Development and Application of a Methodology to Characterize Present-Day and Historical Water-Supply Well Operations
  - **Supplement 3**: Descriptions and Characterizations of Water-Level Data and Groundwater Flow for the Brewster Boulevard and Castle Hayne Aquifer Systems and the Tarawa Terrace Aquifer
  - **Supplement 4**: Simulation of Three-Dimensional Groundwater Flow
  - **Supplement 5**: Theory, Development, and Application of Linear Control Model Methodology to Reconstruct Historical Contaminant Concentrations at Selected Water-Supply Wells
  - **Supplement 6**: Characterization and Simulation of Fate and Transport of Selected Volatile Organic Compounds in the Vicinities of the Hadnot Point Industrial Area and Landfill
  - **Supplement 7**: Source Characterization and Simulation of the Migration of Light Nonaqueous Phase Liquids (LNAPLs) in the Vicinity of the Hadnot Point Industrial Area
  - **Supplement 8**: Field Tests, Data Analyses, and Simulation of the Distribution of Drinking Water with Emphasis on Intermittent Transfers of Drinking Water Between the Hadnot Point and Holcomb Boulevard Water-Distribution Systems

Foreword—Continued

- **Chapter B**: Geohydrologic Framework of the Brewster Boulevard and Castle Hayne Aquifer Systems and the Tarawa Terrace Aquifer
- **Chapter C**: Occurrence of Selected Contaminants in Groundwater at Installation Restoration Program Sites
- **Chapter D**: Occurrence of Selected Contaminants in Groundwater at Above-Ground and Underground Storage Tank Sites

Electronic versions of the Hadnot Point–Holcomb Boulevard report series and supporting information will be made available on the ATSDR Camp Lejeune Web site at: *http://www.atsdr.cdc.gov/sites/lejeune/index.html*. Readers may request a CD–ROM containing the Hadnot Point–Holcomb Boulevard report series and supporting information by emailing ATSDRRecordsCenter@cdc.gov.

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

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per day (gal/d)	3.785	liter per day (L/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)
	Density (for water at 4 °C, at sea level)	
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (kg/m^3)
pound per cubic foot (lb/ft^3)	0.01602	gram per cubic centimeter (g/cm^3)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Concentration Conversion Factors

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

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F = (1.8×°C) +32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C = (°F–32)/1.8

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29). Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above vertical datum (NGVD 29).

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [$(ft^3/d)/ft^2$]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Glossary, Abbreviations, and Definitions

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

— A —

abandoned Permanently discontinuing the use of a water-supply well

all-pipes model A water-distribution system model that contains all pipelines of a water-distribution system network, typically down to 1-inch or 2-inch residential pipelines; *also see* skeletonization

AN-Well Semi-analytical method for LNAPL volume estimation using apparent LNAPL thickness; see Jang et al. (2013) for details

AS/SVE Air sparging/soil vapor extraction; Air sparging is an in situ remedial technology that involves the injection of contaminant-free air into the subsurface saturated zone, enabling a phase transfer of hydrocarbons from a dissolved state to a vapor phase. The air is then vented through the unsaturated zone. Air sparging is most often used together with soil vapor extraction (SVE), but it can also be used with other remedial technologies. When air sparging (AS) is combined with SVE, the SVE system creates a negative pressure in the unsaturated zone through a series of extraction wells to control the vapor plume migration. This combined system is called AS/SVE; *http://www.epa.gov/oust/cat/airsparg.htm*

AST Above-ground storage tank

ATSDR Agency for Toxic Substances and Disease Registry; *http://www.atsdr.cdc.gov*

— B —

BBLAQ Brewster Boulevard lower aquifer

BBLCU Brewster Boulevard lower confining unit

BBUAQ Brewster Boulevard upper aquifer

BBUCU Brewster Boulevard upper confining unit

benzene A widely used chemical formed from both natural processes and human activities. Natural sources of benzene include volcanoes and forest fires. Benzene is also a natural part of crude oil, gasoline, and cigarette smoke. Long-term benzene exposure has effects on the bone marrow and can cause anemia and leukemia. The National Toxicology Program (NTP) Report on Carcinogens (NTP 2011) has recognized benzene as a known human carcinogen based on sufficient evidence in humans

bgs Below ground surface

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

black box A term used in science and engineering that refers to a device or system that can be analyzed in terms of inputs, transfer properties, and outputs, without specific knowledge of its internal dynamic workings

BRAGS Basewide Remediation Assessment Groundwater Study (Baker Environmental, Inc. 1998a, b)

BTEX Benzene, toluene, ethyl benzene, and xylenes. These compounds are some of the VOCs found in petroleum derivatives such as gasoline. BTEX compounds typically occur near petroleum and natural gas production sites, gasoline stations, and other areas with underground storage tanks (USTs) or above-ground storage tanks (ASTs) containing gasoline or other petroleum-related products

— C —

2–COMP A two-component storage-tank mixing mode used in the EPANET 2 water-distribution system model (Rossman 2000)

C-factor Hazen-Williams roughness coefficient

$CaCl_2$ Calcium chloride

calibration *See* model calibration

CAP Community assistance panel

capacity Maximum volume of flow that can be delivered by a water-supply well

CDC Centers for Disease Control and Prevention; *http://www.cdc.gov*

CD–ROM Compact disc–read-only memory

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

CFR Code of Federal Regulations; the codification of the general and permanent rules published in the Federal Register by the departments and agencies of the U.S. Federal Government

CHD Time-variant specified-head option; this option (sometimes also called a package) is used within MODFLOW-2005 (Harbaugh 2005) to simulate specified head boundaries or boundaries where head varies with time; *also see* MODFLOW

CLHDW CDR Camp Lejeune historic drinking water consolidated document repository

CLW Camp Lejeune water document

conservative tracer A chemical compound whose concentration does not change due biological or chemical processes

consumption The use of water by customers of a water utility. In a water-distribution system, consumption should equal production if there are no losses through leaks or pipe breaks; also known as demand

CSTR A continuously stirred-tank reactor, also referred to as a complete mixing storage-tank model used in the EPANET 2 water-distribution system model (Rossman 2000)

— D —

DCE Dichloroethylene; an industrial chemical that is not found naturally in the environment. The USEPA has determined that 1,1-dichloroethylene is a possible human carcinogen

1,1-DCE 1,1-dichloroethylene or 1,1-dichloroethene

1,2-DCE 1,2-dichloroethylene or 1,2-dichloroethene

1,2-cDCE *cis*-1,2-dichloroethylene or *cis*-1,2-dichloroethene

1,2-tDCE *trans*-1,2-dichloroethylene or *trans*-1,2-dichloroethene

total 1,2-DCE total 1,2-dichloroethylene or total 1,2-dichloroethene

degradation by-product *See* biodegradation

delivered water Treated water that is supplied to the water-distribution system. Refers to a volume or rate of water determined at the WTP. *See* finished water. In this study, when raw water volume or rate data are unavailable, delivered water data are used

DEM Digital elevation model

demand The fractional component of consumption that is applied to a pipeline location in a water-distribution system model. In some water-distribution system analyses, the terms consumption and demand are used interchangeably

density The mass per unit volume of material, expressed in terms of kilograms per cubic meter (kg/m^3) or grams per cubic centimeter (g/cm^3) ; the density of water is 1,000 kg/m^3 (1 g/cm^3) at 5° C, but varies with temperature (Peavy et al. 1985)

DNAPL Dense nonaqueous phase liquids; a class of environmental contaminants that have a specific gravity greater than water (Huling and Weaver 1991). Immiscible (nonmixing) DNAPLs exist in the subsurface as a separate fluid phase in the presence of air and water. DNAPLs can vaporize into air and slowly dissolve into flowing groundwater. Examples of DNAPLs include chlorinated solvents, creosote, coal tar, and PCBs (Pankow and Cherry 1996; Kueper et al. 2003)

DON Department of the Navy

drinking water *See* finished water

DRN Drain package; this package is used within MODFLOW-2005 (Harbaugh 2005) to simulate head-dependent conditions and is used to represent agricultural drains and gaining perennial and intermittent streams; *also see* MODFLOW

— E —

EPANET 2 A water-distribution system (or network) model developed by the USEPA (Rossman 2000)

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

EPS Extended period simulation; a type of analysis conducted with a water-distribution system model when system attributes (e.g., filling and emptying of storage tanks) change over time

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

— F —

fate and transport Also known as mass transport; a process that refers to the migration and transformation of contaminants in the subsurface environment

FFCA Federal Facilities Compliance Act of 1992; amended the Resource Conservation and Recovery Act (RCRA) of 1992 and established that federal facilities do not have sovereign immunity from state enforcement of state environmental laws

FIFO A first-in, first-out plug-flow storage-tank mixing model used in the EPANET 2 water-distribution system model (Rossman 2000)

finished water Groundwater that has undergone treatment at a water treatment plant and subsequently is delivered to a family housing unit or other facility—also referred to as drinking water, finished drinking water, or tap water

FOH Federal Occupational Health laboratory (Chicago, Illinois)

FOUO For official use only

free-phase Indicates the occurrence of light nonaqueous phase (LNAPL) hydrocarbon liquids in the subsurface, such as gasoline, that remain undiluted by other gases or liquids present in the subsurface. Although the physical and chemical properties of the free-phase product may change over time, the product nonetheless remains a distinct phase of a nonaqueous hydrocarbon liquid in the subsurface. (Also referred to as free-phase hydrocarbon product or free-phase benzene or free-phase LNAPL)

ft Foot or feet

— G —

gal Gallon or gallons

GC/MS Gas chromatography–mass spectrometry; a method that combines the features of gas-liquid chromatography and mass spectrometry to identify different substances within a test sample

GIS Geographic information system

GMS Groundwater Modeling System; a comprehensive graphical user environment for data analyses, data interpolation, and groundwater simulation developed by the U.S. Army Engineer Research and Development Center (2008)

gpm Gallon(s) per minute

GPS Global positioning system

— H —

HBWTP Holcomb Boulevard water treatment plant; also known as Building 670

HGL Hydraulic grade line

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

historical reconstruction period The period of July 1942–December 1997 when monthly water-supply well operations are derived using a deterministic mass-balance methodology described in Telci et al. (2013); also referred to as prediction period

HPFF Hadnot Point Industrial Area fuel farm, also known as Hadnot Point tank farm

HPHB Hadnot Point–Holcomb Boulevard

HPIA Hadnot Point Industrial Area; a formally designated name and acronym used in many Camp Lejeune references (e.g., Baker Environmental 1994, CH2M HILL 2006). The ATSDR Hadnot Point–Holcomb Boulevard Chapter reports and supplemental information texts follow this naming convention

HPLF Hadnot Point landfill

HPWTP Hadnot Point water treatment plant; also known as Building 20

HSSM Semi-analytical hydrocarbon spill screening model (Weaver et al. 1996)

HSSM-KO The LNAPL transport module of HSSM (Weaver et al. 1996)

HSWA Hazardous and Solid Waste Amendments of 1984

hydraulic gradient The change in potentiometric level per unit of distance in a given direction

— I —

IARC International Agency for Research on Cancer

IAS Initial Assessment Study

IML++ Iterative sparse matrix solver; see Jang et al. (2013)

in service An operating water-supply well that is withdrawing groundwater from an aquifer and supplying it to a water treatment plant

IR Installation Restoration

IRP Installation Restoration Program

— J —

junction *See* pipeline junction

— K —

Kalman filter A general mathematical approach for integrating noisy data in a way that minimizes the mean of the error squared; the method is used in many branches of science and engineering and allows for efficient estimation of past, present, and future states, even when a precise definition of the modeled system is unknown

— L —

LCHAQ Lower Castle Hayne aquifer

LCHCU Lower Castle Hayne confining unit

LCM Linear control model; a model based on linear control theory methodology developed to reconstruct historical contaminant concentrations in water-supply wells. Such a model, TechControl, was developed by the Multimedia Environmental Simulations Laboratory, Georgia Institute of Technology, Atlanta, Georgia; references to LCM in text, figures, tables, appendixes, and supplemental information sections refer to the TechControl linear control model

LHS Latin hypercube sampling; a form of stratified sampling that is typically used to reduce the number of Monte Carlo simulations (realizations) by a significant factor.

LIFO A last-in, first-out plug-flow storage-tank mixing model used in the EPANET 2 water-distribution system model (Rossman 2000)

LNAPL Light nonaqueous phase liquids (NAPLs), which are less dense than water and float; these include lubricants and gasoline, pollutants often associated with leaking gasoline, or oil storage tanks (e.g., benzene)

local grid refinement A grid refinement method of the MODFLOW groundwater-flow model that allows smaller, localized parts of the larger model grid to be refined without refining the entire model grid

LPF The layer property flow package; this package is used in MODFLOW-2005 (Harbaugh 2005) to specify properties controlling flow between cells*; also see* MODFLOW

— M —

Markov process A process that analyzes the tendency of one event to be followed by another event based on the sequence of events. Using this analysis, one can generate a new sequence of random but related events, which will look similar to the original; a stream of events is called a Markov Chain

MC Monte Carlo, as in Monte Carlo simulation or Monte Carlo analysis

MCHAQ Middle Castle Hayne aquifer

MCHCU Middle Castle Hayne confining unit

MCL Maximum contaminant level; a legal threshold limit set by the USEPA on the amount of a hazardous substance that is allowed in drinking water under the Safe Drinking Water Act; usually expressed as a concentration in milligrams or micrograms per liter (USEPA 2003, 2009)

MDPH Massachusetts Department of Public Health

MESL Multimedia Environmental Simulations Laboratory, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA; *http://mesl.ce.gatech.edu*

Mgal Million gallons

MGD Million gallons per day

mg/L milligram per liter; 1 part per million, a unit of concentration

mi Mile or miles

MOC Method of characteristics; a numerical equation solver used by the MT3DMS contaminant fate and transport model code (Zheng and Wang 1999)

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

model node The representation of the end point of a section of pipeline in the EPANET 2 water-distribution system model; also referred to as junction or pipeline junction

MODFLOW A family of three-dimensional groundwater-flow models, developed by the U.S. Geological Survey. MODFLOW-2005 (Harbaugh 2005) is the specific MODFLOW code used for the Hadnot Point–Holcomb Boulevard study area analyses; references to MODFLOW in text, figures, tables, appendixes, and supplemental information refer to MODFLOW-2005

Monte Carlo analysis Also referred to as Monte Carlo simulation; a computer-based method of analysis that uses statistical sampling techniques to obtain a probabilistic approximation to the solution of a mathematical equation or model (USEPA 1997)

Monthly mean concentration The representation of reconstructed (simulated) VOCs on a typical day during a month. The use of this term should not be construed to indicate or represent any statistical property associated with a mean or expected value.

MT3DMS Three-dimensional mass transport, multispecies model developed on behalf of the U.S. Army Engineer Research and Development Center. MT3DMS-5.3 (Zheng and Wang 1999) is the specific version of MT3DMS code used for the Hadnot Point–Holcomb Boulevard study area analyses; references to MT3DMS in text, figures, tables, appendixes, and supplemental information refer to MT3DMS-5.3

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

— N —

NACIP Naval Assessment and Control of Installation Pollution

NAD 83 North American Datum of 1983

NaF Sodium fluoride

NAPL Nonaqueous phase liquids; hazardous organic liquids such as dry cleaning fluids, fuel oil, and gasoline that do not dissolve in water. Dense NAPLs (DNAPLs), such as the chlorinated hydrocarbons (e.g., PCE, TCE) used in dry cleaning and industrial degreasing, are heavier than water and sink through the water column. Hydrocarbon fuels and aromatic solvents are described as light NAPLs (LNAPLs), which are less dense than water and float. These include lubricants and gasoline, pollutants often associated with leaking gasoline or oil storage tanks (e.g., benzene)

NAVD 88 North American Vertical Datum of 1988

NCDENR North Carolina Department of Environment and Natural Resources

NGVD 29 National Geodetic Vertical Datum of 1929

NI-Soil Numerical integration method for LNAPL volume estimation using real (actual) LNAPL thickness; see Jang et al. (2013) for details

NI-Well Numerical integration method for LNAPL volume estimation using apparent LNAPL thickness; see Jang et al. (2013) for details

NJDHSS New Jersey Department of Health and Senior Services

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

NTP National Toxicology Program; a program of the U.S. Department of Health and Human Services, Public Health Service, whose mission is to evaluate agents of public health concern by developing and applying tools of modern toxicology and molecular biology

— O —

OAT One-at-a-time designs or experiments; a particular approach to sensitivity analysis wherein each model parameter is varied one at a time from its respective calibrated value, and the resulting impact on model results (e.g., simulated water levels, contaminant concentrations) is assessed

OLS Ordinary least squares, also known as linear least squares; a standard method for approximating the solution to over-determined systems (sets of equations containing more equations than unknowns)

out of service A water-supply well that is no longer operating by withdrawing groundwater from an aquifer and supplying water to a water treatment plant

— P —

PARDISO Pardiso sparse matrix solver; see Jang et al. (2013) for details

PCE Tetrachloroethylene, 1,1,2,2-tetrachloroethylene, or perchloroethylene; also known as PERC® or PERK®. PCE is a manufactured chemical used for dry cleaning and metal degreasing. In 2012, following its Guidelines for Carcinogen Risk Assessment (USEPA 2005), the USEPA characterized PCE as likely to be carcinogenic in humans by all routes of exposure (USEPA 2012)

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

PEST Model independent, objective parameter estimation and uncertainty analysis code originally developed by Watermark Numerical Computing (Doherty 2003, 2010); the current version is PEST-12, available at *http://www.pesthomepage.org/Downloads.php*

pH A measure of the relative amount of free hydrogen and hydroxyl ions in water; pH has a range of 0–14 with distilled (or pure) water at 25° C having a pH of 7. A pH of less than 7 indicates increasing acidity, and a pH of greater than 7 indicates increasing alkalinity

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

pipeline junction Representation of the end point of a section of pipeline in the EPANET 2 water-distribution system model; also known as model node

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

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

PP Prediction process; see Supplement 2 for details (Telci et al. 2013)

ppb Parts per billion

prediction period See historical reconstruction period and explanation in Telci et al. (2013)

present day The time from January 1998 through June 2008 when daily operational records (data) are available for water-supply well operations; also referred to as training period. See Supplement 2 for details (Telci et al. 2013)

production The processing of finished water by a water utility and the delivery of the water to locations serviced by the water-distribution system. In a water-distribution system, production should equal consumption if there are no losses through leaks, pipe breaks, or non-metered water usage

psi Pound(s) per square inch

PVC Polyvinyl chloride; a type of plastic pipe used in water-distribution systems

— Q —

QA/QC Quality assurance/quality control

— R —

RASA Regional Aquifer-System Analysis; a program of the U.S. Geological Survey that was initiated in 1978 and was completed in 1995. The purpose of this program was to define the regional geohydrology and establish a framework of background information on geology, hydrology, and geochemistry of the Nation's important aquifer systems

raw water Groundwater that is withdrawn from an aquifer and supplied to a water treatment plant, prior to undergoing treatment

RCRA Resource Conservation and Recovery Act of 1976

RI Remedial investigation

RI/FS Remedial investigation/feasibility study

— S —

SARA Superfund Amendments and Reauthorization Act of 1981

saturated zone Zone or area below ground in which all interconnected openings within the geologic medium are completely filled with water and are under pressure greater than that of the atmosphere

SCADA Supervisory control and data acquisition; an electronic method of compiling water-distribution system operations data and controlling the operation of certain facilities (Cesario 1995)

SDWA Safe Drinking Water Act of 1974, also known as Public Law 93-523; the federal legislation enacted to develop a national program to protect the quality of the nation's publicly supplied drinking water

sensitivity analysis A method used to ascertain how a given model output (e.g., concentration) depends upon the input parameters (e.g., time-step size, pumping rate). Sensitivity analysis is an important method for assessing the quality of a given model and a powerful tool for analyzing the robustness and reliability model analyses

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

skeletonization A process of representing the major features of a water-distribution system network in a model by removing non-essential pipelines, while still preserving the general hydraulic characteristics and behavior of the water-distribution system network; *also see* "all-pipes model"

SpillCAD A data management and decision support model for hydrocarbon spills (Environmental Systems & Technologies 1993)

SR Highway or state route

surrogate well Water-supply wells serving the HPWTP and HBWTP that did not have any recorded operational data for present-day period (January 1998–June 2008). See Telci et al. (2013) for details

— T —

TCE 1,1,2-Trichloroethene; commonly referred to as 1,1,2-trichloroethylene or trichloroethylene. TCE is a colorless liquid which is used as a solvent for cleaning metal parts. In 2011, following its Guidelines for Carcinogen Risk Assessment (USEPA 2005), the USEPA characterized TCE as carcinogenic in humans by all routes of exposure (USEPA 2011)

TEACH Toxicity and exposure assessments for children's health; a USEPA Web site (*http://www.epa.gov/teach/*) of chemical summaries providing a compilation of information derived primarily from USEPA and ATSDR resources, and the TEACH database

TechControl Also referred to as LCM; a model based on linear control theory methodology developed to reconstruct historical contaminant concentrations in water-supply wells. TechControl, was developed by the Multimedia Environmental Simulations Laboratory, Georgia Institute of Technology, Atlanta, Georgia; see Guan et al. (2013) for details

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

TechMarkovChain A probabilistic analysis model developed by the Multimedia Environmental Simulations Laboratory at the Georgia Institute of Technology, Atlanta, Georgia, to analyze intermittent connections (1972–1985) of the Hadnot Point and Holcomb Boulevard water-distribution systems (see Sautner et al. 2013b for details)

TechNAPLVoL LNAPL estimate model developed by the Multimedia Environmental Simulations Laboratory at the Georgia Institute of Technology, Atlanta, Georgia

TechWellOp A specialized code for reconstructing monthly water-supply well operations developed by the Multimedia Environmental Simulations Laboratory at the Georgia Institute of Technology, Atlanta, Georgia (see Telci et al. 2013 for details)

TerraBase An intuitive, structure query language-compliant relational database application designed for environmental professionals and managers who need to assess and manage chemical, geological, and spatial data

TOC Top of casing

TP Training process; see Supplement 2 for details (Telci et al. 2013)

training period *See* present day and details in Supplement 2 (Telci et al. 2013)

TT Tarawa Terrace

TTAQ Tarawa Terrace aquifer

TTHMs Total trihalomethanes; the sum of chloroform ($CHCl_3$), bromoform ($CHBr_3$), bromodichloromethane ($CHBrCl_2$), plus dibromochloromethane ($CHBr_2Cl$), which are disinfection by-products formed by chlorination of drinking water (Singer 1993)

TTWTP Tarawa Terrace water treatment plant

TVD Third-order, total-variation-diminishing; a numerical equation solver used by the MT3DMS contaminant fate and transport model code (Zheng and Wang 1999)

— U —

UCHCU Upper Castle Hayne confining unit

UCHLU Upper Castle Hayne aquifer–Lower unit

UCHRBU Upper Castle Hayne aquifer–River Bend unit

UCHRBU&LU Upper Castle Hayne aquifer–River Bend and Lower units

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

uncertainty analysis Determination of the uncertainty (e.g., standard deviation) of the output variables' expected value (e.g., mean) due to uncertainty in model parameters, inputs, or initial state by stochastic modeling techniques (Schnoor 1996)

unsaturated zone Zone or area below ground in which the interconnected openings within the geologic medium contain a mixture of water under pressure less than atmospheric and air under atmospheric pressure; sometimes referred to as the vadose zone or the zone above the water table. The capillary fringe is part of the unsaturated zone and sometimes occurs as completely saturated

USEPA U.S. Environmental Protection Agency; *http://www.epa.gov*

USGS U.S. Geological Survey; *http://www.usgs.gov*

USMCB U.S. Marine Corps Base; *http://www.marines.mil*

UST Underground storage tank

— V —

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

VC Vinyl chloride or chloroethene; a colorless gas that burns easily, is not stable at high temperatures, and has a mild, sweet odor. It is a manufactured substance that does not occur naturally. It can be formed when other substances such as TCA, TCE, or PCE undergo biochemical degradation. The USEPA has characterized VC as a known human carcinogen (USEPA 2000). The NTP Report on Carcinogens (NTP 2011) has recognized vinyl chloride as a known human carcinogen based on sufficient evidence of carcinogenicity in humans

VOC Volatile organic compound; one of a group of carbon-containing compounds that evaporate readily at room temperature and can readily be inhaled. Examples of VOCs include tetrachloroethylene (PCE), trichloroethylene (TCE), vinyl chloride (VC), and benzene. These contaminants typically are generated from metal degreasing, printed circuit board cleaning, dry cleaning, gasoline, and wood preserving processes. VOCs are environmental contaminants, and some are classified as known human carcinogens (e.g., TCE, VC, and benzene)

— W —

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

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

WCA Water Conservation Analysis; an estimate of 1998 water consumption for the Hadnot Point and Holcomb Boulevard water treatment plant service areas (ECG, Inc. 1999)

well history A chronological record of water-supply well operations starting from the time the well was placed into service and ending with the time the well was abandoned

well packet A packet of information for a water-supply well that includes driller's logs, construction drawings, capacity tests, and other well-specific records

working population Defined in the Water Conservation Analysis report (ECG, Inc. 1999) as military personnel and civilians aboard U.S. Marine Corps Base Camp Lejeune, North Carolina

WTP Water treatment plant

— X, Y, Z —

xylene A colorless, sweet-smelling liquid that catches on fire easily; it occurs naturally in petroleum and coal tar. Chemical industries produce xylene from petroleum. There are three forms of xylene in which the methyl groups vary on the benzene ring: *meta*-xylene, *ortho*-xylene, and *para*-xylene (*m*-, *o*-, and *p*-xylenes). These different forms are referred to as isomers. No health effects have been noted at the background levels that people are exposed to on a daily basis

Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina

Chapter A: Summary and Findings

By Morris L. Maslia,[1] René J. Suárez-Soto,[1] Jason B. Sautner,[1] Barbara A. Anderson,[1] L. Elliott Jones,[2] Robert E. Faye,[3] Mustafa M. Aral,[4] Jiabao Guan,[4] Wonyong Jang,[4] Ilker T. Telci,[5] Walter M. Grayman,[6] Frank J. Bove,[1] Perri Z. Ruckart,[1] and Susan M. Moore[1]

Abstract

The Agency for Toxic Substances and Disease Registry (ATSDR) is conducting epidemiological studies to evaluate the potential for health effects from exposures to volatile organic compounds (VOCs) in finished water[7] supplied to family housing units at U.S. Marine Corps Base Camp Lejeune, North Carolina (USMCB Camp Lejeune). The core period of interest for the epidemiological studies is 1968–1985. VOCs of major interest to the epidemiological studies include tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene.

Eight water-distribution systems have supplied or currently (2013) are supplying finished water to family housing and other facilities at USMCB Camp Lejeune. The three distribution systems of interest to this study—Tarawa Terrace, Hadnot Point, and Holcomb Boulevard—have historically supplied finished water to the majority of family housing units at the Base. Historical exposure data needed for the epidemiological studies are limited or unavailable. To obtain estimates of historical exposure, water-modeling methods are used to quantify concentrations of particular contaminants in finished water and to compute the level and duration of human exposure to contaminated finished water.

During 2007–2009, ATSDR published historical reconstruction results for contaminants delivered in finished water to Tarawa Terrace family housing areas and vicinity. Corresponding results for Hadnot Point and Holcomb Boulevard family housing areas and vicinity are presented here as a series of reports supporting ATSDR's health studies at USMCB Camp Lejeune. These reports and associated supplements provide comprehensive descriptions of information, data analyses and interpretations, and modeling results used to reconstruct historical contaminant concentration levels in finished water delivered within the service areas of the Hadnot Point and Holcomb Boulevard water treatment plants (WTPs) and vicinities. This report, Chapter A: Summary and Findings, summarizes analyses and results of reconstructed VOC concentrations in groundwater, in water-supply wells, and in finished water delivered by the Hadnot Point WTP (HPWTP) and Holcomb Boulevard WTP (HBWTP) to family housing areas and vicinities.

Methods and approaches to complete the historical reconstruction process for the Hadnot Point–Holcomb Boulevard study area included (1) information discovery and data mining, (2) three-dimensional, steady-state (predevelopment) and transient groundwater-flow modeling using MODFLOW-2005 and objective parameter estimation using PEST-12, (3) determining historical water-supply well scheduling and operations using TechWellOp, (4) three-dimensional contaminant fate and transport modeling for VOCs dissolved in groundwater using MT3DMS-5.3, (5) estimating the volume of light nonaqueous phase liquid (LNAPL) released to the subsurface at the Hadnot Point Industrial Area using TechNAPLVol, (6) analysis of LNAPL and dissolved phase fate and transport using TechFlowMP, (7) reconstruction of water-supply well concentrations at the Hadnot Point landfill using the linear control theory model (LCM) TechControl, (8) computation of

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[5] Oak Ridge Institute for Science and Education, Oak Ridge, Tennessee; formerly with Georgia Institute of Technology, School of Civil and Environmental Engineering, Atlanta, Georgia.

[6] W.M. Grayman Consulting Engineer, Cincinnati, Ohio.

[7] For this study, finished water is defined as groundwater that has undergone treatment at a water treatment plant and was subsequently delivered to a family housing unit or other facility. Throughout this report and the Hadnot Point–Holcomb Boulevard report series, the term finished water is used in place of terms such as finished drinking water, drinking water, treated water, or tap water.

flow-weighted average concentrations of VOCs assigned to finished water delivered by the HPWTP using a materials mass balance (simple mixing) model, (9) extended period simulation of hydraulics and water quality of the Holcomb Boulevard water-distribution system using EPANET 2, (10) sensitivity analysis of hydraulic, fate and transport, and numerical-model parameter values, (11) uncertainty analysis by coupling Kalman filtering with Monte Carlo simulation within the LCM methodology, and (12) probabilistic analysis of intermittent connections (1972–1985) of the Hadnot Point and Holcomb Boulevard water-distribution systems using the TechMarkov-Chain model.[8] The end result of the historical reconstruction process was the estimation of monthly mean concentrations of selected VOCs in finished water distributed to housing areas served by the HPWTP and HBWTP.

Historical reconstruction results summarized herein provide considerable evidence that concentrations of several contaminants of interest in finished water delivered by the HPWTP substantially exceeded current maximum contaminant levels (MCLs) during all or much of the epidemiological study period of 1968–1985. Reconstructed concentrations of TCE exceeded the current MCL of 5 micrograms per liter (µg/L) prior to and during the entire epidemiological study period and reached a maximum reconstructed concentration of 783 µg/L during November 1983. The most likely date that TCE first exceeded its current MCL is during August 1953; however, this exceedance could have been as early as November 1948. Corresponding finished-water concentrations of PCE exceeded the current MCL of 5 µg/L during most of the period 1975–1985 and also reached a maximum concentration of 39 µg/L during November 1983. Similar results for 1,2-tDCE and VC were also noted during the period 1975–1985. The maximum reconstructed concentrations of 1,2-tDCE and VC were 435 and 67 µg/L, respectively, and also occurred during November 1983. The respective current MCLs for these contaminants are 100 and 2.0 µg/L.

Substantial volumes of liquid hydrocarbon fuels were lost due to leakage to the subsurface within the Hadnot Point Industrial Area. This area contained as many as 10 active water-supply wells. Despite the large volumes lost, finished-water concentrations of benzene only slightly exceeded the current MCL of 5 µg/L during the period 1980–1985. The maximum reconstructed concentration of 12 µg/L of benzene occurred during April 1984.

Within the HBWTP service area, only TCE routinely exceeded its current MCL during intermittent periods (1972–1985). The TCE resulted from transfers of finished water from the Hadnot Point water-distribution system to the Holcomb Boulevard water-distribution system. The maximum reconstructed TCE concentration of 51 µg/L occurred during June 1978 at the Berkeley Manor housing area. During the 8-day period of January 28 through February 4, 1985, the HBWTP was out of service, and the HPWTP continuously supplied finished water to the Holcomb Boulevard housing area. During this period, the maximum reconstructed TCE concentration at the HPWTP was 324 µg/L, which resulted in a maximum reconstructed monthly mean concentration of 66 µg/L within the Paradise Point housing area.

Introduction

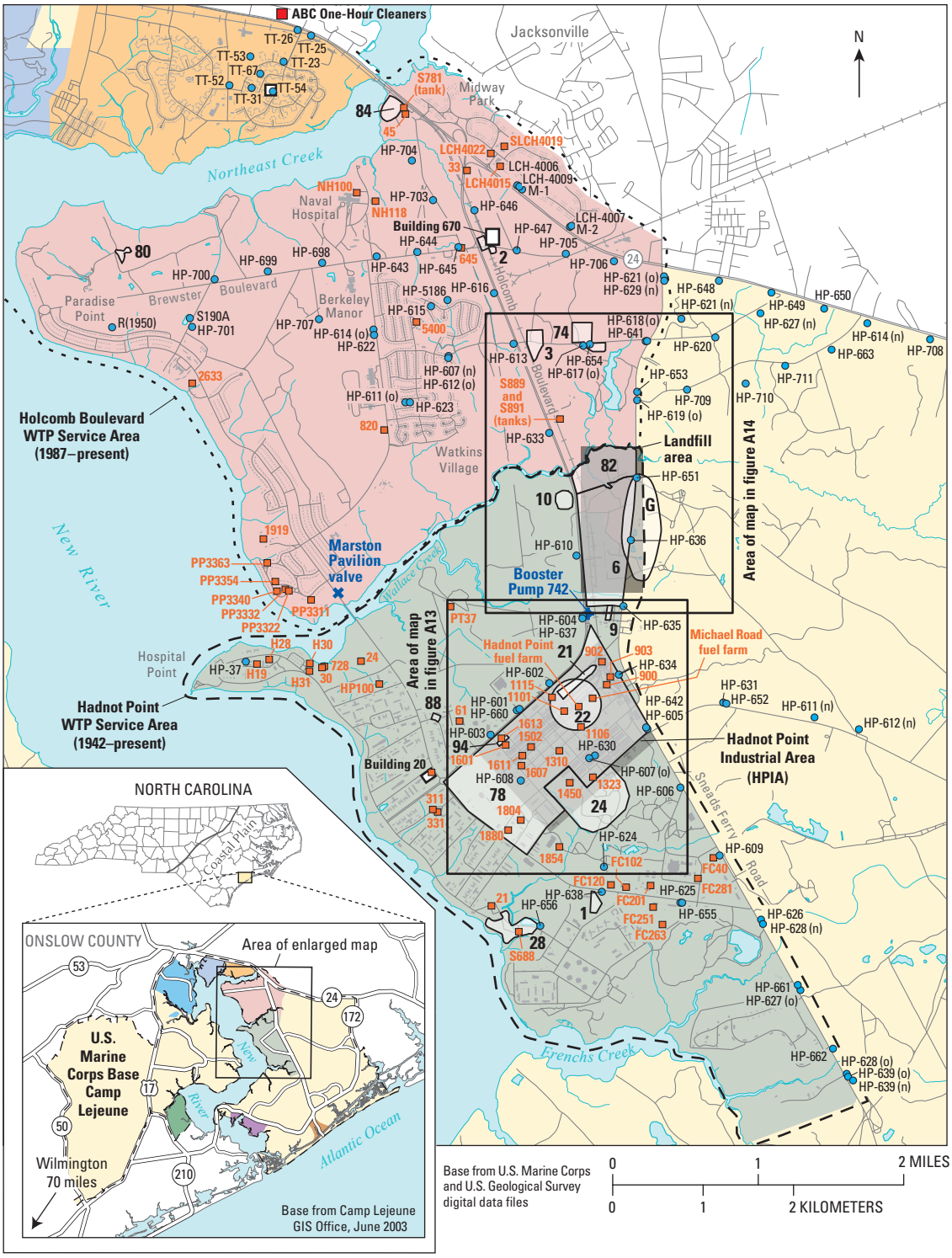
The Agency for Toxic Substances and Disease Registry (ATSDR), an agency of the U.S. Department of Health and Human Services, is conducting epidemiological studies to evaluate the potential for health effects from exposures to finished water contaminated with volatile organic compounds (VOCs) at U.S. Marine Corps Base Camp Lejeune (USMCB Camp Lejeune), North Carolina (Figure A1).[9] The epidemiological studies require estimates or direct knowledge of contaminant concentrations in finished water at monthly intervals. When direct, past knowledge of contaminant concentrations in finished water is limited or unavailable, historical reconstruction is used to provide estimates of contaminant concentrations. At USMCB Camp Lejeune, historical reconstruction methods include linking materials mass balance (mixing) and water-distribution system models to groundwater-flow and contaminant fate and transport models (Maslia et al. 2007, 2009a). Results obtained from the historical reconstruction process, along with household information regarding water use and consumption, can be used in the epidemiological studies to estimate the level and duration of contaminant exposures. To support these studies, the historical reconstruction covers the period 1942–2008. The first year, 1942, was chosen because operations at USMCB Camp Lejeune began in late 1941. The last year, 2008, was chosen to take advantage of more recent water-supply well operational data and contaminant concentration data to assist with model calibration.

During 2007–2009, ATSDR published results summarizing the historical reconstruction of contaminants delivered in finished water to Tarawa Terrace family housing areas and vicinity (herein referred to as the Tarawa Terrace [TT] study area).[10] Several reports summarize the historical reconstruction of contaminant concentrations delivered by the Hadnot Point water treatment plant (HPWTP) and the Holcomb Boulevard water-distribution system (herein referred to as the study area or the HPHB study area). This report, Chapter A: Summary and Findings, is one report of that series and summarizes analyses and results of reconstructed VOC-contaminant concentrations in water-supply wells and in finished water within the HPHB study area.

[8] Specific details pertaining to each of the aforementioned methods and models are provided in the supplements to this report, located on the accompanying CD–ROM.

[9] For a larger map showing water-supply wells, monitor wells, boreholes, and water-distribution system appurtenances, refer to Faye et al. (2010, Plate 1).

[10] The Tarawa Terrace (TT) study area reports are available on the ATSDR Camp Lejeune Web site at *http://www.atsdr.cdc.gov/sites/lejeune/index.html*.



EXPLANATION

Historical water-supply areas of Camp Lejeune Military Reservation

- Montford Point
- Tarawa Terrace
- Holcomb Boulevard
- Hadnot Point
- New River Air Station
- Rifle Range
- Courthouse Bay
- Onslow Beach
- **Other areas of Camp Lejeune Military Reservation**

Contamination sites

- 28 — **CERCLA** (Comprehensive Environmental Response, Compensation, and Liability Act of 1980)—Installation Restoration Program site and identification number (refer to Faye et al. 2010)
- 1115 — **RCRA** (Resource Conservation and Recovery Act of 1976)—Above-ground and underground storage tank site and identifier (refer to Faye et al. 2012)

Water treatment plant (WTP)

- **Name and length of operation**
  - Hadnot Point: 1942–present
  - Holcomb Boulevard: June 1972–present
  - Tarawa Terrace: 1952–1987
- HP-608 — **Water-supply well and identifier**

Figure A1. The Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Purpose of this Report

Results of water-modeling investigations as well as several preliminary studies and investigations necessary for the completion of water-modeling analyses and the historical reconstruction process are summarized in this Chapter A report (Summary and Findings). Supporting information and data are published in Chapters B (Faye 2012), C (Faye et al. 2010), and D (Faye et al. 2012), and detailed analyses are provided in the supplemental sections (Supplements 1–8) included as part of this Chapter A.

Completion of these chapters and supplemental reports required the discovery and extraction of data contained in tens of thousands of documents from numerous sources including USMCB Camp Lejeune, the Department of the Navy (DON), the North Carolina Department of Environment and Natural Resources (NCDENR), the U.S. Environmental Protection Agency (USEPA), and the U.S. Geological Survey (USGS). Accordingly, this Chapter A report includes a description of the methods and approaches of identifying information sources and data mining.

Description of Hadnot Point–Holcomb Boulevard Study Area Reports

The development and calibration of groundwater-flow, contaminant fate and transport, and water-distribution system models are integral to the historical reconstruction processes. They also require substantial preliminary analyses and interpretation of relevant data. These are documented in a series of reports that provide comprehensive descriptions of the information, data, and methods used to conduct the historical reconstruction for the HPHB study area. Additional reports were prepared that describe the development and calibration of several water models and related simulation results. Table A1 lists the title and authorship and summarizes the content of four chapter reports (A–D) and eight supplemental information sections. The supplemental information sections are included as part of this Chapter A.[11] Figure A2 shows the

[11] For purposes of referencing the supplemental information texts in this Chapter A report, the author–date format is used. For example, Chapter A–Supplement 1 is referenced as Sautner et al. (2013a) and Chapter A–Supplement 6 is referenced as Jones et al. (2013). Complete reference citations are listed in the References section of this Chapter A report.

Table A1. Summary of ATSDR chapter reports and supplemental information sections, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[ATSDR, Agency for Toxic Substances and Disease Registry; PCE, tetrachloroethylene; TCE, trichloroethylene; LNAPL, light nonaqueous phase liquid; IRP, Installation Restoration Program; WTP, water treatment plant; RCRA, Resource Conservation and Recovery Act of 1976; BTEX, benzene, toluene, ethylbenzene, and xylenes]

[1]Report chapter	[2]Authors and reference	Chapter or supplemental information section title	Topical summary
A	Maslia ML, Suárez-Soto RJ, Sautner JB, Anderson BA, Jones LE, Faye RE, Aral MM, Guan J, Jang W, Telci IT, Grayman WM, Bove FJ, Ruckart PZ, and Moore SM (Maslia et al. 2013)	Summary and Findings	Summary of detailed technical findings (found in Supplements 1–8 and Chapters B–D) focusing on historical reconstruction analyses and present-day conditions of groundwater flow, contaminant fate and transport, and distribution of finished water
A–Supplement 1	Sautner JB, Anderson BA, Suárez-Soto RJ, and Maslia ML (Sautner et al. 2013a)	Descriptions and Characterizations of Data Pertinent to Water-Supply Well Capacities, Histories, and Operations	A comprehensive listing and analysis of historical through June 2008 water-supply wells, their capacities, operational histories, and supply of finished water
A–Supplement 2	Telci IT, Sautner JB, Suárez-Soto RJ, Anderson BA, Maslia ML, and Aral MM (Telci et al. 2013)	Development and Application of a Methodology to Characterize Present-Day and Historical Water-Supply Well Operations	Describes a method that uses recorded data, other ancillary information, and a training algorithm to synthesize monthly water-supply well operations, 1942–2008
A–Supplement 3	Faye RE, Jones LE, and Suárez-Soto, RJ (Faye et al. 2013)	Descriptions and Characterizations of Water-Level Data and Groundwater Flow for the Brewster Boulevard and Castle Hayne Aquifer Systems and the Tarawa Terrace Aquifer	Describes water-level data for the Brewster Boulevard and Castle Hayne aquifer systems and Tarawa Terrace aquifer, analyzes water-level trends, and presents a potentiometric surface map derived from the water-level data and resulting groundwater-flow directions
A–Supplement 4	Suárez-Soto RJ, Jones LE, and Maslia ML (Suárez-Soto et al. 2013)	Simulation of Three-Dimensional Groundwater Flow	Describes the application and calibration of a three-dimensional groundwater-flow model used to simulate steady-state (predevelopment) and transient groundwater flow for the period 1942–2008

Table A1. Summary of ATSDR chapter reports and supplemental information sections, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[ATSDR, Agency for Toxic Substances and Disease Registry; PCE, tetrachloroethylene; TCE, trichloroethylene; LNAPL, light nonaqueous phase liquid; IRP, Installation Restoration Program; WTP, water treatment plant; RCRA, Resource Conservation and Recovery Act of 1976; BTEX, benzene, toluene, ethylbenzene, and xylenes]

[1]Report chapter	[2]Authors and reference	Chapter or supplemental information section title	Topical summary
A–Supplement 5	Guan J, Anderson BA, Aral MM, and Maslia ML (Guan et al. 2013)	Theory, Development, and Application of Linear Control Model Methodology to Reconstruct Historical Contaminant Concentrations at Selected Water-Supply Wells	Describes the model developed using linear control theory that is capable of reconstructing historical contaminant concentrations using limited geohydrologic and aquifer information; model is applied to water-supply well HP-651 in the Hadnot Point landfill area
A–Supplement 6	Jones LE, Suárez-Soto RJ, Anderson BA, and Maslia ML (Jones et al. 2013)	Source Characterization and Simulation of Fate and Transport of Selected Volatile Organic Compounds in the Vicinities of the Hadnot Point Industrial Area and Landfill	Describes the application and calibration of three-dimensional models of contaminant fate and transport used to reconstruct historical groundwater concentrations of PCE, TCE, and benzene in the vicinity of the Hadnot Point Industrial Area and landfill area for the period 1942–2008
A–Supplement 7	Jang W, Anderson BA, Suárez-Soto RJ, Aral MM, and Maslia ML (Jang et al. 2013)	Source Characterization and Simulation of the Migration of Light Nonaqueous Phase Liquids (LNAPLs) in the Vicinity of the Hadnot Point Industrial Area	Describes the estimation of LNAPL volume in the subsurface and the development and application of a three-dimensional contaminant fate and transport model used to simulate LNAPL and dissolved-phase benzene in the vicinity of the Hadnot Point Industrial Area for the period 1942–2008
A–Supplement 8	Sautner JB, Grayman WM, Telci IT, Maslia ML, and Aral MM (Sautner et al. 2013b)	Field Tests, Data Analyses, and Simulation of the Distribution of Drinking Water with Emphasis on Intermittent Transfers of Drinking Water Between the Hadnot Point and Holcomb Boulevard Water-Distribution Systems	Describes field tests conducted and data gathered during 2004 for the Hadnot Point and Holcomb Boulevard water-distribution systems and simulations of the intermittent supply of Hadnot Point finished water to the Holcomb Boulevard water-distribution system during the period 1972–1985
B	Faye RE (Faye 2012)	Geohydrologic Framework of the Brewster Boulevard and Castle Hayne Aquifer Systems and the Tarawa Terrace Aquifer	Describes detailed analyses of well, borehole, and geophysical data used to develop the geohydrologic framework of the Brewster Boulevard and Castle Hayne aquifer systems and the Tarawa Terrace aquifer; hydraulic characteristics for several geohydrologic units are tabulated; hydraulic conductivity maps are included
C	Faye RE, Anderson BA, Suárez-Soto RJ, and Sautner JB (Faye et al. 2010)	Occurrence of Selected Contaminants in Groundwater at Installation Restoration Program Sites	Detailed accounting of the occurrences of contaminants of concern and their related degradation products in groundwater at IRP sites within the service areas of the Hadnot Point and Holcomb Boulevard WTPs
D	Faye RE, Suárez-Soto RJ, and Maslia ML (Faye et al. 2012)	Occurrence of Selected Contaminants in Groundwater at Above-Ground and Underground Storage Tank Sites	Summaries of RCRA investigations with detailed accounting of the occurrence and distribution of BTEX components, such as benzene, within the soil and groundwater at selected RCRA sites within the service areas of the Hadnot Point and Holcomb Boulevard WTPs

[1] Letter designation of chapters for series, "Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina;" supplemental information sections are part of Chapter A, provided on CD–ROM

[2] See References section for complete reference citation

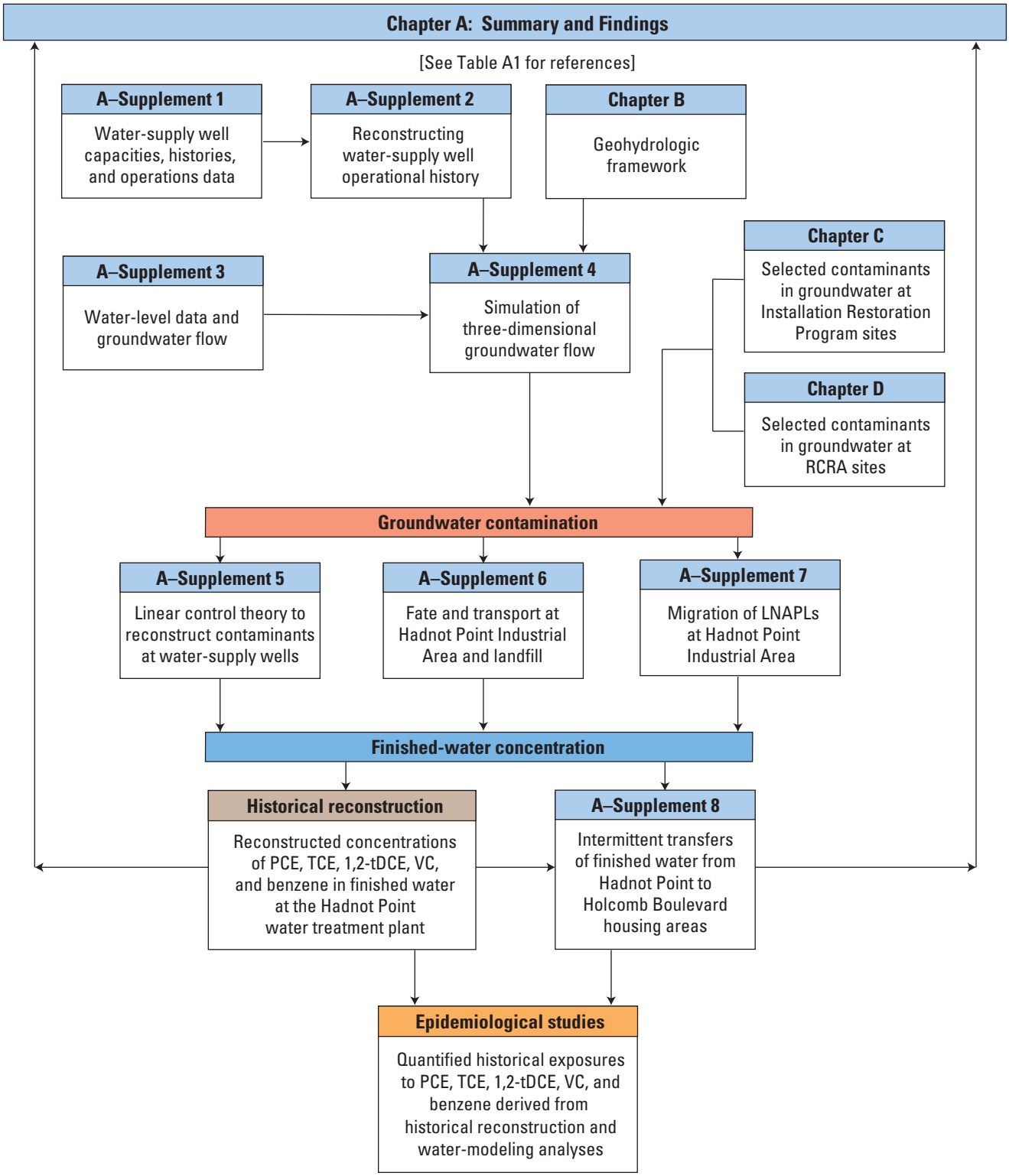


Figure A2. Relation among Chapter A report (Summary and Findings), Chapter A supplements (1–8), Chapters B–D reports, historical reconstruction process, and the ATSDR epidemiological studies, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. [RCRA, Resource Conservation and Recovery Act of 1976; LNAPL, light nonaqueous phase liquid; PCE, tetrachloroethylene; TCE, trichloroethylene; 1,2-tDCE, *trans*-1,2-dichloroethylene; VC, vinyl chloride]

relation of the Chapter reports and supplemental information sections to the overall process of historical reconstruction. Chapters B–D present detailed descriptions of a geohydrologic framework and selected contaminants in groundwater at Installation Restoration Program (IRP) and above-ground and underground storage tank (AST/UST) sites within the HPHB study area. Supplemental information sections 1–8 present detailed analyses and interpretations of data pertinent to groundwater flow, contaminant fate and transport, and the intermittent transfer of contaminated finished water from the HPWTP to the Holcomb Boulevard water-distribution system. Summaries of each chapter report and supplemental information section are provided in Appendix A1. Readers interested in details of a specific topic, for example, the geohydrologic framework for the study area, groundwater-flow model development, model-calibration procedures, or synoptic maps showing groundwater migration of benzene from the Hadnot Point fuel farm, should consult the appropriate chapter report or supplemental information section (Table A1, Appendix A1). Also provided with this Chapter A report is a compact disc–read-only memory (CD–ROM) containing all chapter reports (A–D) and supplemental information sections (1–8). Electronic versions of each chapter report including this Chapter A report and supporting information and data will be made available on the ATSDR USMCB Camp Lejeune Web site at *http://www.atsdr.cdc.gov/sites/lejeune/index.html*.

Background

USMCB 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 A1). In general, the HPHB study area is bordered on the north by Northeast Creek and North Carolina Highway 24 (SR 24), to the west by New River, to the south by Frenchs Creek, and generally to the east by the drainage divides of upstream tributaries of Wallace and Frenchs Creeks. Operations began at USMCB Camp Lejeune during late 1941 (Watson 1995).

Eight water-distribution systems have supplied or currently (2013) are supplying finished water to family housing and other facilities at USMCB Camp Lejeune, North Carolina (Figure A1). The three water-distribution systems of interest to this study—Tarawa Terrace, Hadnot Point, and Holcomb Boulevard—have historically supplied finished water to the majority of family housing units at the Base. Two of the three water-distribution systems were contaminated with VOCs. Groundwater within the Tarawa Terrace WTP service area was contaminated mostly with tetrachloroethylene (PCE). Groundwater within the HPWTP service area was contaminated with trichloroethylene (TCE), PCE, and refined petroleum products, such as benzene, toluene, ethylbenzene, and xylenes (BTEX). Groundwater within the Holcomb Boulevard WTP (HBWTP) service area remained largely uncontaminated except for intermittent supply by contaminated Hadnot Point water during years 1972–1985. Historical base operations and waste-disposal practices at USMCB Camp Lejeune have been identified as responsible for contamination of groundwater and finished-water supplies within the HPHB study area (Faye et al. 2010, 2012).

Information Sources and Data Mining

Substantial effort and resources were dedicated to the task of identifying information sources and extracting data because of the voluminous and disparate sources of information and data pertinent to the HPHB study area. The purpose was to obtain information and data that could be extracted and transformed into digital databases in order to conduct historical reconstruction analyses. To assist in locating information sources at USMCB Camp Lejeune and at other DON facilities, ATSDR and the DON developed a joint technical workgroup during 2010; the specific purpose and goals of the workgroup are detailed in the workgroup charge (U.S. DON and ATSDR 2012).[12]

By its very nature, information discovery and data mining is not an exact process that can be used or relied upon to identify a single, specific piece of information or data point. Nor can this process be used to state unequivocally that every piece of information or every data point has been obtained, viewed, categorized, or interpreted. However, it is important to describe the process so others can judge the adequacy of the effort.

Numerous information sources were identified, located, and assessed prior to extracting usable model-specific data. Once pertinent model-specific data were identified and extracted, they had to be entered into digital databases. Computer model-specific input databases were then developed from these digital databases. A list of information and data sources used to develop model-input databases for the HPHB study area is provided in Appendix A2. The numerous and disparate information sources and databases listed in Appendix A2 are grouped into seven general categories listed below along with examples of pertinent information sources or data within each category.

1. *ATSDR information requests and selected authored reports*: Historical water-supply well data from wellhead management program investigations and reports (Geophex Ltd. 1991; AH Environmental Consultants 2002);

[12] The DON-ATSDR Data Mining Technical Work Group met periodically either in person or by conference call during the period June 2010–August 2011. Summaries of those meetings are available on the ATSDR Camp Lejeune Web site at *http://www.atsdr.cdc.gov/sites/lejeune/data_mining_workgroup.html*.

2. *Databases and information portals*: USMCB Camp Lejeune historic drinking water document repository (CLHDW CDR 2011), underground storage tank (UST) files (UST Web Management Portal 2010–2012), TerraBase, and analytical data associated with Base IRP provided to Catlin Engineers and Scientists by USMCB Camp Lejeune (John R. Townson, USMCB Camp Lejeune, written communication, April 9, 2010);[13, 14]

3. *Drinking-water system information and data*: Reports on drinking-water systems at USMCB Camp Lejeune (AH Environmental Consultants 2001, 2002, 2004a, b, c, 2005), and historical water utility maps for 1956–1987 (Environmental Management Division, Camp Lejeune, written communication, July 2006);

4. *Housing records and information*: Historical paper maps showing housing units, additions to housing units, and estimated number of housing units for the 1940s–1990s (USMCB Camp Lejeune, written communications, date unknown; see footnotes in Faye et al. [2010], Table C1);

5. *Map information and data*: Digital topographic contour maps (USGS, North Carolina Water Science Center, written communication, February 2004) and AutoCAD™ files of USMCB Camp Lejeune features such as topography, utility lines, water-distribution systems, and housing locations (Environmental Management Division, Camp Lejeune, written communication, October 2003; Central Coastal Plain Capacity Use Investigation Report [NCDENR 1998]);

6. *North Carolina documents and reports*: Detailed soil maps for Onslow County, North Carolina (North Carolina Center for Geographic Information Analysis, written communications, November 2003); and

7. *Miscellaneous information, data, and reports*: Precipitation and evaporation data for the Hoffman/Maysville station, North Carolina (National Climatic Data Center 1945–2008), USGS open files on well locations, and water use at USMCB Camp Lejeune (USGS, North Carolina Water Science Center, written communication, March 2004).

The majority of the information sources listed in Appendix A2 were not in readily usable digital format that could be directly used for developing input databases for modeling. Rather, a time-consuming process was required to extract pertinent and usable information. This process consisted of determining potentially pertinent documents and information, reviewing pertinent documents, manually extracting data (in most cases), and then entering these data into digital databases. A generalized three-stage process was developed for reviewing, assessing, and extracting information and data. This process is shown graphically in Figure A3 and described below.

- *Stage 1*: A cursory review was conducted to determine if a particular source of information or data referred to the HPHB study area; if not, the information source or data was noted and not reviewed;

- *Stage 2*: Information sources and data pertinent to the HPHB study area were filtered by content and subject matter (e.g., remedial investigation, lab analysis). Depending on the content and subject matter, certain files were not reviewed in detail (e.g., meeting notes), whereas other files were promoted to a stage 3 review (e.g., site characterization data, laboratory analyses, groundwater-level data); and

- *Stage 3*: If a file contained certain key words or dates (e.g., water supply, VOC, benzene, underground storage tank, 1984), it was reviewed in detail by subject matter experts. Pertinent information and data were identified, and contract staff extracted the information and data and entered it into digital databases. Then, data were extracted from the digital databases and prepared appropriate model-input databases.[15] It is important to note, however, that even with the aforementioned, three-stage review process, because of the volume of information, not every document was reviewed, nor was every page of every document reviewed unless such a review was determined to be critical to extracting information and data pertinent to the historical reconstruction process and specifically to computer model-specific input database development. For example, daily water-supply well operational data available during 1999–2008 consisted of 10,000 pages of pertinent information, all of which were reviewed, evaluated, and transcribed to digital data (Appendix A2).

The types of data reviewed to develop databases and model-input data are listed by category in Table A2. Also listed are approximate numbers of data values extracted from the information sources. Comparison with the number of data values reviewed and extracted from information sources for the TT study area analyses (Maslia et al. 2007) indicates a ten- to twenty-fold increase in the numbers of relevant data. For example, 4,104 groundwater samples were analyzed for chlorinated solvents (PCE, TCE, dichloroethylene [DCE],[16] and vinyl chloride [VC]) for the HPHB study area compared with 192 groundwater samples for the TT study area. Similarly,

[13] TerraBase is an intuitive, structure query language-compliant relational database application designed for environmental professionals and managers who need to assess and manage chemical, geological, and spatial data; see *http://www.terrabase.com*.

[14] Certain documents have been provided to ATSDR by the Department of the Navy (Headquarters Marine Corps, Eastern Area Counsel Office, and Marine Corps Base Camp Lejeune) under terms of "For Official Use Only" (FOUO) documents. Some of these documents are not releasable by ATSDR under the terms of FOUO.

[15] Refer to the report section on Historical Reconstruction Methods and Approaches for a description of specific models applied to the HPHB study area.

[16] DCE or dichloroethylene is the common name of a group of VOCs that include: 1,1-dichloroethylene (1,1-DCE), *trans*-1,2-DCE (1,2-tDCE), and *cis*-1,2-DCE (1,2-cDCE). Refer to Lawrence (2007), Faye and Green (2007), and Faye et al. (2010).

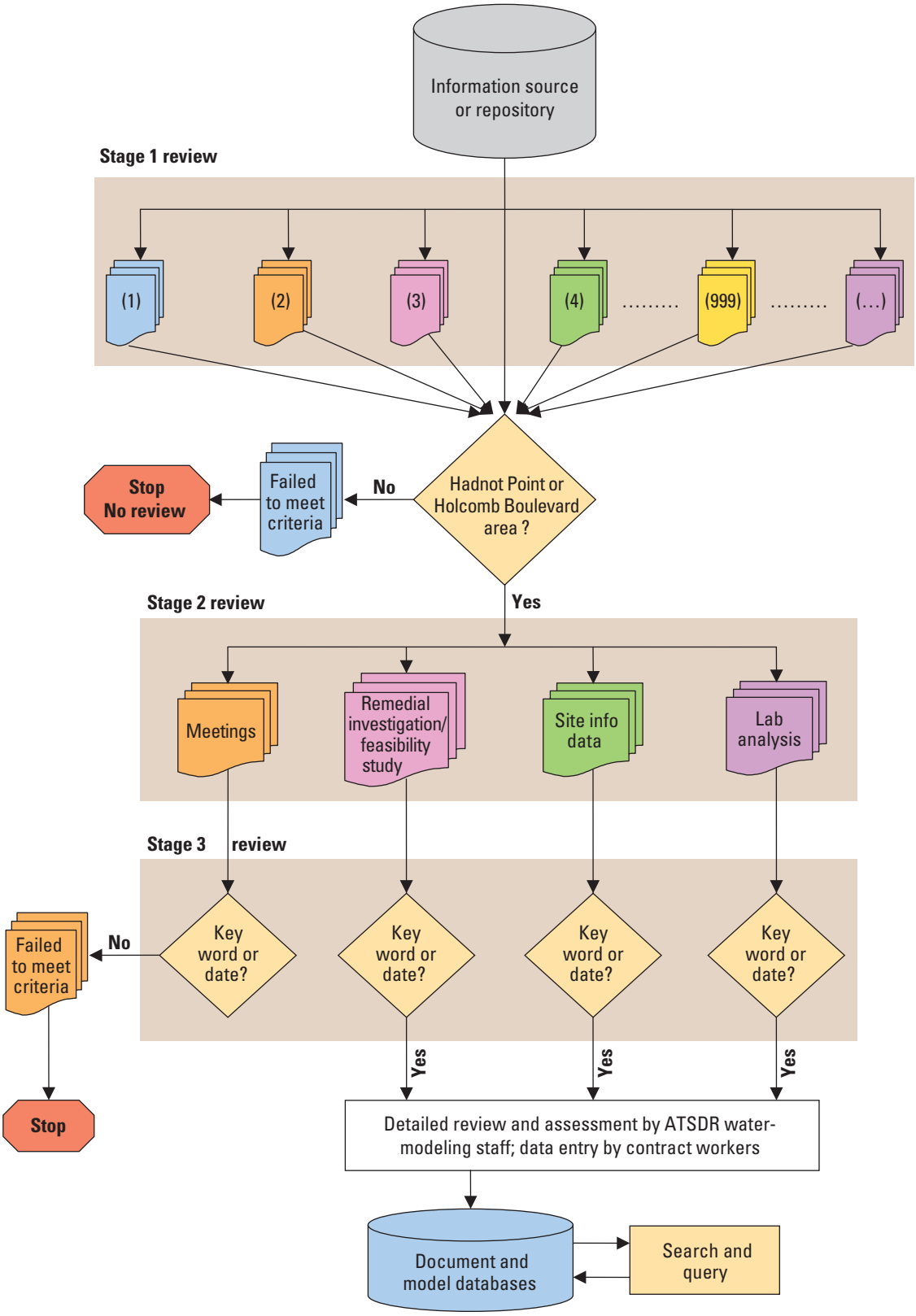


Figure A3. Three-stage process used for identifying relevant information and extracting data for database and model development, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Table A2. Number and type of data extracted from information sources and reviewed for historical reconstruction analyses, Hadnot Point–Holcomb Boulevard and Tarawa Terrace study areas, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[PCE, tetrachloroethylene; TCE, trichloroethylene; DCE, dichloroethylene; VC, vinyl chloride; BTEX, benzene, toluene, ethylbenzene, and xylenes; MCL, maximum contaminant level]

Data category	Approximate number of data values for study area	
	Hadnot Point–Holcomb Boulevard	Tarawa Terrace
Wells, hydropunch points, and boreholes	1,979	222
Water-level measurements	13,833	789
Groundwater samples analyzed for chlorinated solvents (PCE, TCE, DCE, VC)	4,104	192
Groundwater samples analyzed for BTEX	6,433	191
Supply-well and monitor-well aquifer and slug tests	264	33
Water-supply wells analyzed for operational history	[1]100	[2]16
Historically contaminated water-supply wells (concentration exceeding current the MCL)	12	5
Contaminant source areas characterized	23	1
Number of source contaminants[3]	3	1

[1] Hadnot Point and Holcomb Boulevard water-supply wells: 72 wells for Hadnot Point and 24 wells for Holcomb Boulevard; 1 well (HP-656) never put into service; 1 well (HP-37) was emergency standby for Naval Hospital; 2 wells [R(1950) and S-190A] used for golf course irrigation (see Figure A5)

[2] Tarawa Terrace water-supply wells: 3 wells (#6, #7, and TT-45) external to Tarawa Terrace groundwater-flow model domain, but provided raw water to Tarawa Terrace Water Treatment Plant (see Maslia et al. 2007)

[3] For Hadnot Point–Holcomb Boulevard study area, source contaminants are PCE, TCE, and benzene; for Tarawa Terrace study area, source contaminant is PCE

13,833 water-level measurements were extracted from data sources for the HPHB study area compared to only 789 water-level measurements available for the TT study area. For the HPHB study area, data were extracted to compile operational chronologies for nearly 100 supply wells compared to only 16 water-supply well operational chronologies for the TT study area. The substantive increase in the numbers of data values for the HPHB study area compared to the TT study area (Table A2) are indicative of the increase in complexity and difficulty of reconstructing historical contaminant concentrations for the HPHB study area. This point is further highlighted given the multiple source contaminants (3) and numerous contaminant source areas (23) requiring identification and characterization for the HPHB study area as described in Faye et al. (2010, 2012) and discussed in subsequent sections of this report.

Base Housing and Water Supply

USMCB Camp Lejeune consists of 15 different housing areas; families live in base housing for an average of 2 years. Family housing areas currently (2013) served by the HPWTP and HBWTP are Berkeley Manor, Hospital Point, Midway Park, Paradise Point, and Watkins Village (Figure A1).

Construction of family housing at USMCB Camp Lejeune began in 1942, in conjunction with other major infrastructure components at the Base, such as roads, WTPs, and the water-distribution network. Midway Park and Paradise Point were the first housing units constructed, followed in 1947 by Hospital Point Housing, Berkeley Manor in 1961, and Watkins Village in 1978. Housing at Paradise Point was improved and expanded during 1947, 1948, and 1962 (Scott R. Williams, USMCB Camp Lejeune, electronic communication, September 3, 2008). A chronology of family housing unit construction and contemporary population is provided in Faye et al. (2010, Table C1). Family housing occupancy rate was 95 percent or greater in 1998 (ECG, Inc. 1999), and similar rates probably have prevailed at USMCB Camp Lejeune since the Base was established. Thus, since 1963, the population of family housing in the study area has been continuously maintained at about 4,000 to 8,000 residents, depending on the number of available housing units (Faye et al. 2010).

In 1999, the number of occupants of bachelor housing in the study area totaled 13,427 personnel. Of these, 13,129 personnel were served by the HPWTP (ECG, Inc. 1999). The resident bachelor population includes permanently assigned personnel as well as a substantial number of short-term transient personnel and, as such, probably varies substantially from month to month and year to year. Bachelor housing in the study area is located in the vicinity of Hadnot Point between River Road/Julian C. Smith Road and McHugh Boulevard (Faye et al. 2010, Plate 1). Currently (2013) there are 52 bachelor housing units that can house about 14,300 Marines (C.M. Rychak, USMCB Camp Lejeune, electronic communication, July 11, 2012; S.R. Williams, U.S. Marine Corps Headquarters, electronic communication, July 11, 2012).

A summary of water-supply well and water treatment plant construction chronology for the HPHB study area

is provided below.[17] Hadnot Point was the original water-distribution system, serving the entire Base with finished water beginning in the early 1940s. The Tarawa Terrace WTP began delivering finished water during 1952–1953, and the HBWTP began delivering finished water during June 1972 (S.A. Brewer, USMCB Camp Lejeune, written communication, September 29, 2005). Currently (2013), the HPWTP services the Hadnot Point area, and the HBWTP services the Holcomb Boulevard and Tarawa Terrace base housing areas (Figure A1).[18]

The HPWTP (Building 20; Figure A1) was constructed probably during 1941 and 1942, along with much of the original infrastructure of the Base. Original capacity of the HPWTP is unknown. However, a July 21, 1954, USMCB Camp Lejeune property record card indicates a capacity of 5 million gallons per day (MGD) (Scott R. Williams, USMCB Camp Lejeune, written communication, February 22, 2012). A December 15, 1966, memorandum from the Base maintenance officer states that "The plant has a 5,000,000 gallon per day treated water capacity . . ." (Camp Lejeune historic drinking water consolidated document repository [CLHDW CDR] File #2292, p. 1). During May 1986, the plant capacity also was reported to be 5.0 MGD (Naval Facilities Engineering Command 1986). Present-day (2013) capacity is about 5.0 MGD. Figure A4 shows graphs of WTP capacities and monthly delivered finished water in the study area during the period 1942–2008. A tabular listing of average annual rates of delivered finished water is provided in Faye et al. (2010, Table C3); tabular listings of monthly rates of delivered finished water for selected years are provided in Sautner et al. (2013b).

During 1942, the 21 original water-supply wells at USMCB Camp Lejeune (HP-601–HP-621, Figure A1) were placed into operation and provided a total combined capacity of 7.3 MGD (CLHDW CDR File #2292, p. 1). Throughout the years, additional water-supply wells were brought online to increase system capacity or to replace abandoned wells. Some of the water-supply wells were removed from service and eventually were abandoned because of contaminants found in groundwater at nearby disposal sites and in the supply wells themselves. As of June 2008, 27 wells were supplying groundwater to the HPWTP with a total combined capacity of about 5.9 MGD and a delivered groundwater (raw water) flow rate of 2.2 MGD (Sautner et al. 2013a). An operational chronology for water-supply wells in the study area during the period 1942–2008 is shown in Figure A5. This graph shows dates of operation for each well that supplied raw water to the WTPs and the dates when some of the wells were permanently taken out of service. Detailed operational and chronological information for

[17] A detailed chronology of WTPs and water-supply well construction and relevant activities is provided by Faye et al. (2010); a detailed description of water-supply well operational chronology is provided in Sautner et al. (2013a).

[18] The Tarawa Terrace WTP was shut down during 1987 due to contamination of several water-supply wells (Maslia et al. 2007).

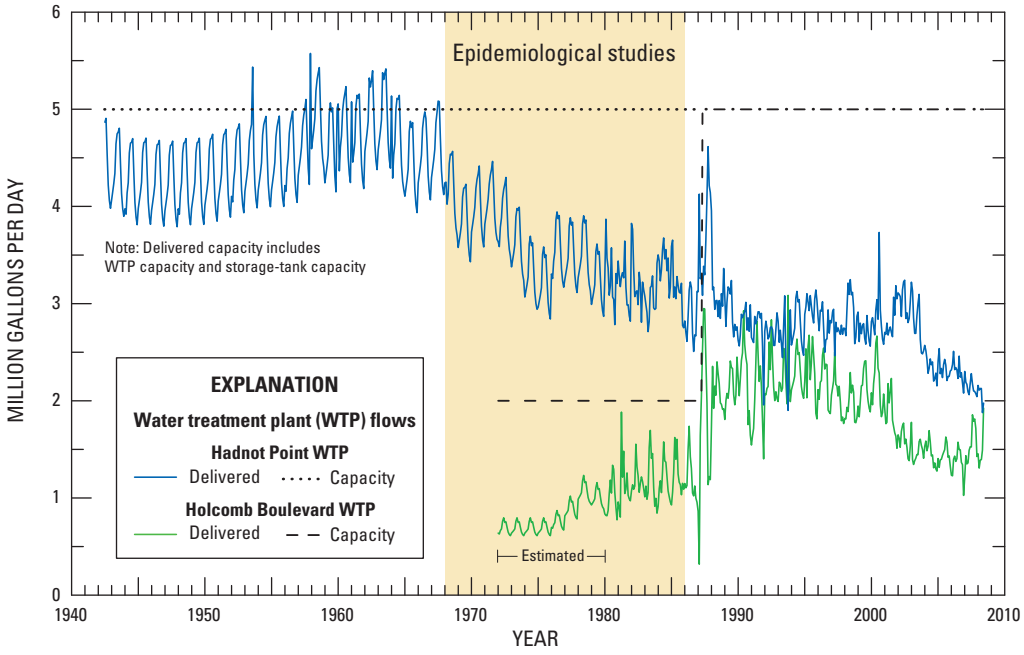


Figure A4. Water treatment plant capacity and monthly delivered finished water, in million gallons per day, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, 1942–2008. (See Sautner et al. [2013b] for details.)

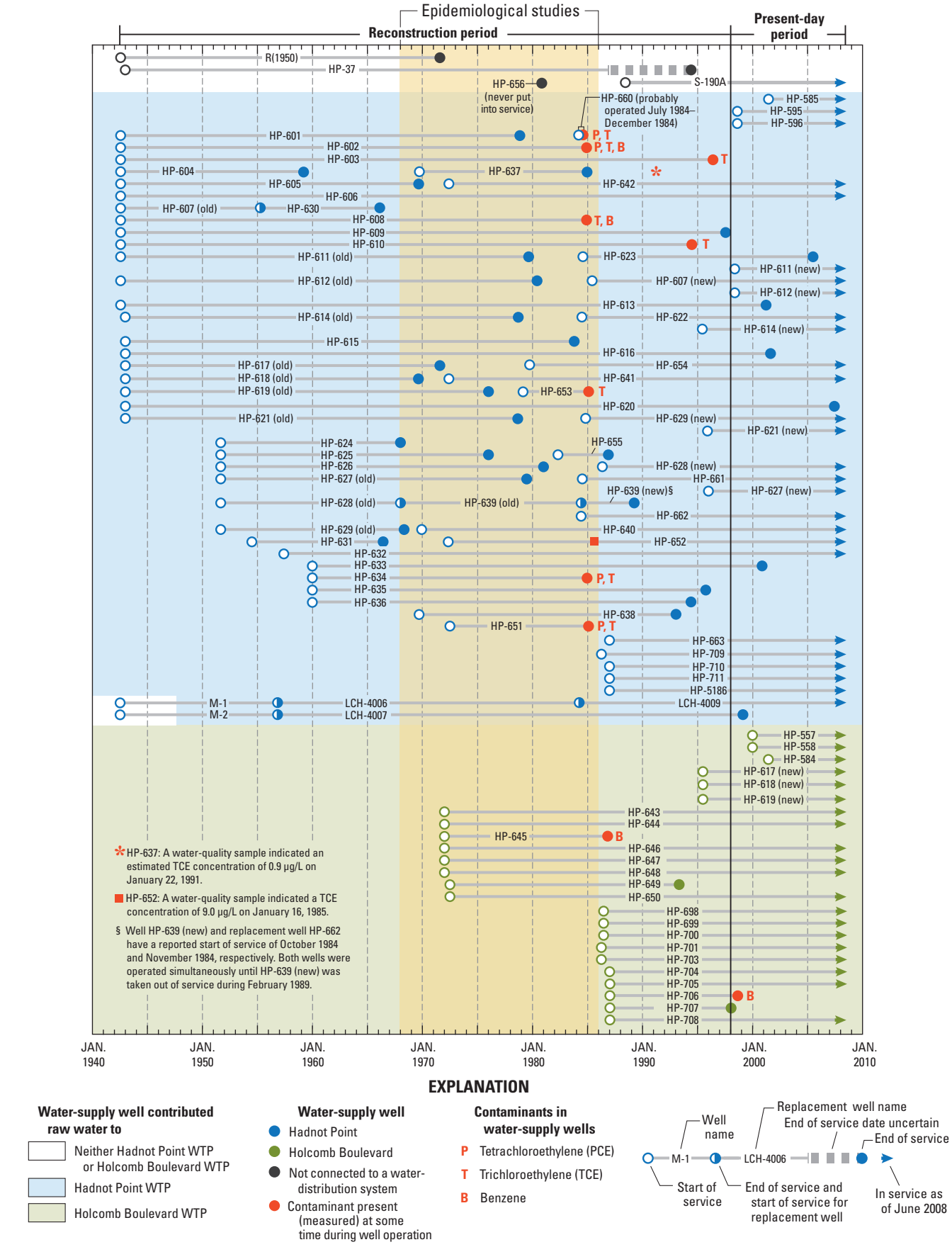


Figure A5. Operational chronology of Hadnot Point and Holcomb Boulevard water-supply wells, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, 1942–2008.

each of the 96 water-supply wells that historically have operated or were operating as of June 2008 within the HPHB study area is tabulated and provided in Sautner et al. (2013a).[19]

Until the summer of 1972, all finished water distributed to bachelor and family housing units and all other facilities within the study area was supplied by the HPWTP (Building 20). Subsequent to June 1972, finished water distributed to Berkeley Manor, Midway Park, Paradise Point, and Watkins Village family housing areas was supplied by the HBWTP (Building 670). Also included in the HBWTP service area are the current U.S. Naval Hospital, the USMCB Camp Lejeune high school, and the Brewster Boulevard junior high school (Figure A1; Faye et al. 2010, Plate 1).

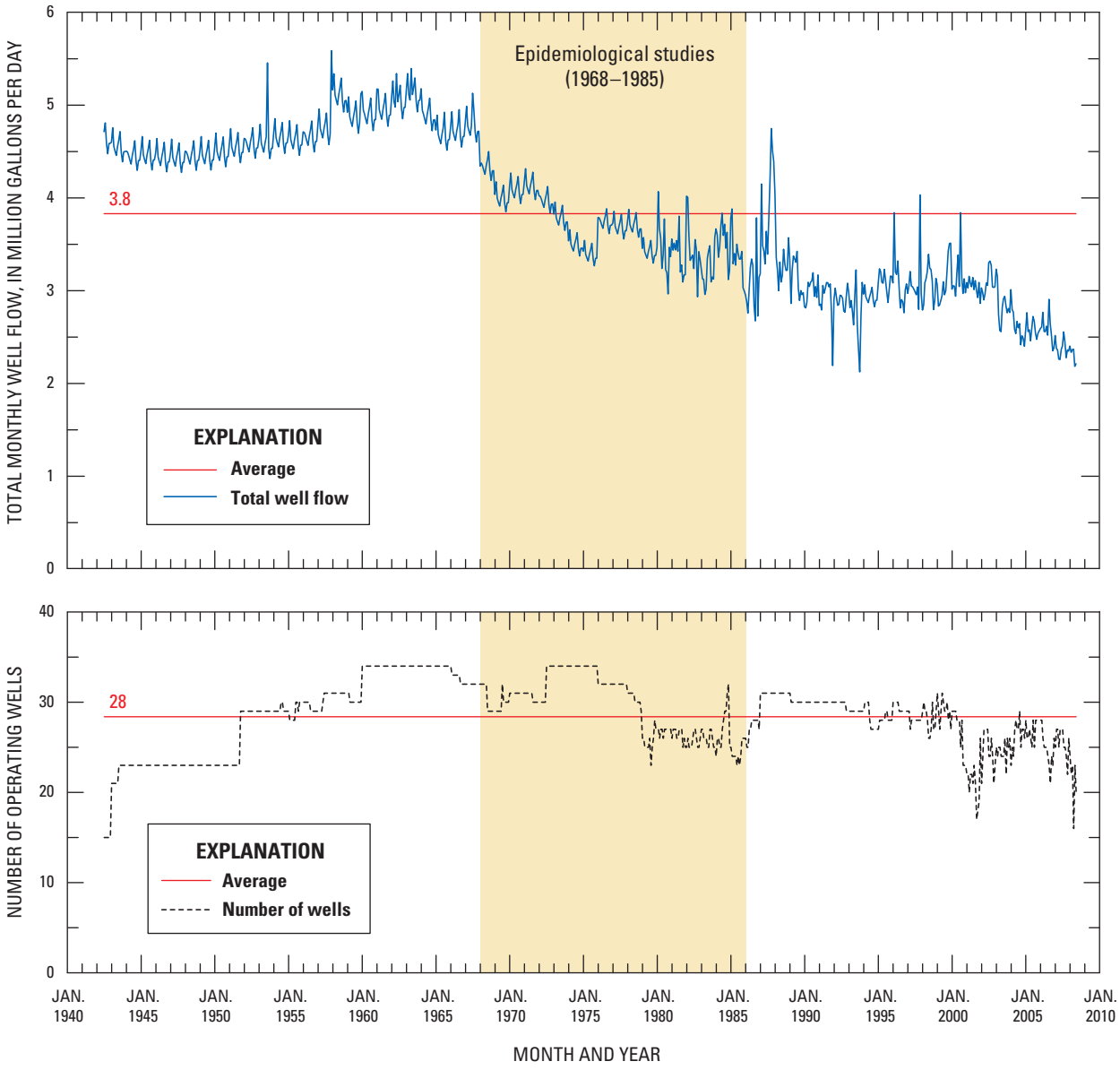
The HBWTP began operations during summer 1972 with a capacity of about 2 MGD (Scott A. Brewer, USMCB Camp Lejeune, written communication, September 29, 2005). The treatment capacity of the plant was increased to 5 MGD probably during 1986 and 1987 (Naval Facilities Engineering Command, Atlantic Division 1986, CLW #4938). Because of the discovery of several contaminated water-supply wells at Tarawa Terrace during 1985, deliveries of finished water from the HBWTP to Tarawa Terrace began during the summer of 1985. After the removal from service of all Tarawa Terrace water-supply wells during February and March 1987, the HBWTP service area was increased to include all of Tarawa Terrace family housing and the Camp Knox trailer park (Maslia et al. 2007, Plate 1). The HBWTP service area was further increased later in 1987 to include the Camp Johnson area, formerly served by the Montford Point WTP and related supply wells (Maslia et al. 2007). The increases in the HBWTP capacity and monthly delivered finished water flows during 1987 are shown in Figure A4 by the spike in the graph. The Holcomb Boulevard water-distribution system is linked to the Hadnot Point water-distribution system near McHugh Boulevard and Wallace Creek (Marston Pavilion valve) and near Holcomb Boulevard and Wallace Creek at booster pump 742 (Figure A1; Naval Facilities Engineering Command, Atlantic Division 1986; ECG, Inc. 1999).[20] For operational reasons, the two water-distribution systems are rarely connected—exceptions being some documented intermittent connections that occurred during the late spring and early summer months of 1978–1986 (Camp Lejeune water documents CLW #6774–#8761). Additional discussion of the aforementioned interconnection period is provided in this report in the section on Intermittent Transfers of Finished Water from Hadnot Point to Holcomb Boulevard and in Sautner et al. (2013b).

Eight water-supply wells (HP-643, HP-644, HP-645, HP-646, HP-647, HP-648, HP-649, and HP-650) provided raw water to the HBWTP when it began operations during the summer of 1972 (Figures A1 and A4). Additional water-supply wells were put into service when the capacity of the HBWTP was increased during 1985–1987 (Figures A4 and A5). Between 1998 and 2001, HP-557, HP-558, and HP-584 were put into service—most likely to provide additional raw water flow for the HBWTP. As of June 2008, 20 wells were supplying groundwater to the HBWTP with a total combined capacity of about 6.9 MGD and a delivered raw water flow rate of 1.9 MGD (Figures A4 and A5; see Sautner et al. [2013a] for details).

Historical reconstruction results need to be determined at monthly intervals for the purposes of the ATSDR epidemiological studies. That is because standard practice in epidemiological studies of adverse reproductive outcomes is an assessment of exposures (whether environmental, occupational, or diet risk factors) at the monthly or trimester level (Rothman et al. 2008, p. 602–603). Ideally, these analyses require monthly contaminant concentrations at water-supply wells and at the WTPs. Determining monthly concentrations at water-supply wells and at the WTPs requires groundwater pumpage data for the historical period and, in particular, the epidemiological study period of 1968–1985. Pumpage data are limited, however, and are not available on a monthly basis for the entire historical period. Figures A6 and A7 show the number of operating wells on a monthly basis supplying raw water to the WTPs. When daily and monthly well operations are known (e.g., January 1998–June 2008), the graph continuously changes on a monthly basis. When the number of operating wells and corresponding operational histories were estimated or reconstructed, the graph becomes more constant. Sautner et al. (2013a) document the operating history for each supply well providing raw water to the HPWTP and HBWTP (Figure A5), and Telci et al. (2013) describe the methodology that was used to reconstruct historical water-supply well operations during the reconstruction period. Figures A6 and A7 also provide the historical monthly well flow (documented and reconstructed) for each of the two WTPs in the study area. Based on documented and reconstructed information, an average of 28 wells supplied water each month to the HPWTP during the period 1942–2008 (Figure A6). For the HBWTP, an average of 8 wells supplied water to the WTP during the period 1972–1985, and an average of 17 wells supplied water to the HBWTP during the period 1986–2008 (Figure A7). Because raw water from all groundwater wells was mixed at the HPWTP prior to treatment and distribution to housing areas (and intermittently to the Holcomb Boulevard housing areas), the start-up and shut-down dates of specific water-supply wells are critical to accurately determining the concentration of contaminants in finished water delivered from the HPWTP. This information is provided in detail in Sautner et al. (2013a) and Telci et al. (2013).

[19] Shown on Figure A5 are 72 Hadnot Point water-supply wells, 24 Holcomb Boulevard water-supply wells, 1 well (HP-656), which was never put into service, 1 well (HP-37), used as an emergency standby well for the Naval Hospital, and wells R(1950) and S-190A used for golf course irrigation. Thus, out of 100 total wells, 96 supplied water to the HPWTP and HBWTP.

[20] Booster pump 742 was removed during 2007, but the two systems can still be interconnected by opening a valve at the same location (Figure A1).



Figures A6. Total monthly well flow (raw water) in million gallons per day and number of operating wells for the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, 1942–2008.

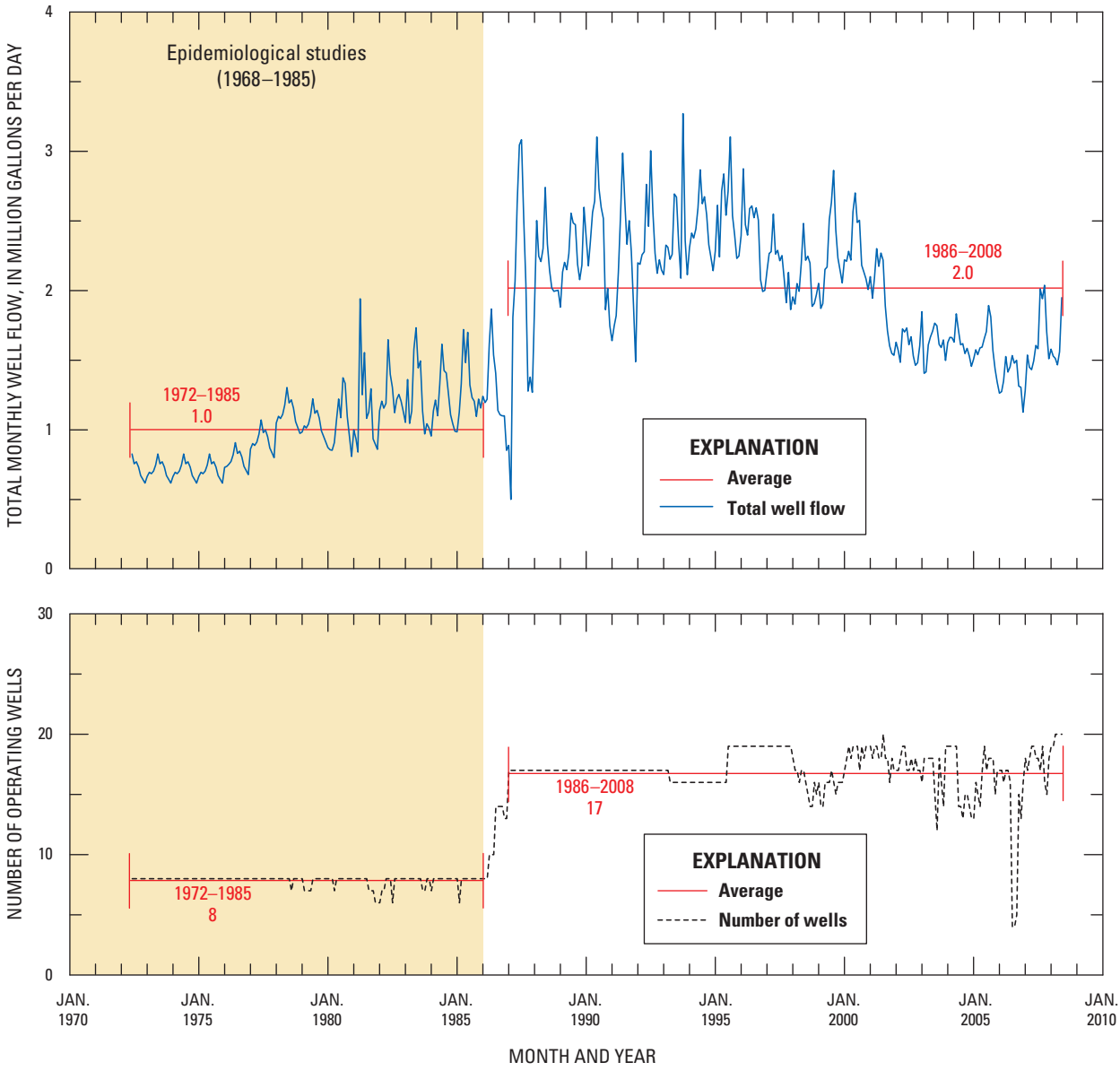


Figure A7. Total monthly well flow (raw water) in million gallons per day and number of operating wells for the Holcomb Boulevard water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, 1972–2008.

Contaminants of Concern for ATSDR Health Studies

The contaminants of concern for the ATSDR health studies and historical reconstruction analyses are VOCs and belong to a class of chemicals referred to as nonaqueous phase liquids, or NAPLs. The specific compounds of interest are chlorinated alkenes and hydrocarbon fuels. PCE, TCE, and their degradation products 1,2-cDCE, 1,2-tDCE, and VC are the chlorinated alkenes of concern (Lawrence 2007). Fuel components of concern are benzene, ethylbenzene, toluene, and xylenes (BTEX) and are some of the common ingredients of gasoline and diesel fuel. The chlorinated alkenes—PCE, TCE, and their degradation products—are part of a group of compounds classified as dense nonaqueous phase liquids (DNAPLs) and are characterized by densities greater than the density of water.[21] Thus, when occurring in the subsurface, DNAPLs are further characterized by an enhanced potential for downward vertical migration (Schwille 1988; Pankow and Cherry 1996). The BTEX components are grouped with compounds commonly identified as light nonaqueous phase liquids (LNAPLs) and are characterized by densities less than the density of water. Downward vertical migration of LNAPLs in the subsurface is generally limited to the vicinity of the water table (Newell et al. 1995).

Because it is confusing to use a variety of names to identify VOCs—especially among the thousands of documents used for the analyses reported herein—the common or alternate names listed in Lawrence (2007) are used in this and all HPHB reports and supplemental information texts. The use of common or alternate names to identify VOCs is accomplished in the HPHB report series for ease of reference to, and recognition of, previously published reports, documents, and laboratory analyses that pertain to the study area described herein.

Health Effects and Maximum Contaminant Levels

Both the USEPA and the National Toxicology Program (NTP) Report on Carcinogens classify benzene and VC as known human carcinogens based on sufficient evidence in humans (NTP 2011). Most recently, following its Guidelines for Carcinogen Risk Assessment (USEPA 2005), the USEPA characterized TCE as carcinogenic in humans by all routes of exposure (USEPA 2011) and PCE as likely carcinogenic in humans by all routes of exposure (USEPA 2012). NTP lists TCE and PCE as reasonably anticipated to be human carcinogens (NTP 2011).[22] The International Agency for Research on Cancer (IARC) classifies TCE as "carcinogenic to humans" and PCE as "probably carcinogenic to humans" (Guha et al. 2012). In addition to cancer, a review of the scientific literature has identified non-cancer diseases that have been associated with the chemicals found in the finished water at USMCB Camp Lejeune (ATSDR 1997a, b). These include aplastic anemia, generalized skin disorders, infertility, kidney diseases, liver disease, lupus, miscarriage, Parkinson's disease, and scleroderma. A comprehensive literature review for cancer and non-cancer endpoints is provided in Bove and Ruckart (2008).

The maximum contaminant level, or MCL, is a legal threshold set by the USEPA (40 CFR, Section 141.60, Effective Dates, July 1, 2002, edition) to quantify the amount of a hazardous substance allowed in finished water under the Safe Drinking Water Act (SDWA) of 1974. The MCL is based upon scientific opinion following a careful review of the scientific literature on the health effects described above. For example, the MCL for PCE was set at 5 micrograms per liter (µg/L) during 1992 because, given the technology at that time, 5 µg/L was the lowest level that water systems could be required to achieve. Effective dates for MCLs presented in this report are as follows: benzene, TCE, DCE, and VC, January 9, 1989; PCE, 1,2-cDCE, and 1,2-tDCE, July 30, 1992 (40 CFR, Section 141.60, Effective Dates, July 1, 2002, edition). The MCLs for contaminants of concern in this study and their effective dates are listed in Table A3. In this report, its supplements, and other HPHB chapter reports, the current MCL for a specific VOC—for example, 5 µg/L for TCE—is used as a reference

Table A3. Maximum contaminant levels and effective dates for contaminants of concern for the ATSDR health studies, Hadnot Point–Holcomb Boulevard study areas, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[ATSDR, Agency for Toxic Substances and Disease Registry]

Contaminant of concern	Maximum contaminant level (MCL),[1] in micrograms per liter	Effective date[2]
Tetrachloroethylene (PCE)	5	July 30, 1992
Trichloroethylene (TCE)	5	January 9, 1989
1,1-dichloroethylene (DCE)	7	January 9, 1989
cis-1,2-dichloroethylene (1,2-cDCE)	70	July 30, 1992
trans-1,2-dichloroethylene (1,2-tDCE)	100	July 30, 1992
Vinyl chloride (VC)	2	January 9, 1989
Benzene	5	January 9, 1989
Toluene	1,000	July 30, 1992
Ethylbenzene	700	July 30, 1992
Xylenes (total)	10,000	July 30, 1992

[1] EPA 816-F-03-016 (USEPA 2003); EPA 816-F-09-004 (USEPA 2009). Up-to-date information on all MCLs for drinking water is available at the U.S. Environmental Protection Agency Web site at *http://water.epa.gov/drink/contaminants/index.cfm* (accessed February 12, 2013)

[2] 40 CFR, Section 141.60, Effective Dates, July 1, 2002, edition

[21] The density of water is 1,000 kilograms per cubic meter (1 gram per cubic centimeter) at 5° C, but varies with temperature (Peavy et al. 1985).

[22] Additional information and data resources on toxicity and exposure assessment for children's health (TEACH) for TCE, VC, and benzene are available at the USEPA TEACH Web site: *http://www.epa.gov/teach/*.

concentration to compare historically measured data and historical reconstruction results. These comparisons are not intended to imply (1) that the MCL was in effect at the time of sample measurement or simulated historical concentration or (2) that a measured or simulated concentration above an MCL was necessarily unsafe. Hereafter, the use of the term MCL should be understood to mean the current MCL associated with a particular contaminant. A complete list of MCLs for common VOCs can be found in USEPA reports EPA 816-F-03-016 (2003) and EPA 816-F-09-004 (2009). A complete list of effective dates for MCLs can be found in 40 CFR, Section 141.60, Effective Dates, July 1, 2002, edition.[23]

Investigations and Occurrence of Groundwater Contamination

With the signing on December 16, 1974, of the Safe Drinking Water Act (SDWA)—known as Public Law 93-523—national standards were established for the levels of contaminants in drinking water. As part of the SDWA of 1974, water-supply wells and sole-source aquifers were protected. Under the SDWA, the USEPA set forth national primary drinking-water regulations, which included MCLs for drinking water (Pontius 2003). With the promulgation of the 2nd national interim public drinking-water regulation on November 29, 1979 (also referred to as the total trihalomethanes [TTHM] rule), the USEPA set an interim MCL for TTHMs of 0.1 milligram per liter (mg/L) as an annual average (USEPA 1979).[24] This rule applied to any community water system serving at least 10,000 people that adds a disinfectant to drinking water during any part of the treatment process. The USMCB Camp Lejeune water utility began testing its drinking water for TTHMs during October 1980 (CLW #436) to comply with the USEPA TTHM rule. During December 1980–March 1981, as part of the sampling program for TTHMs, USMCB Camp Lejeune water utility documents indicated "heavy organic interference at $CHCl_2Br$", "you need to analyze for chlorinated organics by GC/MS", and "water highly contaminated with other chlorinated hydrocarbons (solvents)!" (USMCB Camp Lejeune Water Documents CLW #438, #441, and #443, respectively).[25] These and other documents indicate that the HPWTP was substantially contaminated with TCE and PCE during May 1982 (USMCB Camp Lejeune Water Documents CLW #5176–#5182). Sampling of raw and finished water at Hadnot Point was initiated in early December 1984 (E. Betz, USMCB Camp Lejeune, written communication, February 26, 1985; Camp Lejeune Water Documents CLW #4546–#4557). Locations of historically contaminated water-supply wells within the HPHB study area are shown in Figure A8.

Discovery of contaminated water supplies at USMCB Camp Lejeune initiated a series of assessments of groundwater contamination within the HPHB study area. Under the Installation Restoration Program (IRP), assessments of groundwater contamination were conducted under the auspices of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Additional assessments of groundwater contamination by refined petroleum products from leaking above-ground and underground storage tanks (AST/UST) were conducted under the auspices of the Resources Conservation and Recovery Act (RCRA). Faye et al. (2010) describe soil and groundwater contaminants at 18 IRP (CERCLA) sites by PCE, TCE, and their degradation products, as well as BTEX components, such as benzene. In a companion report, Faye et al. (2012) summarize the results of investigations at 64 designated RCRA study areas and describe the occurrence and distribution of BTEX components, such as benzene, within groundwater of the HPHB study area.

The historical reconstruction analyses presented and discussed herein will be focusing primarily in two general areas (within the HPHB study area) that contributed most substantially to water-supply well contamination—the Hadnot Point Industrial Area (HPIA) and the Hadnot Point landfill (HPLF) area (Figure A8).[26] The spatial distribution of groundwater sample locations for PCE, TCE, and benzene and ranges of PCE, TCE, and benzene concentrations at monitor and water-supply wells for IRP sites within the HPHB study area are shown in Figure A9 for the HPIA and in Figure A10 for the HPLF area. (See also Faye et al. [2010, 2012] for additional data and discussion pertinent to groundwater contaminant sample locations.) In addition, Figure A9 shows locations of fuel-related free product in groundwater and former fuel lines from the former HPIA fuel farm (HPFF) to other locations within the HPIA. Concentrations of TCE at IRP locations were detected in groundwater ranging from about 1 µg/L to 180,000 µg/L. Similarly, PCE was detected in groundwater at concentrations ranging from less than 1 µg/L to 170,000 µg/L. Concentrations of benzene in groundwater were detected at 10 of 18 IRP sites at concentrations ranging from less than 1 µg/L to 43,000 µg/L (Faye et al. 2010, 2012). VOCs were detected in 12 supply wells by sampling and analyses (Figures A5, A8). Since 1984 when sampling began, detected TCE concentrations ranged from less than 1.0 µg/L to 18,900 µg/L (Figure A8; Table A4), and PCE concentrations ranged from 1.5 µg/L to 400 µg/L in the contaminated water-supply wells (Table A5). Detected concentrations of

[23] Up-to-date information on all MCLs for drinking water can be found by accessing the USEPA Web site at *http://water.epa.gov/drink/contaminants/index.cfm#List*.

[24] Total trihalomethanes, or TTHMs, is the sum of chloroform ($CHCl_3$), bromoform ($CHBr_3$), bromodichloromethane ($CHBrCl_2$), and dibromochloromethane ($CHBr_2Cl$), which are disinfection by-products formed by chlorination of drinking water (Singer 1993).

[25] GC/MS, gas chromatography/mass spectrometry; a method that combines the features of gas-liquid chromatography and mass spectrometry to identify different substances within a test sample.

[26] The Hadnot Point Industrial Area (HPIA) is a formally designated name and acronym used in many Camp Lejeune references (e.g., Baker Environmental, Inc. [1994], CH2M HILL [2006]), and the ATSDR HPHB Chapter reports and Chapter A supplements follow this naming convention. The acronym HPLF is used in the ATSDR HPHB report series for brevity and convenience to identify the Hadnot Point landfill.

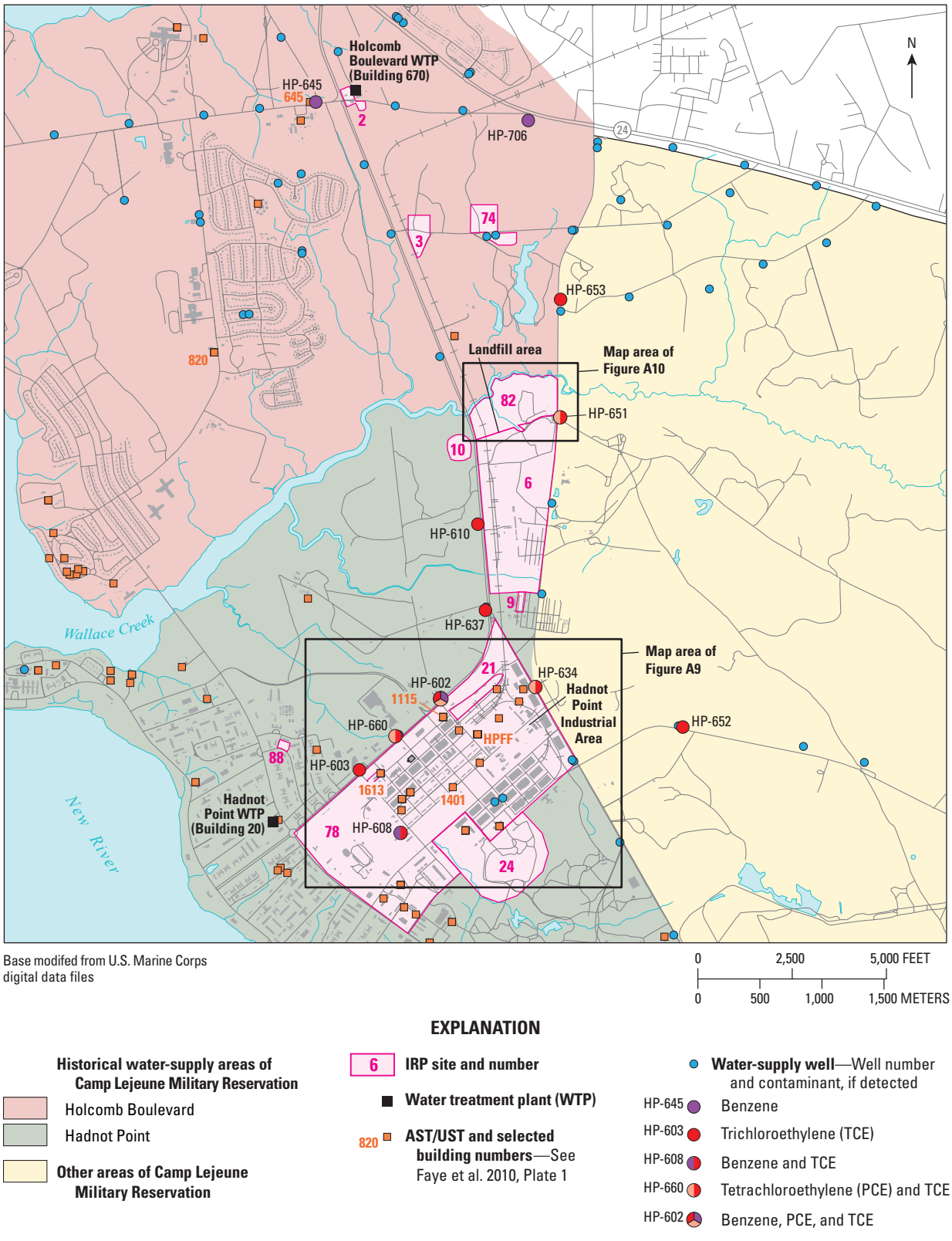


Figure A8. Locations of historically contaminated water-supply wells, Installation Restoration Program (IRP) sites, and above-ground and underground storage tank (AST/UST) sites, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

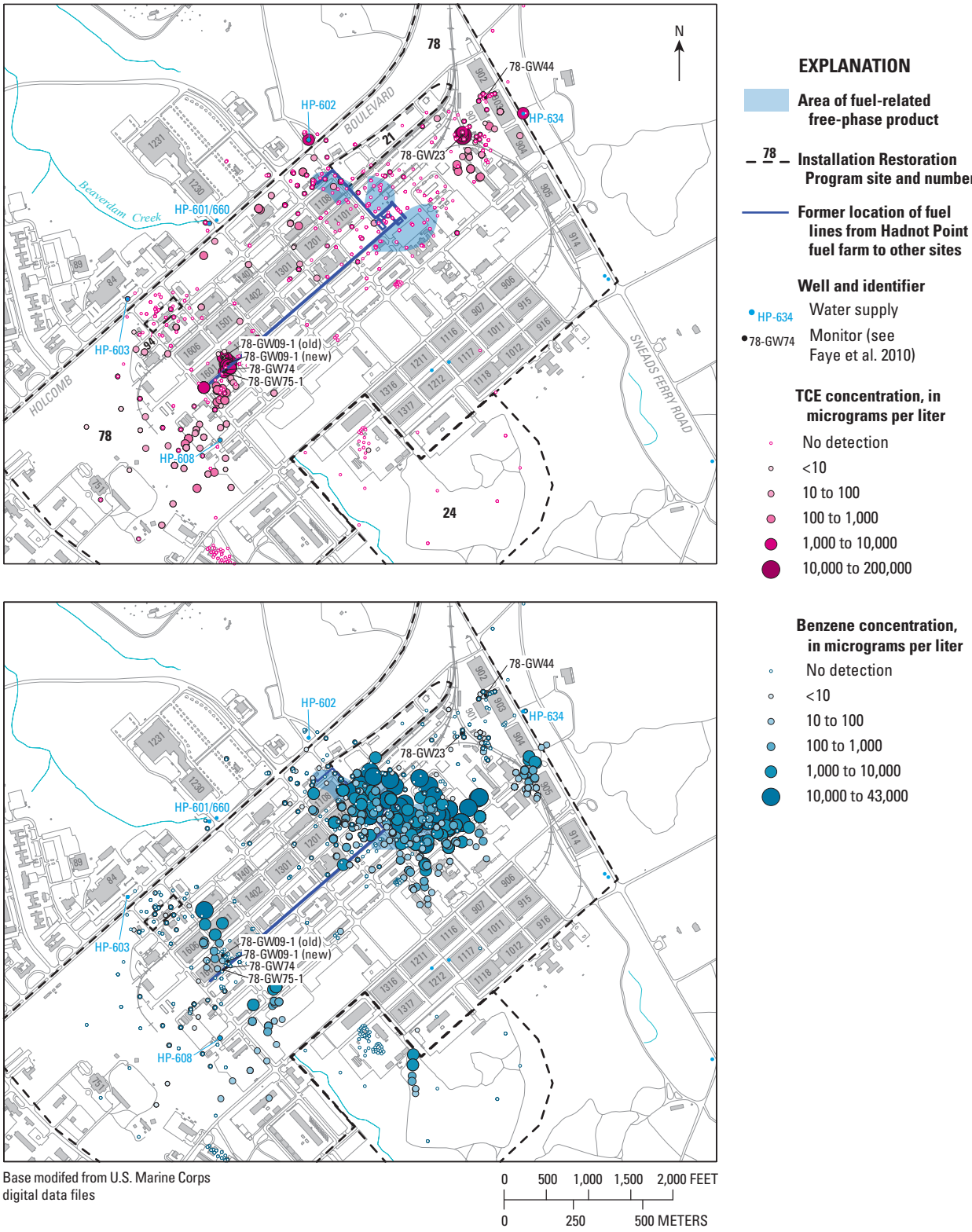


Figure A9. Sampling data for trichloroethylene (TCE), benzene, and fuel-related free product in groundwater for the Hadnot Point Industrial Area, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. (See Figure A8 for location and Figure A13 for selected building numbers.)

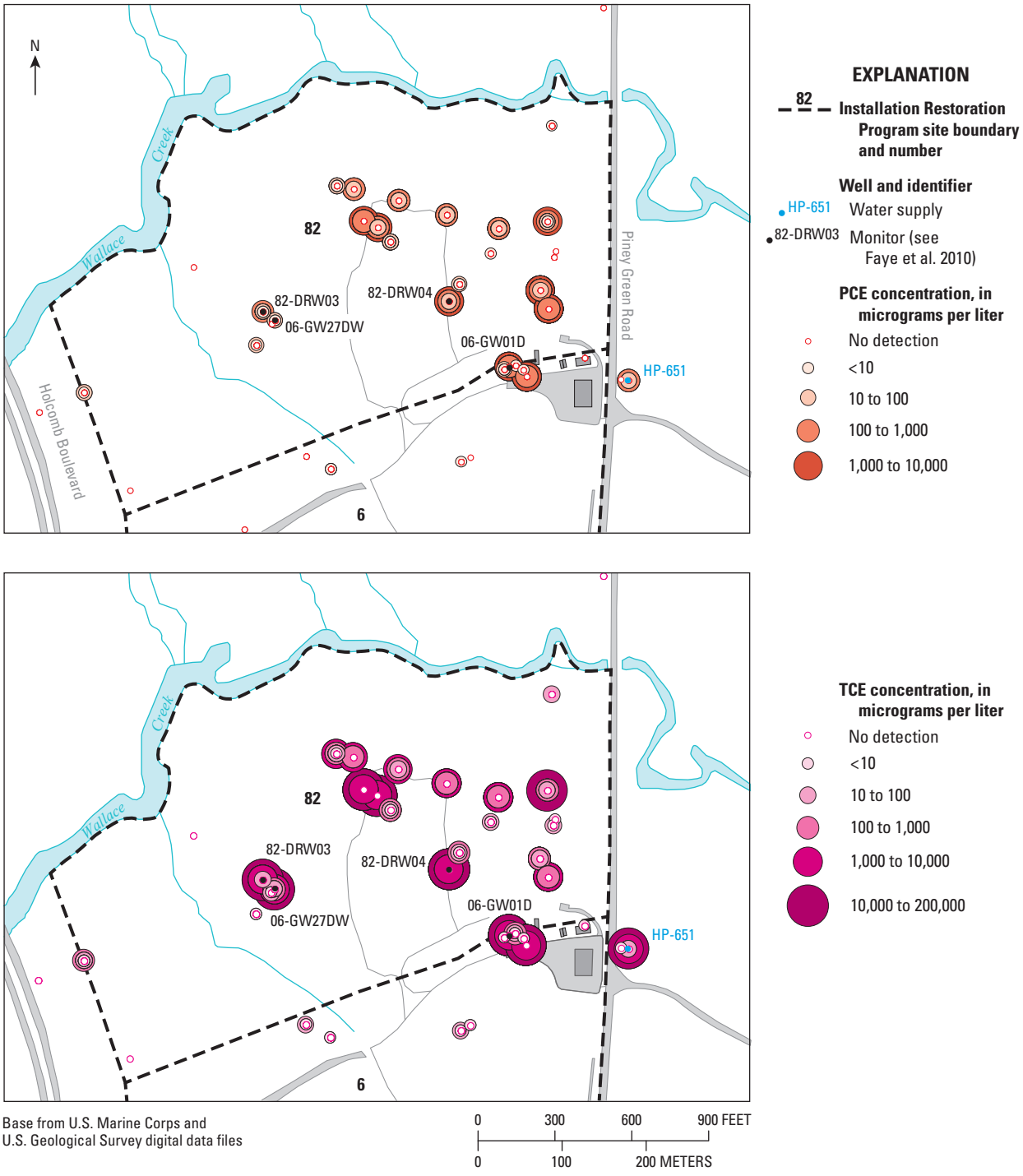


Figure A10. Sampling data for tetrachloroethylene (PCE) and trichloroethylene (TCE) in groundwater for the Hadnot Point landfill area, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. (See Figure A8 for location.)

Table A4. Water-supply wells with reported detections of tetrachloroethylene (PCE), trichloroethylene (TCE), 1,1-dichloroethylene (1,1-DCE), *trans*-1,2-dichloroethylene (1,2-tDCE), *cis*-1,2-dichloroethylene (1,2-cDCE), total 1,2-dichloroethylene (total 1,2-DCE), or vinyl chloride (VC), Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.[1]

[<, constituent is less than the detection limit. Number following the "<" is the detection limit; —, constituent concentration not determined in laboratory analysis; ND, constituent not detected; J, estimated concentration; D, sample diluted for analysis]

Well name	Sample date	[2] Concentration, in micrograms per liter						
		PCE	TCE	1,1-DCE	1,2-tDCE	1,2-cDCE	Total 1,2-DCE	VC
HP-602	7/6/1984	<1.9	<1.4	<1.3	7.8	—	—	<0.9
	11/30/1984	24	1,600	2.4J	630	—	—	18
	12/10/1984	<500	540	<500	380	—	—	<500
	12/13/1984	3.2	300	—	110	—	—	—
	12/14/1984	<50	340	<50	230	—	—	<50
	2/4/1985	1.5J	38	<10	74	—	—	<10
	11/12/1986	<4.1	2.2	<2.8	14	—	—	<4.9
	1/22/1991	<5.0	0.7J	<5.0	—	—	12	<10
HP-603	12/4/1984	<10	4.6J	<10	<10	—	—	<10
	12/12/1984	<10	<10	<10	<10	—	—	<10
	1/16/1985	<10	<10	<10	<10	—	—	<10
	8/11/1988	<10	<10	<10	<10	—	—	<10
	6/26/1990	<5.0	<5.0	<5.0	—	—	—	<10
	1/22/1991	<5.0	1.0J	<5.0	—	—	<5.0	<10
	9/20/1995	<0.50	3.0	<0.50	<0.50	2.4	—	<0.50
HP-608	12/4/1984	<10	110	<10	5.4J	—	—	<10
	12/10/1984	<10	13	<10	2.4J	—	—	<10
	2/4/1985	<10	9.0	<10	<10	—	—	<10
	11/12/1986	<4.1	66	<2.8	8.5	—	—	<4.9
HP-610	2/4/1985	<10	<10	<10	<10	—	—	<10
	10/1/1992	<1.0	37	—	—	—	—	<2.0
HP-634	12/4/1984	<10	<10	<10	<10	—	—	<10
	12/10/1984	<10	<10	<10	2.3J	—	—	<10
	1/16/1985	10	1,300	<10	700	—	—	6.8
	11/12/1986	<4.1	<1.9	<2.8	2.9	—	—	<4.9
	1/22/1991	<5.0	<5.0	<5.0	—	—	1.0J	<10
HP-637	12/4/1984	<10	<10	<10	<10	—	—	<10
	12/10/1984	<10	<10	<10	<10	—	—	<10
	1/16/1985	<10	<10	<10	<10	—	—	<10
	1/22/1991	<5.0	0.90J	<5.0	—	—	<5.0	<10
	8/26/1992	<5.0	<5.0	<5.0	<5.0	<5.0	—	<5.0
HP-651	1/16/1985	386	3,200	187	3,400	—	—	655
	2/4/1985	307	17,600	<200	8,070	—	—	179
	2/4/1985	400	18,900	<200	7,580	—	—	168
	11/12/1986	45	32	7.0	140	—	—	140
	1/22/1991	53	13	2.0J	—	—	75	70
HP-652	1/16/1985	<10	9.0	<10	<10	—	—	<10
	11/12/1986	<3.0	<3.0	<2.8	<1.6	—	—	<1.0
	1/22/1991	<5.0	<5.0	<5.0	—	—	<5.0	<10
	9/20/1995	<0.50	<0.50	<0.50	<0.50	<0.50	—	<0.50
	12/11/2001	<0.50	<0.50	<0.50	<0.50	<0.50	—	<0.50
HP-653	1/16/1985	<10	5.5	<10	<10	—	—	<10
	11/12/1986	<4.1	2.6	<2.8	<1.6	—	—	<4.9
	1/22/1991	<5.0	<5.0	<5.0	—	—	<5.0	<10
HP-660	12/4/1984	5.0J	210	<10	88	—	—	<10
	12/10/1984	4.4J	230	<10	99	—	—	<10
	1/16/1985	<10	26	<10	88	—	—	<10
	11/12/1986	<4.1	<1.9	<2.8	<1.6	—	—	<4.9
	1/22/1991	<5.0	1.0J	<5.0	—	—	2.0J	<10

[1] See Faye et al. (2010) for a complete tabulation of contaminants in water samples collected at water-supply wells in the Hadnot Point–Holcomb Boulevard study area

[2] Concentrations above the detection limit are highlighted in red

Table A5. Water-supply wells with reported detections of benzene, toluene, ethylbenzene, or total xylenes, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.[1]

[<, constituent is less than the detection limit. Number following the "<" is the detection limit; —, constituent concentration not determined in laboratory analysis; ND, constituent not detected; J, estimated concentration]

Well name	Sample date	[2] Concentration, in micrograms per liter			
		Benzene	Toluene	Ethylbenzene	Total xylenes
Hadnot Point Water Treatment Plant Service Area					
HP-602	7/6/1984	380	10	8.0	—
	11/30/1984	120	5.4J	<10	—
	12/10/1984	720	<500	<500	—
	12/13/1984	<1.0	<1.0	<2.0	—
	12/14/1984	230	12J	<50	—
	2/4/1985	<10	<10	<10	—
	11/12/1986	50	<6.0	<7.2	<12
	1/22/1991	17	<5.0	<5.0	<5.0
HP-603	12/4/1984	<10	<10	<10	—
	12/10/1984	<10	<10	<10	—
	1/16/1985	<10	<10	<10	—
	8/11/1988	<10	<10	<10	<10
	6/26/1990	<5.0	<5.0	<5.0	<5.0
	1/22/1991	<5.0	<5.0	<5.0	<5.0
	9/20/1995	<0.50	<0.50	<0.50	<0.50
HP-608	12/4/1984	3.7J	<10	<10	—
	12/10/1984	4.0J	<10	<10	—
	2/4/1985	1.6	<10	<10	—
	11/12/1986	<4.4	<6.0	<7.2	<12
HP-651	1/16/1985	<10	<10	<10	—
	2/7/1985	<10	<10	<10	—
	11/12/1986	<4.4	<6.0	<7.2	<12
	1/22/1991	<5.0	0.9J	<0.5	<0.5
Holcomb Boulevard Water Treatment Plant Service Area					
HP-645	2/4/1985	<10	<10	<10	—
	11/6/1986	20	7.5	ND	ND
	2/17/1987	290	15	38	36
HP-706	9/19/1995	0.60	<0.50	<0.50	<0.50
	1/13/1998	6.1	—	—	—

[1] See Faye et al. (2010) for a complete tabulation of contaminants in water samples collected at water-supply wells in the Hadnot Point–Holcomb Boulevard study area

[2] Concentrations above the detection limit are highlighted in red

benzene ranged from less than 1 µg/L to 720 µg/L. Concentrations of TCE detected in finished water at the HPWTP ranged from less than 1 µg/L to 1,400 µg/L. Concentrations of PCE detected in finished water at the HPWTP ranged from less than 4 µg/L to 100 µg/L. Benzene contamination also was detected in HPWTP water, although the treatment status was unknown. Benzene concentrations in water at the HPWTP ranged from 1 µg/L to 2,500 µg/L (Faye et al. 2010).[27]

Faye et al. (2012) report that concentrations of BTEX components detected during investigations of groundwater contamination at RCRA-designated locations are relatively high in the vicinity of Buildings 645, 820, 1115, and 1613, and at the former HPFF (Figures A8 and A9). Note, Buildings 1115 and 1613 are located within the HPIA while Buildings 645 and 820 are located external to the HPIA (Figure A8). Maximum observed benzene concentrations in monitor wells ranged from 3,650 µg/L near Building 645 to 43,000 µg/L at Building 1115. Corresponding maximum concentrations in the vicinity of Buildings 820 and 1613 were 36,000 µg/L and 17,300 µg/L, respectively. The maximum observed benzene concentration in monitor wells at the former HPFF was 29,000 µg/L. These relatively high benzene concentrations in groundwater are not necessarily indicative of the occurrence of free-phase hydrocarbon product.[28] Rather, the existence and extent of free-phase hydrocarbon product is based on interpretations of free product thickness, as presented in Faye (2012, Figures D23–D25). Plumes of BTEX components were also observed at each of these locations. Occurrences of BTEX components greater than detection limits also occurred at various times in supply wells proximate to Buildings 645, 1115, and 1613 (Figure A8) and ranged from 1.6 µg/L of benzene in well HP-608 to 720 µg/L of benzene in well HP-602 (Table A5). Concentrations of chlorinated alkenes such as PCE and TCE also occur in conjunction with plumes of BTEX components, and respective plumes are probably mixed at several locations. In general, detected concentrations of chlorinated alkenes were less than 10 µg/L, and most are less than detection limits.

Detailed analyses of concentrations of selected VOCs, including PCE, TCE, and benzene, within the HPIA and HPLF area were used to estimate mass and volume of the aforementioned contaminants in groundwater and in VOC recovery wells (Table A6). With the exception of volumes of benzene quantified by Jang et al. (2013), all estimates of mass (and volume) in the subsurface should be considered minimum values because (1) the amount of mass removed from the underlying aquifers at Hadnot Point and vicinity by water-supply wells during 1942–1985 is unknown and (2) biodegradation of PCE and TCE into their respective daughter products (Lawrence 2007) probably occurred prior to the years used for computing mass estimates listed in Table A6. Estimates of contaminant mass like those listed in Table A6 (with the exception of the benzene computation as previously noted) typically represent only a small fraction of the total mass in the subsurface (Pankow and Cherry 1996). Mackay and Cherry (1989, Table 1) list dissolved mass and volume of seven organic contaminant plumes characterized as "relatively well-documented."[29] The estimated mass and volume of TCE and PCE in the subsurface at the HPIA and HPLF area typically exceed—in some cases substantially exceed—those reported by Mackay and Cherry (1989, Table 1).

Identification and Characterization of Contaminant Sources

Identified information sources such as site assessments, remedial investigations, and leaking underground storage tank reports (Appendix A2), in addition to contaminant source inventories and histories that have been published for IRP and AST/UST sites within the study area (Faye et al. 2010, 2012), were used to characterize contaminant sources. An inventory of potential contaminant source areas in the vicinity of historically contaminated water-supply wells for the HPHB study area (Figure A8) is listed in Table A7. Identification of documented source areas, associated timelines, and reference documents pertinent to source identification for primary contaminants of concern to this study (PCE, TCE, and benzene) are listed in Table A8. Locations of historically contaminated water-supply wells and IRP and AST/UST sites for the study area also are shown in Figure A8 for the study area and in Figures A9 and A10 for the HPIA and HPLF area, respectively. In addition to the contaminant source information summarized herein and presented in detail in Jones et al. (2013), additional background information for these sites is provided in Faye et al. (2010, 2012).

The HPIA source areas include (1) TCE and benzene releases around building 1601, (2) TCE releases around buildings 901, 902, and 903, (3) benzene releases in the fuel farm area, (4) benzene releases in Building 1613, and (5) possible TCE releases around Buildings 1115 and 1401 (Figure A8). Building 1601 was constructed during the 1940s and was originally used as a garage for motor vehicles and a vehicle maintenance facility. Disposal of waste oil and other chemicals in a 1,600-gallon (gal) underground storage tank (UST 1601) was probably the source for detections of TCE—and possibly

[27] A benzene concentration of 2,500 µg/L was obtained at the HPWTP on November 19, 1985, when all contaminated water-supply wells were reported to have been shut down (Camp Lejeune Water Documents CLW #1406–1407, JTC Environmental Consultants, Inc. 1985).

[28] The term free-phase hydrocarbon product (also referred to as free-phase product, free-phase benzene, or free-phase LNAPL) as used in the HPHB report series indicates the occurrence of light nonaqueous phase (LNAPL) hydrocarbon liquids in the subsurface, such as gasoline, that remain undiluted by other gases or liquids present in the subsurface. Although the physical and chemical properties of the free-phase product may change over time, the product nonetheless remains a distinct phase of a nonaqueous hydrocarbon liquid in the subsurface. When specific concentrations of chemicals of concern are presented and discussed, the term BTEX or BTEX component is used.

[29] Reference is to the last column of Table 1 in Mackay and Cherry (1989), which lists estimated chemical mass dissolved in a plume as equivalent dense nonaqueous phase liquid volume in liters or equivalent 55-gallon drums.

Table A6. Summary of estimates of subsurface contaminant mass pertinent to fate and transport in groundwater, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.[1]

[USMCB, U.S. Marine Corps Base; ATSDR, Agency for Toxic Substances and Disease Registry; LNAPL, light nonaqueous phase liquid; UST, underground storage tank; Georgia Tech, Georgia Institute of Technology; lbs, pounds; VOCs, volatile organic compounds; GMS, Groundwater Modeling System software; TCE, trichloroethylene; PCE, tetrachloroethylene]

Source area	Contaminant	Contaminant mass component	[2,3] Estimated mass, in kilograms	[2,3] Estimated volume, in gallons	[3] Basis	Reference
Hadnot Point Industrial Area (HPIA)						
Hadnot Point fuel farm (HPFF)	Benzene	Contaminant mass in total fuel recovered	27,500	8,280	**Reported** total fuel recovery of 414,118 gallons from HPFF/Building 1115 area remediation systems as of July 2010	USMCB Camp Lejeune (July 2010)
	Benzene	Contaminant mass in subsurface free product	55,100–72,600	16,600–21,900	**Calculated** free product (LNAPL) volume estimate of 830,324–1,096,901 gallons developed by using analytical methodology in SpillCAD software	Baker (not dated) (UST File #01185, p. 526–563)
	Benzene	Contaminant mass in total subsurface fuel	26,500–72,900	8,000–22,000	**Calculated** order-of-magnitude estimate of the amount of fuel in the subsurface (400,000–1,100,000 gallons of fuel)	CH2M HILL 2001 [UST File #670]
	Benzene	Contaminant mass in subsurface LNAPL	59,700–93,400	18,000–28,200	**Calculated** amount of LNAPL (901,000–1,408,000 gallons) in the subsurface based on a semi-analytical solution using apparent LNAPL thickness in wells (TechNAPLVol model)	Jang et al. (2013)
	Benzene	Contaminant mass in subsurface LNAPL	59,700–93,400	18,000–28,200	**Calculated** amount of LNAPL (901,000–1,409,000 gallons) in the subsurface based on a three-dimensional numerical integration using apparent LNAPL thickness in wells (TechNAPLVol model)	Jang et al. (2013)
	Benzene	Contaminant mass in subsurface LNAPL	62,000–107,000	18,700–32,400	**Calculated** amount of LNAPL (935,000–1,618,000 gallons) in the subsurface based on a three-dimensional numerical integration using actual LNAPL thickness in soil (TechNAPLVol model)	Jang et al. (2013)
Building 1601	Benzene	Contaminant mass from reported VOC recovery	43	13	**Calculated** amount of benzene based on 96.2 lbs cumulative total VOCs reportedly recovered as of July 2011 from 78 South remediation system. (Assumed total VOCs equivalent to benzene for calculation)	ATSDR calculation utilizing data contained in Rhea Engineers and Consultants, Inc. (2011a)
	Benzene	Contaminant mass in groundwater (dissolved and sorbed phase)	10–17	3–5	**Calculated** from groundwater-quality data for benzene during 1984–1988 (pre-remediation). Methods: three-dimensional interpolation (GMS software)	U.S. Army Engineer Research and Development Center (2008)
	TCE	Contaminant mass from reported VOC recovery	44	8	**Calculated** amount of TCE based on 96.2 lbs cumulative total VOCs reportedly recovered as of July 2011 from 78 South remediation system. (Assumed total VOCs equivalent to TCE for calculation)	ATSDR calculation utilizing data contained in Rhea Engineers and Consultants, Inc. (2011a)
	TCE	Contaminant mass in groundwater (dissolved and sorbed phase)	388–521	70–94	**Calculated** from groundwater-quality data for TCE during 1984–1988 (pre-remediation). Methods: two- and three-dimensional interpolation techniques (Surfer® and GMS software)	U.S. Army Engineer Research and Development Center (2008); Golden Software, Inc. (2011b)

Table A6. Summary of estimates of subsurface contaminant mass pertinent to fate and transport in groundwater, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.[1]—Continued

[USMCB, U.S. Marine Corps Base; ATSDR, Agency for Toxic Substances and Disease Registry; LNAPL, light nonaqueous phase liquid; UST, underground storage tank; Georgia Tech, Georgia Institute of Technology; lbs, pounds; VOCs, volatile organic compounds; GMS, Groundwater Modeling System software; TCE, trichloroethylene; PCE, tetrachloroethylene]

Source area	Contaminant	Contaminant mass component	[2,3] Estimated mass, in kilograms	[2,3] Estimated volume, in gallons	[3] Basis	Reference
Hadnot Point Industrial Area (HPIA)—Continued						
Building 901/902/903 area	TCE	Contaminant mass from reported VOC recovery	61	11	**Calculated** amount of TCE based on 129.2 lbs cumulative total VOCs reportedly recovered as of July 2011 from 78 South remediation system. (Assumed total VOCs equivalent to TCE for calculation)	ATSDR calculation utilizing data contained in Rhea Engineers and Consultants, Inc. (2011a)
	TCE	Contaminant mass in groundwater (dissolved and sorbed phase)	388–2,440	70–440	**Calculated** from groundwater-quality data for TCE during 1984–1988 (pre-remediation). Methods: two- and three-dimensional interpolation techniques (Surfer® and GMS software)	U.S. Army Engineer Research and Development Center (2008); Golden Software, Inc. (2011b)
Hadnot Point landfill (HPLF)						
	PCE	Contaminant mass in groundwater (dissolved and sorbed phase)	461–3,690	75–600	**Calculated** from groundwater-quality data for PCE during 1984–1995 (pre-remediation). Methods: two- and three-dimensional interpolation techniques (Surfer® and GMS software)	U.S. Army Engineer Research and Development Center (2008); Golden Software, Inc. (2011b)
	TCE	Contaminant mass from reported VOC recovery	168,000	16,800	**Calculated** amount of TCE based on 205,143 lbs cumulative total VOCs from remediation system. (Assumed total VOCs equivalent to TCE for calculation)	ATSDR calculation utilizing data contained in Rhea Engineers and Consultants, Inc. (2011a, b)
	TCE	Contaminant mass in groundwater (dissolved and sorbed phase)	12,200–31,600	2,200–5,700	**Calculated** from groundwater-quality data for TCE in groundwater data during 1984–1995 (pre-remediation). Methods: two- and three-dimensional interpolation techniques (Surfer® and GMS software)	U.S. Army Engineer Research and Development Center (2008); Golden Software, Inc. (2011b)

[1] With the exception of the benzene mass estimates derived from Jang et al. (2013) analyses, the contaminant mass estimates listed should be considered minimum values. Contaminant mass estimates developed from reported remediation system recoveries do not include any adjustment factor for remediation efficiency

[2] Values rounded to a maximum of three significant digits; the following factors are used to convert from mass units (kg) to foot-pound volume units (gal): 1 gal = 3.875 L; 1 L = 1,000 cm^3; and chemical densities in g/cm^3 are specified below. Therefore, volume (gal) = mass (kg) × 1,000 g/kg ÷ density (g/cm^3) ÷ 1,000 cm^3/L ÷ 3.785 L/gal

[3] The following reference values and conversion factors were utilized for calculations:

A benzene content of 2 percent by volume was utilized to convert fuel/LNAPL volume estimates into benzene volume estimates. Unleaded gasoline typically contains 1–2 percent benzene by volume (ATSDR 2007).

Density of benzene, 0.876 grams per cubic centimeter (g/cm^3); density of TCE, 1.464 g/cm^3; density of PCE, 1.623 g/cm^3 (Lawrence 2007).

Sources:

Agency for Toxic Substances and Disease Registry 2007

ATSDR-DON Data Mining & Discovery Technical Work Group Meeting, USMCB Camp Lejeune, July 21–22, 2010

Baker Environmental, Inc., Preliminary Draft Report [not dated] (UST Management Web Portal File #01185, p. 526–563)

CH2M HILL 2001

Lawrence 2007

Rhea Engineers and Consultants, Inc. 2011b

Table A7. Inventory of potential contaminant-source areas in the vicinity of historically contaminated water-supply wells, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[AST/UST, above-ground storage tank/underground storage tank; IRP, Installation Restoration Program; PCE, tetrachloroethylene; TCE, trichloroethylene; HPFF, Hadnot Point fuel farm; Bldg, Building; J, laboratory qualifier indicating concentration was estimated]

[1]Historically contaminated water-supply wells	Contaminants detected	Sample dates	Number of detections/ number of analyses	Statistics for detected concentrations, in micrograms per liter					Potential source locations	
				Minimum	25th percentile	50th percentile	75th percentile	Maximum	[2]AST/UST sites	[3]IRP sites (source areas)
Hadnot Point Industrial Area (HPIA)										
HP-602	Benzene PCE TCE	7/1984–1/1991	6/8 3/8 7/8	17 1.5 0.7J	67.5 2.4 20.1	175 3.2 300	342.5 13.6 440	720 24 1,600	HPFF, Bldg 1115, Bldg 1101	Site 78 (Bldg 901/902 area), Site 21
HP-603	TCE	12/1994–9/1995	3/7	1.0J	2.0	3.0	3.8	4.6J	Bldg 1613, Bldg 61, Bldg 1502, Bldg 1601, Bldg 1607	Site 78 (Bldg 1601), Site 94
HP-608	Benzene TCE	12/1984–11/1986	3/4 4/4	1.6 9.0	2.7 12	3.7 39.5	3.9 77	4 110	Bldg 1601, Bldg 1502, Bldg 1607, Bldg S1856	Site 78 (Bldg 1601), Site 24
HP-634	PCE TCE	12/1984–1/1991	1/5 1/5	10 1,300	10 1,300	10 1,300	10 1,300	10 1,300	Bldg 738, Bldg 900, Bldg 903	Site 78 (Bldg 901/902 area), Site 21
HP-660	PCE TCE	12/1984–1/1991	2/5 4/5	4.4 1.0J	4.6 19.8	4.7 118	4.9 215	5.0 230	Bldg 1115, Bldg 1401, Bldg 1502, Bldg 1601, Bldg 1613	Site 78 (Bldg 1601), Site 94
Hadnot Point landfill area (HPLF)										
HP-651	PCE TCE	1/1985–1/1991	5/5 5/5	45 13	53 32	307 3,200	386 17,600	400 18,900	Unknown	Site 6, Site 82
HP-653	TCE	1/1985–1/1991	2/3	2.6	3.3	4.1	4.8	5.5	Unknown	Unknown
HP-610	TCE	2/1985–10/1992	1/2	37	37	37	37	37	Unknown	Site 6
HP-645 Area										
HP-645	Benzene	11/1986–2/1987	2/3	20	87.5	155	222.5	290	Bldg 645, Bldg 40	Site 2
Other areas										
HP-637	TCE	12/1984–8/1992	1/5	0.9J	0.9J	0.9J	0.9J	0.9J	Unknown	Site 6, Site 9, Site 78
HP-652	TCE	1/1985–12/2001	1/5	9.0	9.0	9.0	9.0	9.0	Unknown	Unknown
HP-706	Benzene	9/1995–1/1998	2/2	0.6	2.0	3.4	4.7	6.1	Unknown	Unknown

[1]See Figure A8 for locations

[2]Sites managed under the AST/UST program at Camp Lejeune. At these sites, an environmental release has occurred and subsequent investigations and/or remediation activities are conducted under the auspices of the Resource Conservation and Recovery Act (RCRA) and within the North Carolina Department of Environment and Natural Resources underground storage tank regulatory framework; refer to Faye et al. (2012) for additional details on selected AST/UST sites at Camp Lejeune

[3]Sites managed under the IRP at Camp Lejeune. At these sites, an environmental release has occurred and subsequent investigations and/or remediation activities are conducted within the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) regulatory framework. Within Site 78, specific local source areas are listed parenthetically; refer to Faye et al. (2010) for additional details on IRP sites at Camp Lejeune

Table A8. Identification of documented source areas, timelines, primary contaminants, and location of major dissolved-phase sources, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[HPFF, Hadnot Point fuel farm; UST, underground storage tank; AS/SVE; air sparging/soil vapor extraction; MW, monitor well; µg/L, microgram per liter; gal, gallon; LUST, leaking underground storage tank; CERCLA, Comprehensive Environmental Response, Compensation, and Liability Act of 1980; TCE, trichloroethylene; PCE, tetrachloroethylene]

[1] Source-area timeline [reference documents]	Primary contaminant; number of major sources	Location of major dissolved-phase sources
Hadnot Point Industrial Area (see Figure A13)		
Hadnot Point fuel farm events **1941**, HPFF USTs installed [UST #669, UST #670] **1942**, Building 1115 USTs installed [UST #670] **1993 January**, HPFF and Building 1115 USTs removed [UST #1186, UST #670] **2000 December**, Piping removal (extensive) at HPFF/Building 1115 [UST #417] **Building 1613 events** **1950s**, USTs installed [UST #548, UST #546] **1995 January**, USTs and contaminated soil removed [UST #535, UST #548] **1998–2004**, AS/SVE remediation system operated **Building 1601 events** **1940s**, Building 1601 built [UST #172, UST #195] UST removal date unknown	Benzene; three sources	HPFF/Building 1115/Building 1101 free product footprint Building 1613 free product footprint Building 1601 locations of maximum measured benzene in groundwater (78-GW75-1 and 78-GW74) and former location of USTs and dispenser island at southeast corner of building; MW 78-GW75-1 (5,500 µg/L in 2003; 3,200 µg/L in 2004); MW 78-GW74 (3,200 µg/L in 2004) (See Figure A9 for building and monitor well [MW] locations)
Building 1601 events **1940s**, Building 1601 built [UST #172, UST #195] **1942**, 1,500-gal UST install date listed in LUST study completed in 1990 by Geraghty and Miller [UST #504, UST #507] **1993 June 29**, UST excavated/removed [UST #624] **Building 901/902/903 events** **1948**, Buildings 900, 901, 902, 903 constructed [CERCLA #258, p. 149] TCE UST installation date unknown; removal/abandonment date unknown, but probably occurred prior to onset of remediation efforts around January 1995 [Sovereign Consulting, Inc. 2007]	TCE; two sources	Building 1601 locations of maximum measured TCE in groundwater (MW 78-GW09-1 (old) and (new)) and former location of 1,500-gal waste UST on north side of building; MW 78-GW09-1 (old) (5,000–14,000 µg/L during 1987–1991); MW 78-GW09-1 (new) (at/above 1,000 µg/L during 1993–1996) Building 901/902/903 locations of max measured TCE in groundwater (MW 78-GW23; 13,000 µg/L in 1987), maximum measured vinyl chloride in groundwater (MW 78-GW44; 1,600–6,700 µg/L during 2000–2004), and former locations of USTs containing TCE/solvent waste at Building 901 and between Buildings 902/903. (See Figure A9 for building and monitor well [MW] locations)
Hadnot Point landfill area (see Figure A14)		
Landfill **1940s**, reportedly used as a waste disposal area (Site 6 and Site 82; Figure A8) beginning in the 1940s	PCE and TCE; one source	Location of maximum measured concentration of TCE and PCE in groundwater (MW 06-GW01D) TCE ranged from 6,400 to 180,000 µg/L during 1992–2004; PCE ranged from 210 to 6,500 µg/L during 1992–2004 (See Figure A10 for monitor well [MW] locations)

[1] UST # refers to UST Web Management Portal file number (see References section of this report for complete details); CERCLA # refers to CERCLA Administrative Record file number (provided on digital video disc [DVD] in Maslia et al. 2007)

benzene—in well HP-608.[30] The steel tank (UST 1601) was installed in 1942 according to Geraghty and Miller (1990) and removed during remediation activities performed during June 1993 (UST File #624). Two additional tanks and fuel dispenser islands located southeast from Building 1601 could have also contributed to the contamination of benzene detected in HP-608. It is likely that these UST systems developed leaks in joints, valves, or other system components over time.

TCE releases around Buildings 901, 902, and 903 probably occurred from the leaking of two USTs and the degreasing activities around this area (Figure A9). A 440-gal UST located east of Building 901 could have possibly contributed to the contamination of TCE in the area (Environmental Science and Engineering, Inc. 1988). Similarly, a UST of unknown capacity between Buildings 902 and 903 could have contributed to the TCE contamination in the area. The installation date of these tanks is unknown; however, the buildings surrounding this area were constructed around 1948, and presumably the tanks were installed at the same time. The highest concentration of TCE around this area (13,000 µg/L) corresponds to an unpaved area southeast of Building 901 where contaminants could have entered the subsurface due to degreasing activities near Building 901. The contaminants probably entered the groundwater system near the sources identified previously and migrated west and northwest in the direction of groundwater flow. Around 1963, groundwater flow in this area was affected by the onset of pumping in well HP-634, causing the TCE plume to migrate somewhat backward toward the water-supply well. Sources around Buildings 901–903 were probably removed prior to remediation efforts that began around January 1995 (Sovereign Consulting Inc. 2007), but specific installation and removal dates are unknown (Table A8).

TCE releases around Buildings 1115 and 1401 have been documented to a lesser degree. The presence of chlorinated alkenes around Building 1115 is documented by Faye et al. (2012, Table D5), and the concentrations varied from below detection limits to maximum values of 160 µg/L for TCE, 11 µg/L for PCE, 110 µg/L for total DCE, and 6 µg/L for VC. The chlorinated alkenes found around Building 1115 are presumably the result of natural attenuation of TCE. The application of the aforementioned TCE sources in the HPIA for contaminant fate and transport modeling is discussed herein in the section on Trichloroethylene (TCE) Concentrations in Groundwater and in detail in Jones et al. (2013).

The area identified in this report as the HPLF (Figures A8 and A10) consists of part of IRP site 6 (Storage/Disposal Lot 203) and IRP site 82 (VOC Disposal Area at Piney Green Road), which are described in Faye et al. (2010). These IRP sites were actively used as waste disposal areas beginning during the 1940s. Maximum measured TCE concentrations in groundwater have been detected at monitor well 06-GW01D and ranged from 6,400 to 180,000 µg/L (Table A8). Corresponding concentrations of total 1,2-dichloroethylene (1,2-DCE) and VC ranged from 730 to 36,000 µg/L and from 10 to 800 µg/L, respectively, indicating that degradation pathways were essentially complete at IRP site 6 as early as 1993. Concentrations of PCE at IRP site 6 detected in monitor well 06-GW01D ranged from an estimated 210 to 6,500 µg/L. Other monitor wells contained detections of TCE and (or) PCE at concentrations greater than detection limits. For example, total VOCs at monitor well 06-GW01D are reported in Faye et al. (2010, Figures C21 and C22) to exceed 12,100 µg/L during January 2002 and 22,900 µg/L during July 2004. Areal distributions of TCE are also provided in Faye et al. (2010, Figures C23 and C24) and indicate that TCE distributions within the Upper Castle Hayne aquifer–River Bend unit exceeded 50,000 µg/L during January 2000.

Specific data pertinent to the timing of initial deposition of contaminants to the ground or subsurface, chronologies of waste-disposal operations, such as dates and times when contaminants were deposited in the HPLF, or descriptions of the temporal variation of contaminant concentrations in the subsurface generally are not available. Determining these types of source identification and characterization data becomes part of the historical reconstruction process, whereby simulation tools such as models are used to test source locations, varying concentrations, and beginning and ending dates for leakage and migration of source contaminants to the subsurface and the underlying groundwater-flow system. The aforementioned contaminant-source information, along with details on site histories provided in Faye et al. (2010, 2012), was used to identify contaminant sources for placement in simulation models of contaminant fate and transport described in Jones et al. (2013) and Jang et al. (2013).

[30] UST 1601 tank capacity is reported as 1,600 gal in Catlin and Associates (1996) and as 1,500 gal in Geraghty and Miller (1990). The 1,600-gal capacity (Catlin and Associates 1996) is used in the ATSDR analyses (Jones et al. 2013).

Historical Reconstruction Methods and Approaches

Given the limited number of historical contaminant-specific data measurements during most of the period relevant to the epidemiological studies, ATSDR used historical reconstruction to estimate the spatial and temporal distributions of contaminant-specific concentrations in groundwater and finished water serving the HPHB study area. Characteristically, historical reconstruction includes the application of simulation tools, such as models, to re-create or represent past conditions (Rodenbeck and Maslia 1998; McLaren/Hart-ChemRisk 2000; Costas et al. 2002; Reif et al. 2003; Kopecky et al. 2004; Maslia et al. 2005; Sahmel et al. 2010). To achieve the goal of reconstructing historical finished-water concentrations, five tasks were undertaken:

1. Identifying chemical compounds and their sources (contaminants of concern) that contaminated finished water at USMCB Camp Lejeune,
2. Estimating when contaminated groundwater arrived at water-supply wells and the duration of the contamination,
3. Determining the distribution of contaminated finished water throughout the water-distribution systems serving the HPHB study area,
4. Quantifying the spatial and temporal distributions of monthly finished-water contaminant concentrations, and
5. Computing contaminant concentration ranges (or bounds) based on conducting sensitivity and uncertainty analyses.

Groundwater was used as the sole source of water supply for USMCB Camp Lejeune. Of critical need, in terms of historical reconstruction, was information and data on the monthly raw water production of supply wells (to enable computation of flow-weighted finished-water concentrations) and the distribution of finished water to family housing areas. The supply of finished water for the HPHB study area was composed of the following: (1) supply of water from groundwater wells to the HPWTP (1942–present) and the HBWTP (1972–present), (2) delivery of finished water from the WTPs through a network of pipelines and storage tanks to housing areas and other facilities, and (3) intermittent transfers of Hadnot Point finished (contaminated) water through connecting pipelines to the Holcomb Boulevard water-distribution system during late spring and early summer months for years 1972–1985. Because the ATSDR epidemiological studies need finished-water concentrations of contaminants of concern at monthly intervals, the use and application of numerical and computational models—herein referred to as the "water-modeling process"—was designed to provide historical finished-water concentrations at these monthly intervals.

Water-Modeling Process

The water-modeling process is characteristically iterative and described by a five-step approach shown graphically in Figure A11. The five steps of the process are (1) review information sources, (2) extract information and data and develop databases, (3) develop, simulate, and calibrate model, (4) determine if model conceptualization or calibration issues exist, and if they do, use subject matter experts (ATSDR water-modeling staff) to iteratively refine model databases and search for additional information sources, and (5) assess when sufficient agreement exists between water-level and contaminant concentration data (historical and present-day) and model results. At that point, historical finished-water concentration simulation results are extracted from model-output databases and provided to ATSDR health studies staff for use in the USMCB Camp Lejeune epidemiological analyses.[31] This iterative five-step water-modeling process was applied to all historical reconstruction analyses for USMCB Camp Lejeune.

The analyses and simulation tools used as part of the historical reconstruction process for the HPHB study area are listed in Table A9. Brief descriptions of each analysis and simulation tool, the type of analysis (e.g., data analysis, interpretation, simulation), and supporting references also are listed in Table A9. For specific details pertinent to a particular model or model code, refer to the appropriate Chapter A supplement listed in the reference citations in Table A9. Using the data extracted from various information sources (Appendix A2), the following components (listed in Table A9) composed the water-modeling process shown in Figure A11.

1. Geohydrologic framework information, aquifer and confining unit hydraulic data, and climatic data were used to determine predevelopment (prior to 1942) groundwater-flow characteristics.[32] Detailed analyses of well and geohydrologic data used to develop the framework of the Brewster Boulevard and Castle Hayne aquifer systems and Tarawa Terrace aquifer are described in Faye (2012).
2. Water-level data were used to characterize groundwater flow in the study area. Detailed water-level data and analyses are presented in Faye et al. (2013).
3. To simulate predevelopment groundwater-flow conditions, the code MODFLOW-2005 (Harbaugh 2005)—a three-dimensional groundwater-flow model code—was used.[33] Estimates of model parameter values also were obtained

[31] ATSDR water-modeling staff was blinded to the status and locations of cases and controls of the epidemiological studies.

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

[33] MODFLOW-2005 (Harbaugh 2005) is the specific MODLFOW code used for the HPHB study area analyses; references to MODFLOW in text, figures, tables, appendixes, and supplemental information refer to MODFLOW-2005.

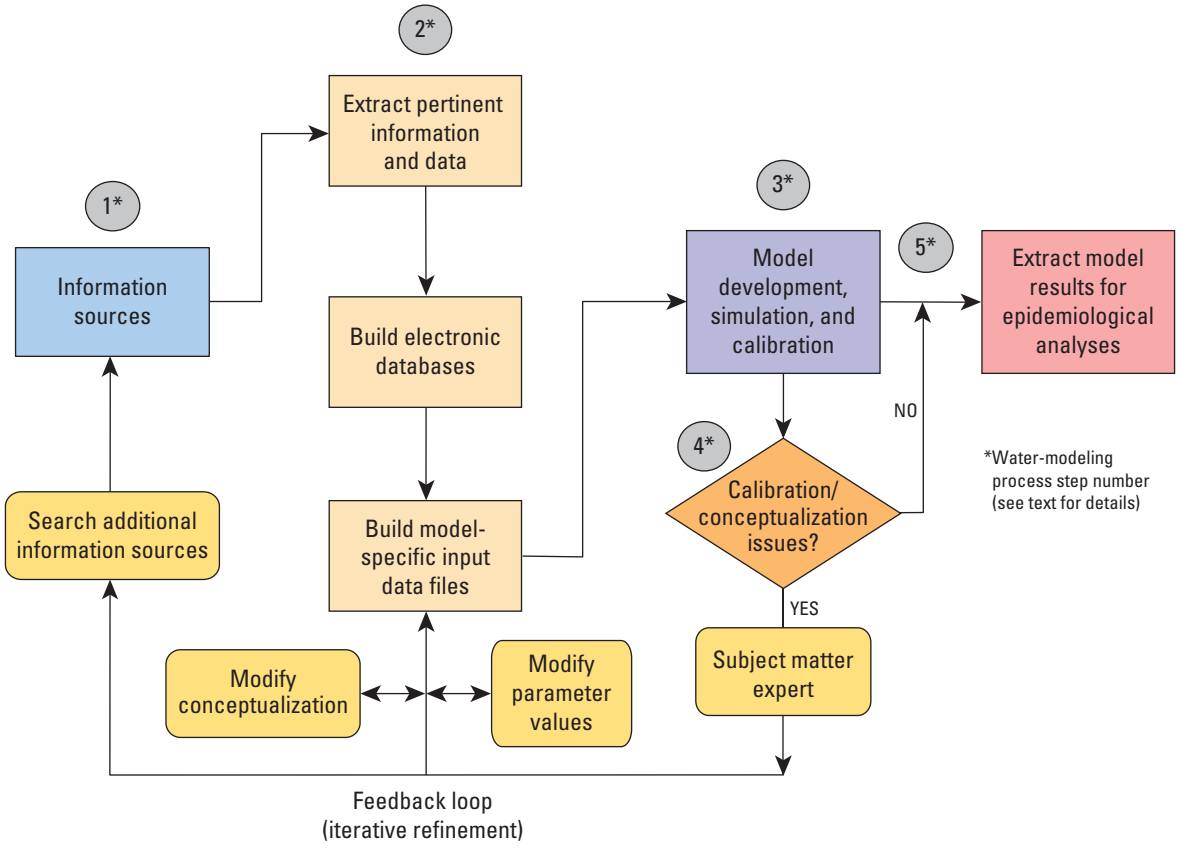


Figure A11. Water-modeling process used for reconstructing historical finished-water concentrations, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

using the objective parameter estimation code PEST-12 (Doherty 2003, 2010).[34] For predevelopment groundwater flow, the study area was characterized using a model grid consisting of uniform finite-difference cells of 300 feet (ft) × 300 ft (152 rows, 172 columns, and 7 layers). Total model area is 84 square miles (mi^2), and the active model domain area is 50 mi^2 (Table A10). Details are provided in Suárez-Soto et al. (2013).

4. To simulate the transient (unsteady) effects caused primarily by the onset and continued operation of water-supply wells in the study area, historical water-supply well operating schedules were developed. This was accomplished by documenting water-supply well capacities and histories (Sautner et al. 2013a) and reconstructing operating schedules on a monthly basis for the period 1942–2008 (Telci et al. 2013); operational chronologies for all water-supply wells in the study area also are shown in Figure A5.

5. Transient groundwater conditions primarily caused by the onset and continued operation of water-supply wells within the HPHB study area (and the onset of remediation pumping during the late 1990s and 2000s) also were simulated using the MODFLOW three-dimensional groundwater-flow model code. Water-supply well operations were accounted for and could vary on a monthly basis. To address historical water-supply well operations and the absence of nearby hydrologic boundaries, the active model domain (Figure A12) was further discretized into two individual variably spaced grid models, one for the HPIA and one for the HPLF. Grid cell sizes ranged from 300 ft × 300 ft in areas distant from the HPIA and HPLF area to uniform grid cells of 50 ft × 50 ft within the HPIA and HPLF area. The uniform 50-ft × 50-ft cell model areas for the HPIA and the HPLF are herein referred to as the contaminant fate and transport subdomain model areas. (A single variably spaced grid model that contained both the HPIA and HPLF area with 50-ft × 50-ft cell areas was not developed due to computational limitations.[35]) The HPIA variably spaced grid model is characterized by 288 rows, 298 columns, and 7 layers;

[34] PEST-12 (Doherty 2003, 2010) is the specific PEST code used for parameter estimation; references to PEST in text, figures, tables, appendixes, and supplemental information refer to PEST-12.

[35] The Tarawa Terrace study demonstrated that finite-difference cells could not have larger dimensions than 50 ft × 50 ft (Faye 2008) to satisfy numerical fate and transport simulation properties associated with the Peclet number (Daus and Frind 1985; Zheng and Bennett 2002). This cell-size dimension constraint also was applied to the HPIA and HPLF subdomain areas (Figure A12). See additional discussion in the Sensitivity Analysis section of this report and in Jones et al. (2013).

Table A9. Analyses and simulation tools used to reconstruct historical finished-water concentrations, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[ft, foot; HPIA, Hadnot Point Industrial Area; HPLF, Hadnot Point landfill; VOC, volatile organic compound; BTEX, benzene, toluene, ethylbenzene, and xylenes; IRP, Installation Restoration Program; AST/UST, above-ground storage tank/underground storage tank; TCE, trichloroethylene; PCE, tetrachloroethylene; GIS, geographic information system; LNAPL, light nonaqueous phase liquid; 1,2-tDCE, *trans*-1,2-dichloroethylene; VC, vinyl chloride; WTP, water treatment plant]

Analysis	Description	Analysis type and simulation tool	[1] Reference
Geohydrologic framework	Detailed analyses of well and geohydrologic data used to develop framework of the Brewster Boulevard and Castle Hayne aquifer systems and Tarawa Terrace aquifer	Data analysis and interpretation	Faye (2012)
Water-level analyses and groundwater flow	Characterizations of water-level data and groundwater flow	Data analysis and interpretation	Faye et al. (2013)
Predevelopment groundwater flow	Steady-state, three-dimensional groundwater flow, occurring prior to initiation of water-supply well activities (1942) using a grid of uniform cells of 300 ft × 300 ft	Simulation using MODFLOW-2005	Harbaugh (2005); Suárez-Soto et al. (2013)
Historical water-supply well operations	Documenting water-supply well capacities, histories, and reconstructing operating schedules on a monthly basis for the period 1942–2008	Data analysis, interpretation, and simulation using TechWellOp	Sautner et al. (2013a); Telci et al. (2013)
Transient groundwater flow	Unsteady-state, three-dimensional groundwater flow occurring primarily because of the initiation and continued operation of water-supply wells (July 1942–June 2008), using a variably spaced grid ranging in area from 300 ft × 300 ft to 50 ft × 50 ft in the HPIA and HPLF model subdomain areas	Simulation using MODFLOW-2005	Harbaugh (2005); Suárez-Soto et al. (2013)
Properties of VOCs in groundwater	Properties of degradation pathways of common organic compounds in groundwater	Literature survey	Lawrence (2007)
Occurrence of selected contaminants in groundwater	Description and summaries of groundwater contaminants of selected VOCs and BTEX components at IRP and AST/UST sites; listing of water-supply and monitor well location and construction data	Data analysis	Faye et al. (2010, 2012)
Computation of mass for PCE, TCE, and benzene	Estimates of mass (volume) of TCE, PCE, and benzene in groundwater using field data and a variety of analytical and numerical techniques (Tables A6, A15, and A16)	Site investigation data, GIS spatial analyses, LNAPL volume analyses (TechNAPLVol)	Ricker (2008); Faye et al. (2010, 2012); Jones et al. (2013); Jang et al. (2013)
Fate and transport of TCE, PCE, and benzene	Simulation of the fate and migration of TCE and benzene from sources in the HPIA; simulation of the fate and migration of PCE from the HPLF	Simulation using MT3DMS-5.3	Zheng and Wang (1999); Zheng (2010); Jones et al. (2013)
Fate and transport of benzene (LNAPL)	Simulation of the fate and migration of benzene as an LNAPL from sources at the Hadnot Point fuel farm in the HPIA	Simulation using TechFlowMP	Jang and Aral (2007, 2008a, b); Jang et al. (2013)
Concentrations of PCE, TCE, 1,2-tDCE, and VC in a water-supply well	Reconstructing concentrations of PCE, TCE, 1,2-tDCE, and VC in water-supply well HP-651 (HPLF) using a linear control model (LCM) methodology	Simulation using TechControl	Guan et al. (2009, 2010, 2013)
TCE, PCE, 1,2-tDCE, VC, and benzene in WTP finished water	Computations of concentrations of TCE, PCE, 1,2-tDCE, VC, and benzene in drinking water from the Hadnot Point WTP using results from fate and transport and linear control model simulations	Materials mass balance model using principles of conservation of mass and continuity—algebraic	Masters (1998); Jones et al. (2013)
Parameter sensitivity and uncertainty	Assessment of parameter sensitivity and uncertainty associated with model simulations of groundwater flow, fate and transport, and water distribution	One-at-a-time sensitivity analysis (OAT), Monte Carlo (MC) simulation using Latin hypercube sampling (LHS), and MC simulation	Saltelli et al. (2000); Suárez-Soto et al. (2013); Jones et al. (2013); Sautner et al. (2013b)
Intermittent pump operation for transfer of finished water	Probabilistic analysis of the occurrence of pumping operations during the period 1972–1985 for transferring Hadnot Point finished water to Holcomb Boulevard housing areas	Probabilistic Markov analysis using TechMarkovChain	Ross (1977); Sautner et al. (2013b)
Distribution of TCE, PCE, 1,2-tDCE, VC, and benzene throughout the Holcomb Boulevard housing areas	Simulation of hydraulics and water quality in the water-distribution system serving the Holcomb Boulevard housing areas, 1972–1985; intermittent pumping operations estimated by using data and Markov analysis	Simulation using EPANET 2	Rossman (2000); Sautner et al. (2013b)

[1] Refer to Table A1 for correspondence between references and HPHB study area chapter reports and supplement designations

Table A10. Description and characteristics of model properties used to simulate three-dimensional groundwater flow and contaminant fate and transport, Hadnot Point–Holcomb Boulevard and Tarawa Terrace study areas, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[ft, foot; mi², square mile; TCE, trichloroethylene; PCE, tetrachloroethylene; —, not applicable]

Model feature	[1]Hadnot Point–Holcomb Boulevard study area					[4]Tarawa Terrace study area
	[2]Uniform grid	[3]Variably spaced grid		Fate and transport model subdomain		
		Hadnot Point Industrial Area	Hadnot Point landfill area	Hadnot Point Industrial Area	Hadnot Point landfill area	
Number of rows	152	288	348	132	204	200
Number of columns	172	298	268	168	132	270
Number of layers	7	7	7	7	7	7
Total number of finite-difference cells	183,008	600,768	652,848	155,232	188,496	378,000
Number of active domain or subdomain cells	108,695	453,654	532,287	155,232	188,496	191,927
Finite-difference cell size (ft×ft)	300×300	300×300–50×50	300×300–50×50	50×50	50×50	50×50
Total model or subdomain area (mi²)	84	84	84	2.0	2.4	4.8
Active domain area (mi²)	50	50	50	2.0	2.4	2.5
Contaminant-source areas (contaminants)	—	—	—	Building 900 (TCE); Building 1115 (TCE); Building 1401 (TCE); Building 1601 (TCE, benzene)[5]	Hadnot Point landfill (PCE, TCE)	ABC One-Hour Cleaners (PCE)

[1] Groundwater-flow simulation using MODFLOW-2005 (Harbaugh 2005); fate and transport simulation using MT3DMS (Zheng and Wang 1999); see Figure A12 for locations of active model boundaries and contaminant fate and transport model subdomains

[2] Uniform grid of 300-ft×300-ft cells used for simulating and calibrating predevelopment (steady-state) groundwater flow

[3] Variably spaced grid used for simulating and calibrating transient groundwater flow and contaminant fate and transport

[4] Groundwater-flow simulation using MODFLOW-96 (Harbaugh and McDonald 1996); fate and transport simulation using MT3DMS (Zheng and Wang 1999); uniform and coincident grids used for groundwater-flow and fate and transport simulations, refer to Maslia et al. (2007), Faye and Valenzuela (2007), and Faye (2008)

[5] Benzene occurs as a light nonaqueous phase liquid (LNAPL) at Building 1115 and at the Hadnot Point fuel farm (HPFF); see Jang et al. (2013) for modeling details.

the corresponding HPLF area model is characterized by 348 rows, 268 columns, and 7 layers. The HPIA subdomain model is 2.0 mi² in area and consists of 132 rows, 168 columns, and 7 layers; the corresponding HPLF area subdomain model is 2.4 mi² in area and consists of 204 rows, 132 columns, and 7 layers. Descriptions and characterizations of the groundwater-flow model discretization properties used to simulate three-dimensional groundwater flow and contaminant fate and transport in the HPHB study area and comparison with the model used in the TT study area are listed in Table A10. A map of the active model domain for groundwater flow and the HPIA and HPLF area subdomain model areas selected for transient groundwater flow and contaminant fate and transport is shown in Figure A12.

6. Groundwater velocities or specific discharges derived from the calibrated transient groundwater-flow model were used in conjunction with contaminant source, fate, and property data in the HPIA to simulate the fate and transport of TCE and benzene (as single species) dissolved in groundwater using the model code MT3DMS-5.3 (Zheng and Wang 1999; Zheng 2010).[36] In addition, the fate and transport of PCE and TCE from source areas in the HPLF area to water-supply well HP-651 was also simulated using the MT3DMS code. As explained above, variably spaced finite-difference grids were used for HPIA and HPLF contaminant fate and transport model subdomain areas so that grid cell sizes would be uniform at 50 ft × 50 ft. Details pertaining to the fate and transport model calibration and reconstruction of PCE, TCE, and benzene dissolved in groundwater are provided in Jones et al. (2013). The HPIA and HPLF contaminant fate and transport model subdomain areas, contaminant sources, and nearby historically operated water-supply wells are shown in Figures A13 and A14, respectively.

[36] MT3DMS-5.3 (Zheng and Wang 1999; Zheng 2010) is the specific version of the MT3DMS code used for the HPHB study area analyses; references to MT3DMS in text, figures, tables, appendixes, and supplemental information refer to MT3DMS-5.3.

7. The occurrence of benzene as an LNAPL in the subsurface in the vicinity of the HPFF and HPIA is described in Faye et al. (2010 and 2012). Estimates of subsurface LNAPL volume were developed using historical measurements of LNAPL thickness over time—monitor well data—in the HPIA combined with the TechNAPLVol code that uses semi-analytical and numerical methods in a three-dimensional domain (Jang et al. 2013). The resulting saturation profile from the LNAPL volume analysis was used within the TechFlowMP model code (Jang and Aral 2007, 2008a, b) to simulate the dissolution of LNAPL constituents and the fate and transport of dissolved-phase benzene. Details pertinent to the application of TechFlowMP to the HPIA subdomain area and historical reconstruction results for the fate and transport of benzene are described in detail by Jang et al. (2013). The historical area of free product (fuel) and location of former fuel lines from the HPFF to other sites within the HPIA are shown in Figure A13.

8. An alternative method, a linear state-space representation of a contaminated aquifer system designated as the linear control model (LCM) methodology, was developed to reconstruct contaminant concentrations in water-supply wells (Guan et al. 2013). Using the model code TechControl, this simplified approach was used to reconstruct historical contaminant concentrations, including PCE, TCE, 1,2-tDCE, and VC, in water-supply well HP-651 in the HPLF area (Figure A14). Details pertinent to the development, testing, and application of the LCM methodology are presented in Guan et al. (2013). Results from the LCM application at water-supply well HP-651 are compared to simulated PCE and TCE concentrations obtained using the MT3DMS numerical fate and transport code (item 6, above) later in this report.

9. Reconstructed (simulated) monthly mean concentrations of PCE, TCE, 1,2-tDCE, VC, and benzene for finished water at the HPWTP were determined by using a materials mass balance model (simple mixing) to compute the flow-weighted average concentration of the aforementioned contaminants. This computational method is based on the principles of continuity and conservation of mass (Masters 1998). The use of the materials mass-balance method is justified because all raw water from water-supply wells within the HPWTP service area was mixed at the HPWTP prior to treatment and distribution. Details of this method are described in a subsequent section of this report.

10. Intermittent operations of booster pump 742 and the opening of the Marston Pavilion valve transferred contaminated Hadnot Point finished water to Holcomb Boulevard family housing areas and other facilities (Figure A1). Owing to missing data related to pump and valve operations, probabilistic analyses of the intermittent water transfers during the period 1972–1985 were conducted using a Markov analysis (Ross 1977) and the code TechMarkovChain. Results provided probabilistic estimates of the intermittent transfer of contaminated Hadnot Point finished water to the Holcomb Boulevard family housing areas. Details of the application of the TechMarkovChain code to the HPHB study area are described in Sautner et al. (2013b).

11. Using the reconstructed monthly mean concentrations of PCE, TCE, 1,2-tDCE, VC, and benzene in finished water from the HPWTP and the Markov analysis to estimate the occurrence of intermittent water transfers, extended period simulations of hydraulics and water quality for the water-distribution system serving the Holcomb Boulevard housing areas and other facilities during the period 1972–1985 were conducted using the model code EPANET 2 (Rossman 2000). Details pertaining to these analyses are presented in Sautner et al. (2013b) and are summarized in a subsequent section of this report.

12. Assessment of parameter sensitivity, variability, and uncertainty associated with model simulations of groundwater flow, contaminant fate and transport, and water-distribution system analyses were conducted using one-at-a-time (and a variation of the one-at-a-time) sensitivity analysis (Saltelli et al. 2000), Monte Carlo simulation (Tung and Yen 2005), and the parameter estimation code PEST (Doherty 2003, 2010). Details relevant to the application of parameter estimation and sensitivity and uncertainty analyses for the HPHB study area models are provided in Guan et al. (2013), Jang et al. (2013), Jones et al. (2013), Sautner et al. (2013b), and Suárez-Soto et al. (2013), and are summarized in subsequent sections of this report.

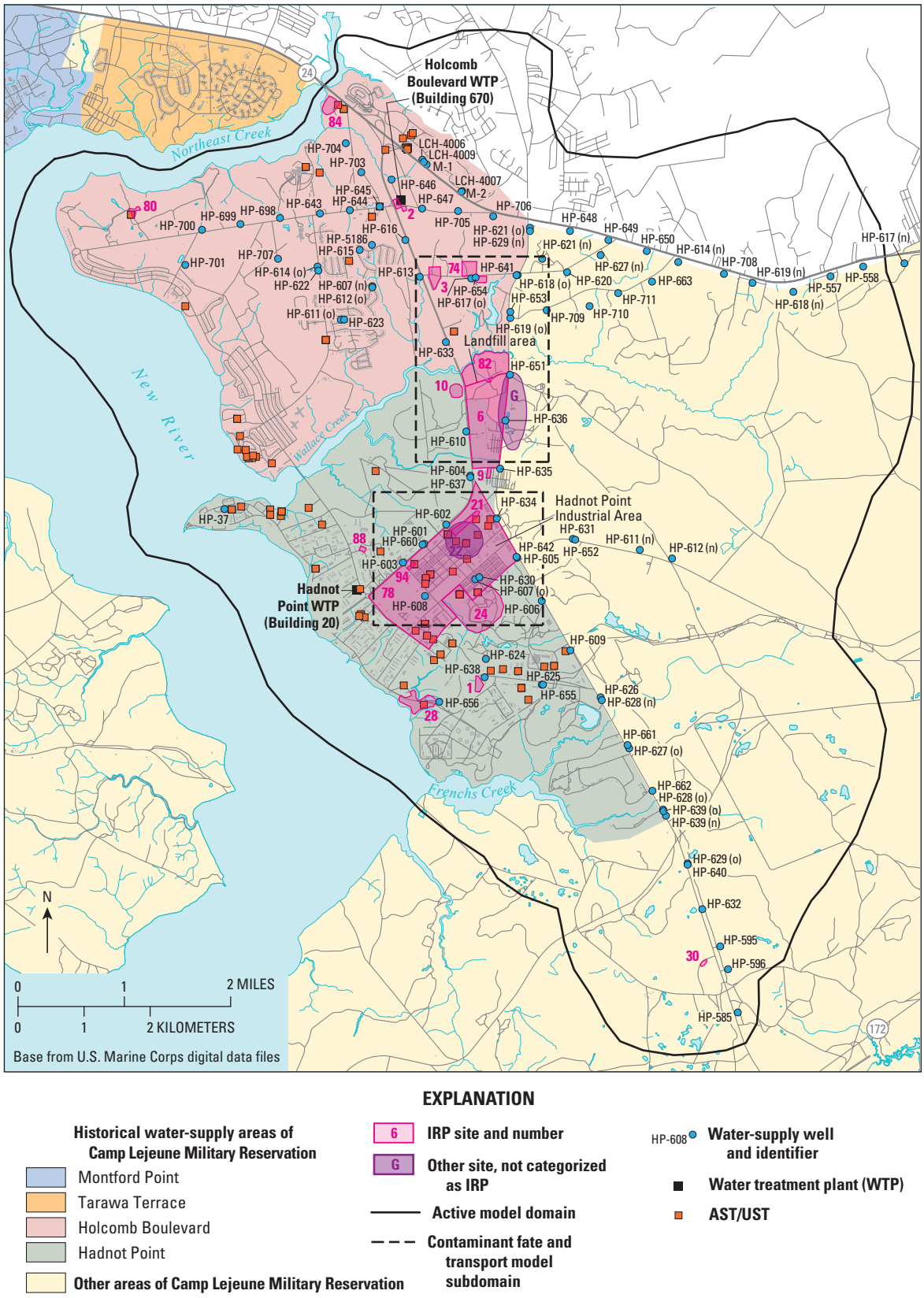


Figure A12. Groundwater-flow model domain, contaminant fate and transport model subdomains, Installation Restoration Program (IRP) sites, above-ground and underground storage tank (AST/UST) sites, and water-supply wells, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

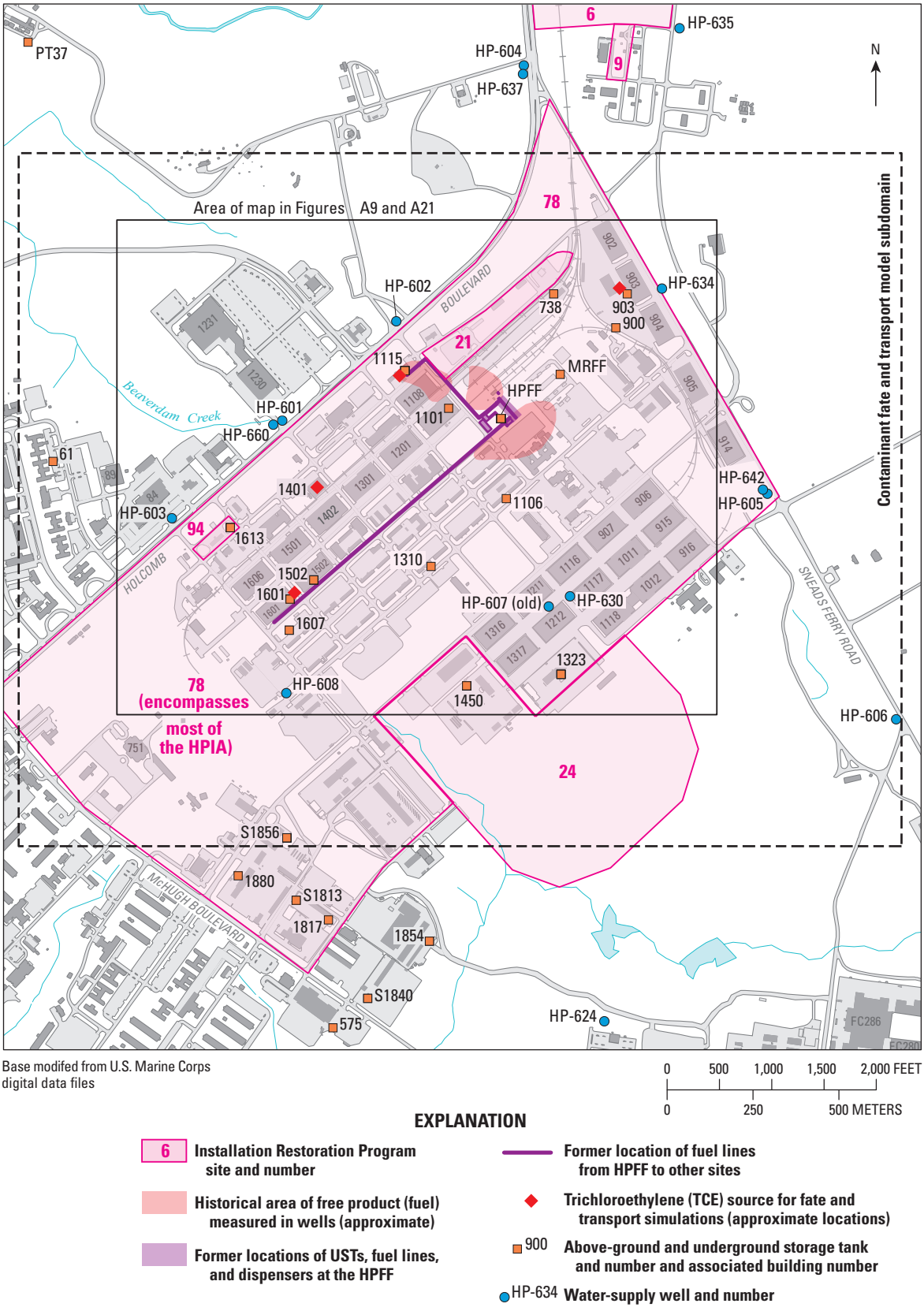


Figure A13. Contaminant fate and transport model subdomain for the Hadnot Point Industrial Area (HPIA) and vicinity, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. [HPFF, Hadnot Point fuel farm; MRFF, Michael Road fuel farm; UST, underground storage tank]

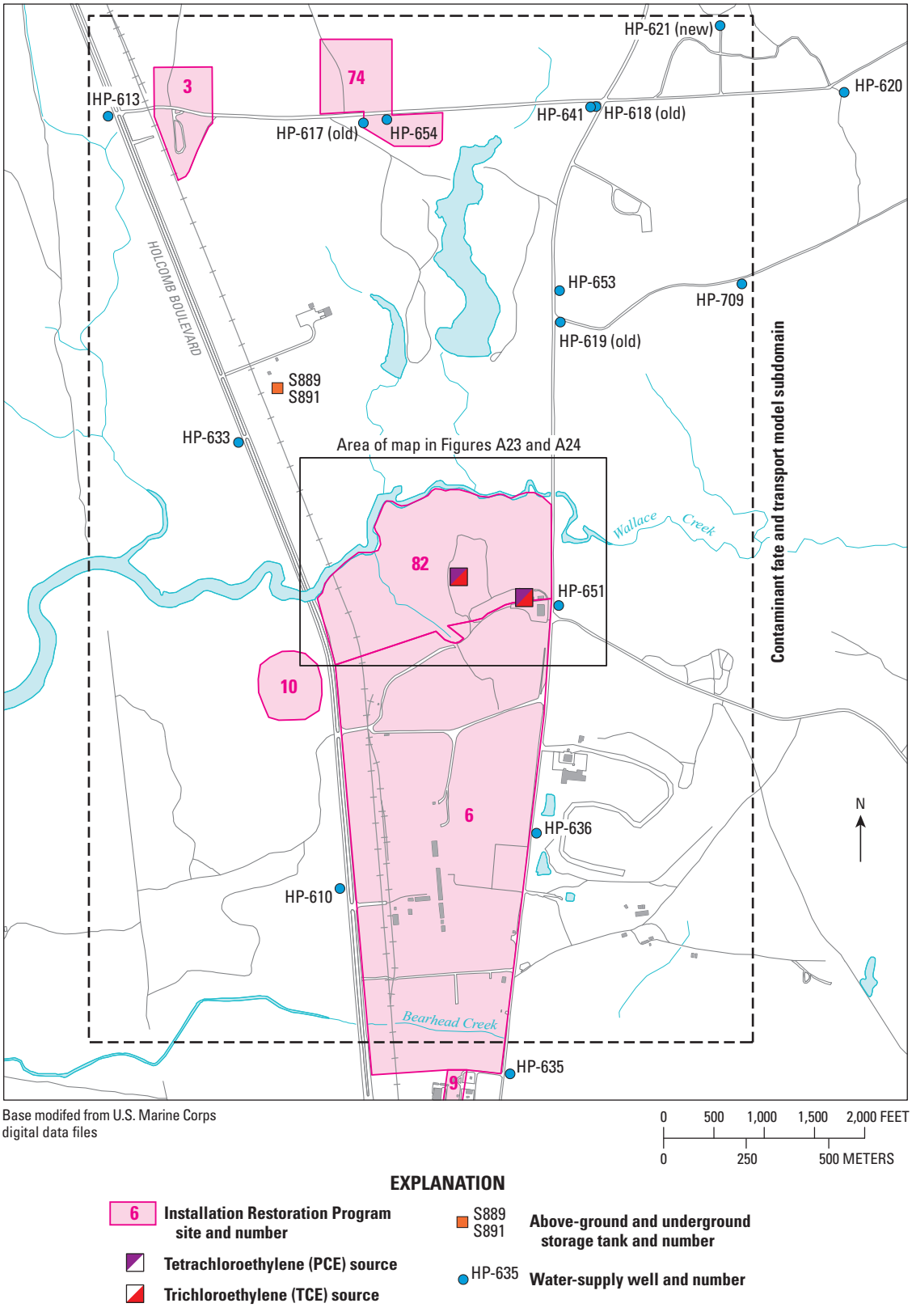


Figure A14. Contaminant fate and transport model subdomain for the Hadnot Point landfill (HPLF) area and vicinity, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Model Calibration Approach

Detailed discussions pertinent to model calibration approaches and good model calibration practice are provided in Hill and Tiedeman (2007). Calibrations of models used for the HPHB study area analyses were accomplished in a hierarchical or step-wise approach consisting of four successive stages or levels. Simulation results achieved for each calibration level were refined by adjusting model parameter values and comparing these results with simulation results of previous levels until results at all levels were within ranges of reasonable calibration measures. The step-wise order of model-calibration levels consisted of simulating (1) predevelopment (steady or nonpumping) groundwater-flow conditions, (2) transient (time varying or pumping) groundwater-flow conditions, (3) the fate and transport (migration) of VOCs (PCE, TCE, and benzene) from their sources at the HPIA and HPLF areas to Hadnot Point water-supply wells, and (4) the concentrations of VOCs in finished water at the HPWTP.[37] During the period 1972–1985, the intermittent transfer of contaminated Hadnot Point finished water to Holcomb Boulevard family housing areas was also simulated using calibrated finished-water concentrations at the HPWTP from step 4 above. Detailed discussion of calibration procedures, calibration results and statistics, and simulation results are provided in the respective Chapter A supplemental information sections (Table A1, Appendix A1). Of note are the following five Chapter A supplemental information sections that readers can refer to for specific details pertinent to model input data, calibration procedures, and historical reconstruction results:

- Three-dimensional groundwater flow (predevelopment and transient)—described in Suárez-Soto et al. (2013);
- Three-dimensional contaminant fate and transport of PCE, TCE, and benzene in the vicinities of the HPIA and HPLF area—described in Jones et al. (2013);
- Linear control theory methodology to reconstruct contaminant concentrations of PCE, TCE, 1,2-tDCE, and VC in water-supply well HP-651—described in Guan et al. (2013);
- Dissolution of benzene from an LNAPL source area and subsequent three-dimensional fate and transport of dissolved-phase benzene in the HPIA—described in Jang et al. (2013); and
- Distribution of finished water from the HPWTP to the Holcomb Boulevard water-distribution system—described in Sautner et al. (2013b).

Linear Control Model Methodology to Reconstruct Water-Supply Well Concentrations

The typical approach used to simulate water-supply well concentrations for contaminants dissolved in groundwater is to (1) apply a groundwater-flow model (e.g., MODFLOW) to the study area containing pumping water-supply wells, (2) extract groundwater velocities from the groundwater-flow model simulation results, and (3) use the temporally and spatially varying velocities in conjunction with contaminant-source, fate, and transport properties with a fate and transport model code (e.g., MT3DMS) to quantify contaminant concentrations at water-supply wells. This was the approach used for the TT study area (Faye and Valenzuela 2007; Faye 2008) and also is the approach applied to the HPHB study area. An alternative computational method to reconstruct contaminant concentrations in water-supply wells also was investigated because (1) perhaps a simpler computational method requiring fewer resources could yield reliable historical reconstruction results and (2) results from an alternative computational method, if reliable, could be used to assess confidence in results derived from the MODFLOW and MT3DMS simulations. For these reasons, the linear control model (LCM) methodology, which is a linear state-space representation of a contaminated groundwater aquifer system, was developed and applied to water-supply well HP-651 (Figure A14) using the HPLF area contaminant data (Guan et al. 2009, 2010, 2013). The LCM methodology, which is based on linear control theory (Aliev and Larin 1998; Pardalos and Yatsenk 2008), does not require site-specific knowledge of the spatial distribution of aquifer and transport properties (e.g., hydraulic conductivity, porosity, contaminant source concentration). Rather, it relies on two matrices to describe (1) the subsurface movement of a contaminant under predevelopment or natural conditions and (2) the effects of pumping operations on contaminant concentrations. This method, therefore, characterizes the aquifer, contaminant sources, and the dynamics of contaminant migration as a "black box."[38] The LCM methodology can be applied to individual water-supply wells to reconstruct historical concentrations; however, this method does require contaminant concentration data from the water-supply well and some nearby monitor wells once the water-supply well has ceased pumping. Details of the LCM methodology development and application to the HPLF area are provided in Guan et al. (2013). Comparisons between results obtained using a numerical model, MT3DMS, and the LCM are presented and discussed in the section on Historical Reconstruction Analyses and Results.

[37] A detailed discussion of the aforementioned hierarchical approach of model calibration is provided in Maslia et al. (2007), Faye and Valenzuela (2007), and Faye (2008).

[38] In science and engineering, the term "black box" refers to a device or system that can be analyzed in terms of inputs, transfer properties, and outputs, without specific knowledge of its internal dynamic workings.

Computation of Contaminated Finished-Water Concentrations

Two approaches were utilized to compute historical concentrations of finished water delivered to housing areas within the HPHB study area. The specific approach depended on whether or not water was transferred from the Hadnot Point to the Holcomb Boulevard water-distribution system (i.e., the intermittent connection of the aforementioned two water-distribution systems). Groundwater from all water-supply wells was mixed at the HPWTP prior to treatment and distribution. Therefore, a materials mass balance (simple mixing) model, which is based on the principles of continuity and conservation of mass (Masters 1998), was used as one approach to compute monthly mean concentrations of finished water delivered to base housing and other facilities during the period 1942–May 1972. Application of the simple mixing model presumes that the computed concentrations of finished water at the WTP are nearly equal to the concentrations of finished water at any location throughout the WTP service area. This approach was used by Maslia et al. (2007) to reconstruct historical finished-water concentrations for the TT study area and is represented by the schematic diagram shown in "A. Mixing-model approach" in Figure A15. This approach was tested and confirmed by Maslia et al. (2009b) by comparing mixing-model results with EPANET 2 (Rossman 2000) water-distribution system model results. (The schematic representation of the network model is shown in "B. Network-model approach" in Figure A15.) Maslia et al. (2009b) demonstrated that after 2 weeks, spatially distributed concentrations throughout the TT water-distribution system—computed using EPANET 2—were identical to the concentrations at the TTWTP computed using the mixing-model approach (Figure A15*A*). Because study epidemiologists require monthly finished-water concentrations, the mixing-model approach was considered a useful method to compute historical finished-water concentrations at the HPWTP and at locations serviced by the HPWTP for any given historical month.[39]

[39] Prior to the onset of service at the HBWTP during June 1972 (Scott A. Brewer, USMCB Camp Lejeune, written communication, September 29, 2005).

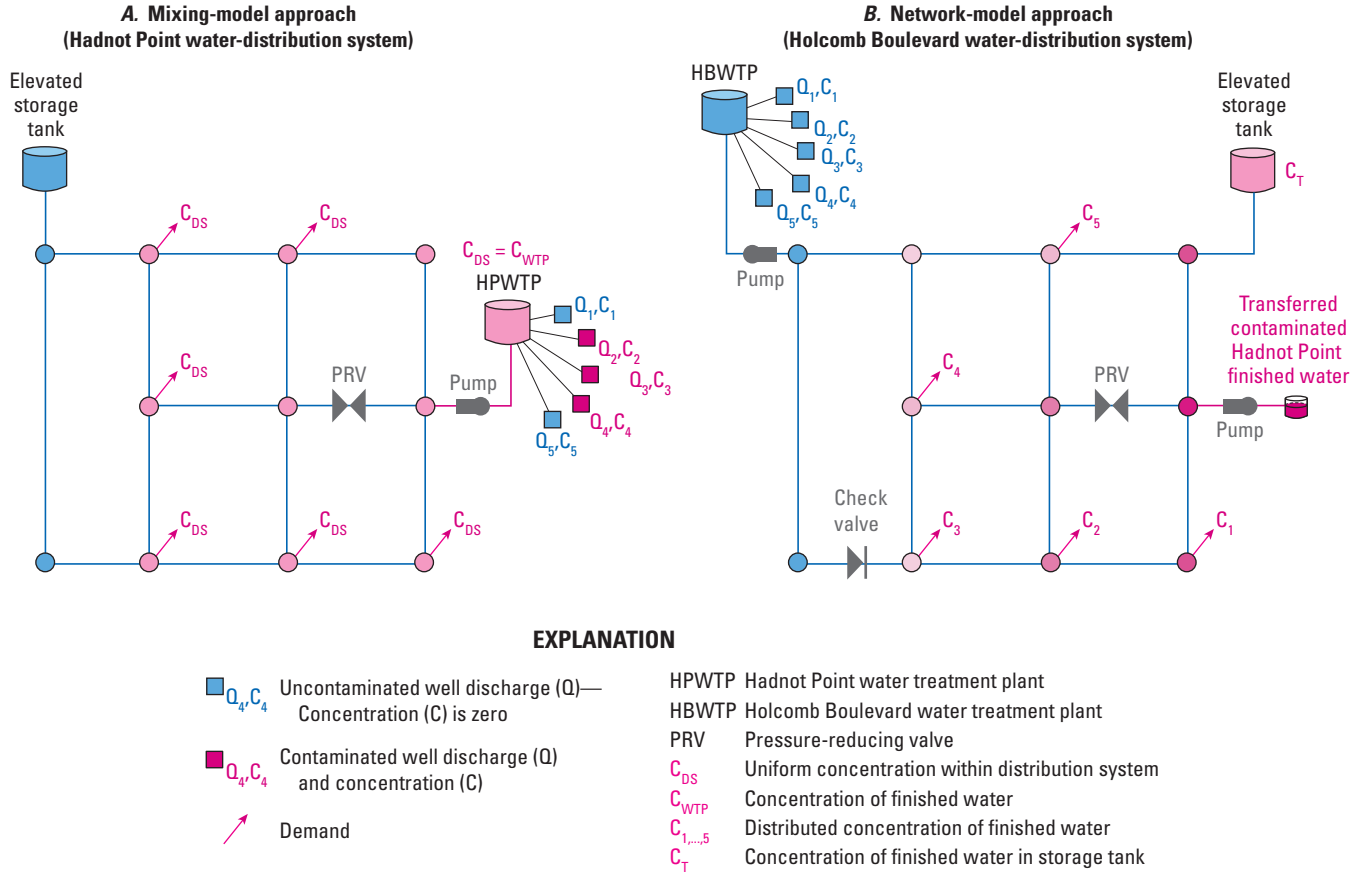


Figure A15. Schematic node-link representations for water-distribution systems: *(A)* mixing-model approach used for the Hadnot Point water treatment plant analyses and *(B)* network-model approach used for the Hadnot Point–Holcomb Boulevard interconnection analyses, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

The materials mass balance (mixing model) approach is based on the following equations:

$$Q_T = \sum_{i=1}^{NWP} Q_i \qquad \text{(A1)}$$

and

$$C_{WTP} = \frac{\sum_{i=1}^{NWP} C_i Q_i}{Q_T}\ , \qquad \text{(A2)}$$

where

NWP is the number of water-supply wells simulated as operating (pumping) during the month of interest,

Q_i is the simulated groundwater pumping rate of water-supply well i,

Q_T is the total simulated groundwater pumping rate from all operating water-supply wells during the month of interest,

C_i is the simulated concentration of a contaminant for water-supply well i, and

C_{WTP} is the concentration of finished water delivered from the HPWTP for the month of interest.

Equation A1 is known as the continuity equation, and Equation A2 describes the conservation of mass (Masters 1998). In addition to contaminated water-supply wells (Figures A5 and A8), all other operating water-supply wells for each month of the historical reconstruction that were not contaminated (C_i = 0.0 µg/L, in Equation A2) are included in the calculations of Equations A1 and A2 to derive the monthly mean finished-water concentrations delivered by the HPWTP.

Alternatively, if water from all supply wells is not completely mixed at the WTP, then a more rigorous and complex water-distribution system modeling approach must be used to quantify the spatial distribution of contaminant concentrations within each water-distribution system and, specifically, within each pipeline of a water-distribution system network. A schematic node-link representation of the interconnection between the Hadnot Point and Holcomb Boulevard water-distribution systems is shown in Figure A15*B*, representing a hypothetical variation in finished-water concentrations within a water-distribution system network. In this situation, a numerically-based water-distribution system model, such as EPANET 2 (Rossman 2000), is routinely applied and calibrated to determine the spatial and temporal distributions of finished-water concentrations within the water-distribution system. A detailed description and discussion of the application of the EPANET 2 model to the distribution of contaminated finished water within the Holcomb Boulevard water-distribution system during intermittent water transfers for 1972–1985 are provided in Sautner et al. (2013b).

Historical Reconstruction Analyses and Results

Summaries of results of the historical reconstruction investigations within the HPHB study area are discussed and presented in the following sections of this Chapter A report. Results are presented for the following: (1) simulation of three-dimensional groundwater flow within the study area, (2) simulations of the migration of TCE within the HPIA fate and transport model subdomain, (3) estimation of LNAPL volumes in the subsurface using semi-analytical solutions and numerical integration, LNAPL dissolution, and migration of benzene within the HPIA fate and transport model subdomain, (4) simulation of the migration of PCE and TCE within the HPLF fate and transport model subdomain, (5) simulation of concentrations of PCE, TCE, 1,2-tDCE, and VC at water-supply well HP-651, located within the HPLF area (Figure A14), (6) computation of contaminant mass balances derived from using the MT3DMS fate and transport model code, (7) computation of monthly mean finished-water concentrations of PCE, TCE, 1,2-tDCE, VC, and benzene at the HPWTP, and (8) reconstructed concentrations of PCE, TCE, 1,2-tDCE, VC, and benzene within the Holcomb Boulevard housing areas during periods of intermittent water transfers from the HPWTP to the HBWTP service areas during 1972–1985.

A listing of reconstructed (simulated) monthly mean concentrations in groundwater at historically contaminated and other selected water-supply wells in the HPIA and HPLF area (HP-601, HP-602, HP-603, HP-608, HP-634, HP-651, and HP-660) is provided in Appendix A3.[40] Maps showing reconstructed (simulated) water levels and distributions of TCE and benzene within the HPIA fate and transport model subdomain are provided in Appendixes A4 and A5, respectively. Maps showing reconstructed water levels and distributions of TCE and PCE within the HPLF area contaminant fate and transport model subdomain are provided in Appendix A6. A listing of reconstructed monthly mean concentrations of PCE, TCE, 1,2-tDCE, VC, and benzene in finished water at the HPWTP is provided in Appendix A7. Finally, a listing of the monthly finished-water concentrations of PCE, TCE, 1,2-tDCE, VC, and benzene for years 1972–1985 for Holcomb Boulevard housing areas is provided in Appendix A8. For more detailed analyses of results pertinent to a specific simulation (e.g., migration of TCE within the HPIA), readers should refer to the appropriate Chapter A supplemental text (Table A1, Figure A2).

[40] Reconstructed monthly mean concentrations represent model output of concentration on the last day of the month for each month. For example, the reconstructed TCE concentration at water-supply well HP-651 for November 1984 of 6,895 µg/L represents the concentration occurring on November 30, 1984.

Simulation of Three-Dimensional Groundwater Flow

A three-dimensional groundwater-flow model was developed and calibrated based on interpretations of geohydrologic data (Faye 2012), analyses and interpretations of water-level data, and the conceptual model of groundwater flow for the study area (Faye et al. 2013). The groundwater-flow model of the study area consists of 7 layers that were correlated with geologic and hydrogeologic units (Table A11). Model layers 1, 3, 5, and 7 are correlated with water-bearing units or aquifers, and corresponding model layers 2, 4, and 6 are correlated with semi-confining units or aquitards. Reference to "model layer" in subsequent figures, tables, and appendixes refers to the model-layer numbering scheme listed in Table A11 for the study area. Calibrated model parameter values used for simulating groundwater flow and contaminant fate and transport for the HPHB study area are listed in Table A12. Readers should refer to the appropriate Chapter A supplemental text (Table A1) for specific details on derivation and justification for calibrated model values listed in Table A12. Calibrated model input files for groundwater flow and contaminant fate and transport for use with the MODFLOW (Harbaugh 2005) and MT3DMS (Zheng and Wang 1999; Zheng 2010) model codes, respectively, are provided on the CD-ROM that accompanies this report.

A calibrated predevelopment water-level model-input database was a pre-requisite for conducting transient groundwater-flow and contaminant fate and transport simulations—specifically in the HPIA and HPLF subdomain areas (Figure A12). Predevelopment groundwater flow was conceptualized using approximately 773 water-level measurements, which are listed in Faye et al. (2013). A predevelopment (steady-state) potentiometric surface map of the Brewster Boulevard aquifer system for the study area was developed (Figure A16) by using these water-level data along with stream-gage data, climatic data (e.g., precipitation and evapotranspiration data obtained from sources listed in Appendix A2), and the geohydrologic framework (Table A11). This potentiometric surface map shows water-level measurements that were used as control points, water-level contours (blue lines), and the generalized directions of groundwater flow (blue arrows) used as the basis for calibrating the predevelopment, three-dimensional groundwater-flow model for the HPHB study area (see Suárez-Soto et al. [2013] for details).

The simulated predevelopment potentiometric contours for the Brewster Boulevard aquifer system, derived from simulated water levels located at the centroids of the finite-difference grid cells for the active model domain, also are shown in Figure A17. Suárez-Soto et al. (2013) assess the goodness of fit of the

Table A11. Correlation between geologic and hydrogeologic units and model layers, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[—, not applicable]

[1]Geologic units			[1]Hydrogeologic units	[1]Thickness	[2]Model layer number
System	Series	Formation	Aquifer and confining unit	Range, in feet	
Quaternary	Holocene Pleistocene	Undifferentiated	Brewster Boulevard upper aquifer	4 to 42	1
Tertiary	Pliocene	Absent	Absent	Absent	
	Miocene	Pungo River Formation, undifferentiated	Brewster Boulevard upper confining unit	1 to 22	
			Brewster Boulevard lower aquifer	4 to 48	
		Belgrade Formation, undifferentiated	Brewster Boulevard lower confining unit	2 to 30	2
			Tarawa Terrace aquifer (upper part)	8 to 86	3
	Oligocene	River Bend Formation, undifferentiated	Tarawa Terrace aquifer (middle and lower parts)		
			Upper Castle Hayne confining unit (previously designated the Tarawa Terrace confining unit in Faye [2007])	4 to 40	4
	Late Eocene	Unnamed	Upper Castle Hayne aquifer–River Bend unit	16 to 70	5
		Castle Hayne Formation	Local confining unit	8 to 23	
			Upper Castle Hayne aquifer–Lower unit	10 to 48	
	Middle Eocene		Middle Castle Hayne confining unit	12 to 27	6
			Middle Castle Hayne aquifer	62 to 122	7
			Lower Castle Hayne confining unit	18 to 38	Base of model
			Lower Castle Hayne aquifer	64 to 86	
	Paleocene	Beaufort Formation, undifferentiated	Beaufort confining unit (generally occurs at top of Beaufort Formation)	—	

[1] From Faye (2012)

[2] From Suárez-Soto et al. (2013)

Table A12. Calibrated model parameter values used to simulate groundwater flow and contaminant fate and transport, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.[1]

[—, not applicable; in/yr, inch per year; ft, foot; ft³, cubic foot; d, day; g, gram; mg, milligram; L/kg, liter per kilogram; PCE, tetrachloroethylene; TCE, trichloroethylene; HPIA, Hadnot Point Industrial Area; HPLF, Hadnot Point landfill]

[2]Model parameter	[3]Model layer number						
	1	2	3	4	5	6	7
[4]Pre-development (steady-state) groundwater-flow model, conditions prior to 1942—Uniform grid (300-ft × 300-ft cells)							
Horizontal hydraulic conductivity, K_{xx} (ft/d)	0.5–46.8	1.0–20.0	1.0–50.0	1.0–35.0	2.3–50.0	1.0–20.0	20.0
Ratio of vertical to horizontal hydraulic conductivity, K_{zz}/K_{xx}	1:10	1:15	1:10	1:15	1:10	1:15	1:10
Infiltration (recharge), $I_{i,j}$ (in/yr)	2.5–22.0	—	—	—	—	—	—
[4]Transient groundwater-flow model, January 1942–June 2008—Variably spaced grid (300-ft × 300-ft – 50-ft × 50-ft cells)							
Specific yield, S_y	0.05	—	—	—	—	—	—
[5]Specific storage, S_s (1/ft) range of values	—	1.3×10^{-5} to 1.9×10^{-4}	4.3×10^{-6} to 3.6×10^{-5}	1.0×10^{-5} to 3.8×10^{-5}	4.0×10^{-6} to 8.3×10^{-6}	1.4×10^{-5} to 3.6×10^{-5}	3.4×10^{-6} to 7.7×10^{-6}
Infiltration (recharge), $I_{i,j}$ (in/yr)	Varies[6]	—	—	—	—	—	—
[7]Pumpage, Q (ft³/d)	Varies	Varies	Varies	Varies	Varies	Varies	Varies
[4]Contaminant fate and transport models, January 1942–June 2008—Subdomain area (50-ft × 50-ft cells)							
[8]Distribution coefficient, K_d (ft³/mg):							
PCE	1.1×10^{-8}	1.1×10^{-8}	1.1×10^{-8}	1.1×10^{-8}	1.1×10^{-8}	1.1×10^{-8}	1.1×10^{-8}
TCE	5.3×10^{-9}	5.3×10^{-9}	5.3×10^{-9}	5.3×10^{-9}	5.3×10^{-9}	5.3×10^{-9}	5.3×10^{-9}
Benzene	4.0×10^{-9}	4.0×10^{-9}	4.0×10^{-9}	4.0×10^{-9}	4.0×10^{-9}	4.0×10^{-9}	4.0×10^{-9}
Bulk density, ρ_b (g/ft³)	46,700	46,700	46,700	46,700	46,700	46,700	46,700
Effective porosity, n_E	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Biodegradation, λ (d⁻¹):							
HPIA (TCE)	2.0×10^{-3}	2.0×10^{-3}	2.0×10^{-3}	2.0×10^{-3}	2.0×10^{-3}	2.0×10^{-3}	2.0×10^{-3}
HPIA (benzene)	1.0×10^{-4}	1.0×10^{-4}	1.0×10^{-4}	1.0×10^{-4}	1.0×10^{-4}	1.0×10^{-4}	1.0×10^{-4}
HPLF (PCE and TCE)	1.4×10^{-4}	1.4×10^{-4}	1.4×10^{-4}	1.4×10^{-4}	1.4×10^{-4}	1.4×10^{-4}	1.4×10^{-4}
Effective molecular diffusion coefficient, D^*(ft²/d)	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}
Dispersivity (ft):							
Longitudinal, α_L	25	25	25	25	25	25	25
Transverse, α_T	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Vertical, α_V	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Source concentration, C (mg/L):							
HPIA (TCE)	640	640	640	0	0	0	0
HPIA (benzene—dissolved)	1.7	—	—	—	—	—	—
HPIA (benzene—LNAPL)	17	—	—	—	—	—	—
HPLF (PCE)	42–105	33–83	27–66	18–46	6–16	0	0
HPLF (TCE)	256–384	256–384	256–384	256–384	256–384	256–384	256–384

[1] Refer to Suárez-Soto et al. (2013), Jones et al. (2013), and Jang et al. (2013) for details

[2] Symbolic notation used to describe model parameters obtained from Harbaugh (2005), Zheng and Wang (1999), and Zheng (2010)

[3] See Table A11 for correlation between geologic and hydrogeologic units and model layers for the HPHB study area; refer to Faye (2012) and Suárez-Soto et al (2013) for details; aquifers are designated as model layers 1, 3, 5, and 7; confining units are designated as model layers 2, 4, and 6

[4] See Figures A12–A14 for groundwater-flow model domain and contaminant fate and transport model subdomains

[5] Specific storage (S_s) was specified as input for MODFLOW-2005 (Harbaugh 2005); based on cell-by-cell thicknesses, storage coefficient (or storativity) of 4×10^{-4} determined using the equation $S = S_s \times b$, where S is the storage coefficient (dimensionless), S_s is specific storage (1/ft), and b is the cell thickness (ft)

[6] Transient infiltration was varied on a monthly basis using the ratio of monthly precipitation divided by average, long-term precipitation; see Suárez-Soto (2013) for details

[7] Pumpage varies by month and model cell; refer to Sautner et al. (2013a) and Telci et al. (2013) for details on the derivation of historical monthly water-supply well operations; refer to Suárez-Soto et al. (2013) for details pertaining to assigning monthly water-supply well pumpage to cells and model layers using the multi-node well-flow package for MODFLOW-2005

[8] Refer to Jones et al. (2013) for derivation of K_D values based on a survey reported in the scientific literature; to convert from model K_D units of ft³/mg to units of L/kg reported in Jones et al. (2013), multiply model K_D values by 28,381,652.21.

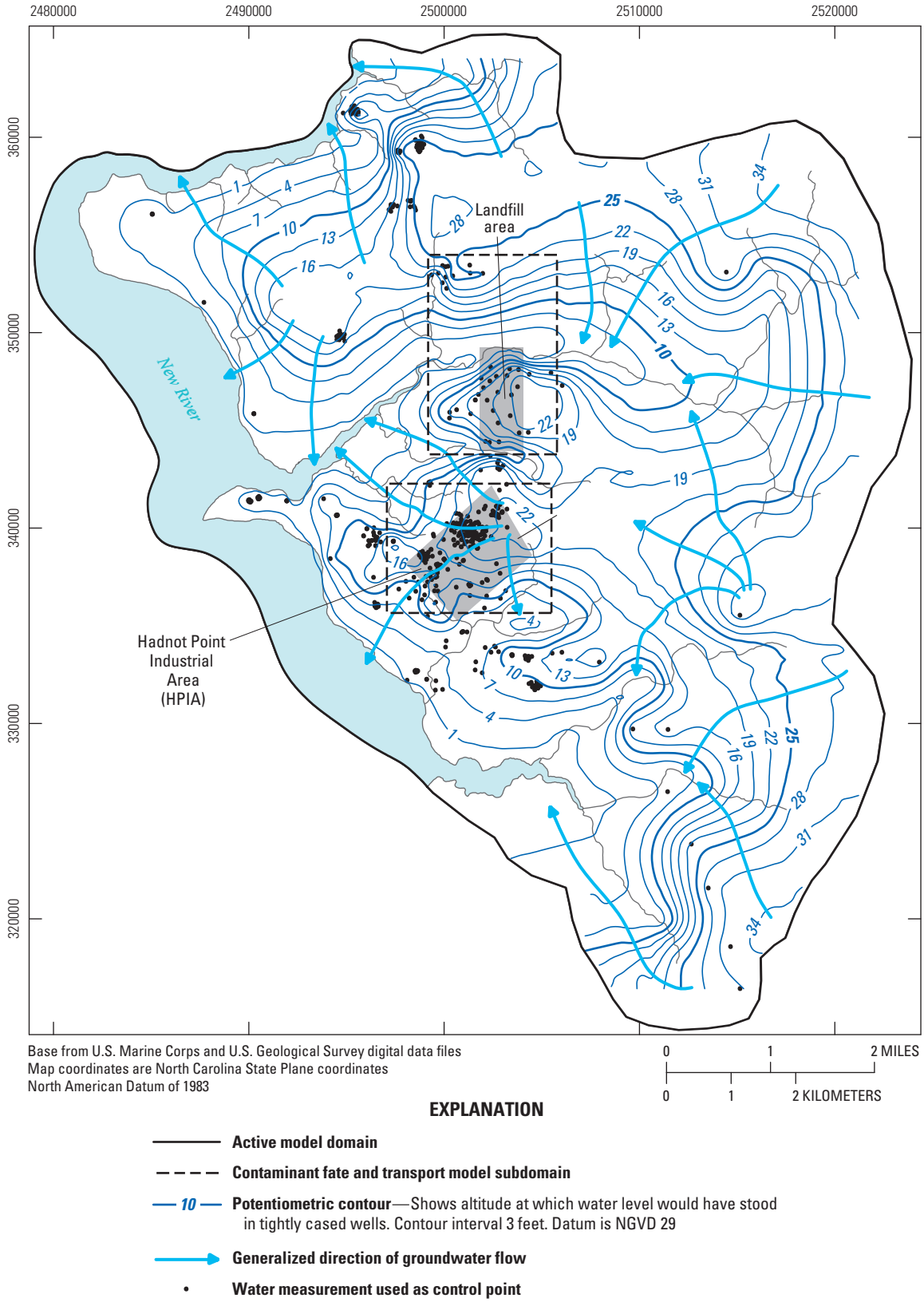


Figure A16. Estimated predevelopment (steady-state) potentiometric surface and generalized directions of groundwater flow, Brewster Boulevard aquifer system, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina (see Faye et al. 2013 for details).

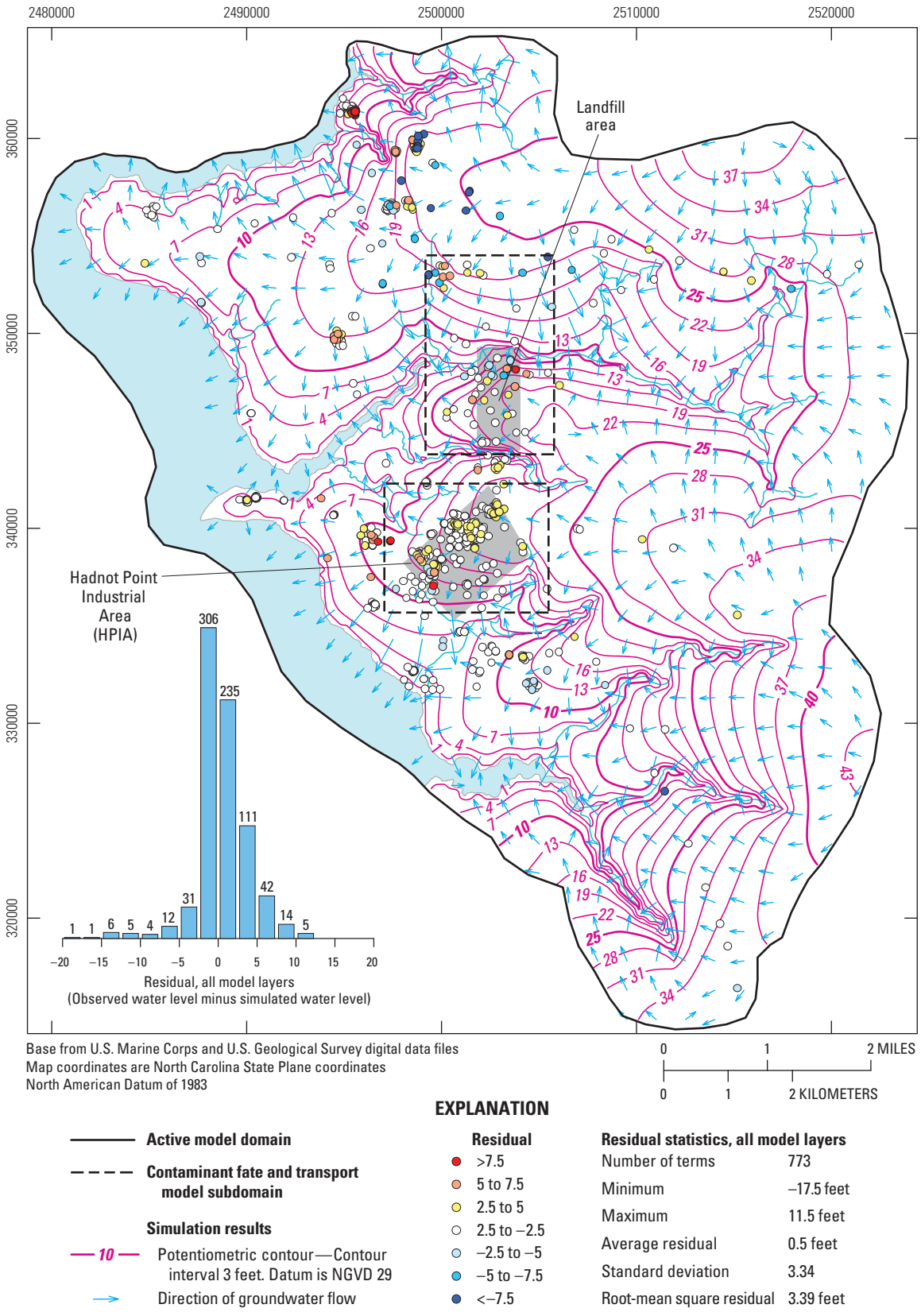


Figure A17. Simulated predevelopment (steady-state) potentiometric surface, directions of groundwater flow, and water-level residuals derived from the calibrated three-dimensional groundwater-flow model, Brewster Boulevard aquifer system, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina (see Suárez-Soto et al. 2013 for details).

predevelopment calibration by calculating residuals between measured and simulated water levels. Results of the residual analysis are also shown on this map of the study area (Figure A17). Within the areas of interest for contaminant fate and transport (the HPIA and HPLF areas), the resulting residuals generally range within ±5 ft. For the entire active model domain, nearly 90 percent of the residuals are within a range of ±5 ft, which is indicative of an acceptable calibration. Also shown in Figure A17 are simulated directions of groundwater flow, which indicate groundwater originating in the highlands areas and discharging to streams, creeks, and the New River, and flowing through the HPIA and HPLF area. Comparing the simulated directions of groundwater flow (Figure A17) with the estimated directions of groundwater flow (Figure A16) indicates general agreement between model results and the conceptual model of groundwater flow for the HPHB study area.

The transient-state groundwater-flow model simulates monthly conditions starting in January 1942 and ending in June 2008. Transient conditions include the effects of pumping from 96 water-supply wells that operated in the study area during different periods from January 1942 through June 2008 and the stress induced by variations in infiltrations (recharge). Water-supply well pumpage and operational data were obtained by reconstructing historical monthly water-supply well operations and are described in Sautner et al. (2013a) and Telci et al. (2013). Comparison of transient model results with continuous water-level data useful for assessment and calibration of the transient model are provided in Suárez-Soto et al. (2013). Simulated three-dimensional specific discharge[41] derived from the calibrated, three-dimensional, transient groundwater-flow model was then used to determine groundwater velocities,[42] which are required to simulate contaminant fate and transport within the HPIA and HPLF subdomain model areas. Details are provided in Suárez-Soto et al. (2013) and Jones et al. (2013).

Simulation of Contaminant Fate and Transport—Hadnot Point Industrial Area

The area identified as the HPIA contaminant fate and transport model subdomain includes the area formally designated as the HPIA and contains IRP sites 21, 24, 78, and 94, about 15 AST/UST sites, and 11 water-supply wells (Figure A13). In addition, the HPIA contains IRP site 22, which is formally named the Hadnot Point Industrial Area fuel farm (HPFF) or the Hadnot Point tank farm. Descriptions and site histories for IRP and AST/UST sites are contained in Faye et al. (2010, 2012). Detailed water-supply well operational histories are provided Sautner et al. (2013a) and Telci et al. (2013).

[41] Specific discharge also is known as seepage velocity or Darcy velocity.

[42] Groundwater velocity is defined as specific discharge divided by porosity.

Trichloroethylene (TCE) Concentrations in Groundwater

Within the HPIA fate and transport model subdomain area (Figure A13), four TCE source locations were identified from numerous potential contaminant sources for inclusion in contaminant fate and transport model simulations. These sources are located near the Building 900 area and near Buildings 1115, 1401, and 1601 (Figures A9 and A13; Table A13). For historical reconstruction and modeling purposes, TCE sources were introduced to the HPIA subdomain area during January 1951 (Buildings 1115, 1401, and 1601) and January 1957 (Building 900 area); sources were removed from model simulations during June 1993 (Buildings 1115 and 1601), December 1993 (Building 1401), and December 1994 (Building 900 area). All contaminated water-supply wells were removed from service by December 1985 and were similarly accounted for during model simulations. Contaminant source locations, concentrations, and durations for historical reconstruction simulations are listed in Table A13.

Figure A18 shows the reconstructed (simulated) TCE concentrations for selected water-supply wells at the HPIA (wells HP-601/660, HP-602, HP-608, and HP-634).[43] Monthly reconstructed TCE concentration results for selected water-supply wells also are tabulated and listed in Appendix A3. These results are simulated values that occur on the last day of the month (e.g., January 31); they are interpreted as being representative of simulated values on any given day of that month. The results are designated and referred to herein as "monthly mean concentrations of TCE."[44] The reconstructed concentrations at water-supply wells are flow-weighted concentration values for supply wells that are open to multiple water-bearing units (Jones et al. 2013; Suárez-Soto et al. 2013). As can be seen in the graphs of Figure A18, observation data in water-supply wells are very limited and in some instances provide as few as one data point by which to compare reconstructed TCE concentrations (e.g., HP-634). For water-supply wells HP-602 and HP-608, measurements were taken 1 day apart or within a 1-month or less time span (Table A4), whereas model results represent a mean concentration over an entire month. Not only does this make it difficult to calibrate a numerical model that at best only approximates the physics, chemistry, and biology of "real-world" conditions, but it calls into question which observation data and data values should be used for comparisons with simulated concentrations. Given the aforementioned limitations and constraints, the reconstructed (simulated) TCE concentrations provide reasonable agreement with observed data and "real-world" conditions.

[43] Water-supply well HP-660 replaced HP-601 and probably operated from July 1984 to December 1984—see Figure A5 and Sautner et al. (2013a).

[44] The designation of "monthly mean concentration" also applies to other contaminants of concern listed in Appendix A3 (PCE, 1,2-tDCE, VC, and benzene).

Table A13. Contaminant sources, locations, concentrations, and durations used for historical reconstruction of TCE, PCE, and benzene concentrations in groundwater, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.[1]

[TCE, trichloroethylene; PCE, tetrachloroethylene; mg/L, milligram per liter; LNAPL, light nonaqueous phase liquid; µg/L, microgram per liter; °C, degree Celsius; g/cm^3, gram per cubic centimeter]

Source location	Contaminant	[2]Source concentration (mg/L)	[3]Number of model sources	Source duration
Hadnot Point Industrial Area (Figure A11)				
Building 900 area	TCE	640	3	Jan. 1957–Dec. 1994
Building 1115	TCE	640	1	Jan. 1951–June 1993
Building 1401	TCE	640	1	Jan. 1951–Dec. 1993
Building 1601	TCE	640	1	Jan. 1951–June 1993
Building 1601	Benzene (dissolved)	1.7	1	Jan. 1951–Dec. 1994
Building 1115	Benzene (LNAPL)[4]	17	Multiple[4]	Jan. 1951–June 2008
Building 1613	Benzene (LNAPL)[4]	17	Multiple[4]	Jan. 1964–June 2008
Hadnot Point fuel farm	Benzene (LNAPL)[4]	17	Multiple[4]	Jan. 1951–June 2008
Hadnot Point landfill area (Figure A12)				
[5]Source 1	TCE	[6]256–384	2	Jan. 1948–June 2008
[5]Source 2	PCE	[6]6–105	2	Jan. 1948–June 2008

[1] All model sources are specified concentration (type 1) boundary conditions; model simulation time is January 1942–June 2008; refer to Jones et al. (2013) and Jang et al. (2013) for details

[2] Current maximum contaminant level (MCL) for TCE, PCE, and benzene is 5 µg/L; density (20 °C): TCE, 1.464 g/cm^3; PCE, 1.623 g/cm^3; benzene, 0.876 g/cm^3 (Lawrence 2007); solubility in water (25 °C): TCE, 1,280 mg/L; PCE, 210 mg/L; benzene, 1,780 mg/L (Lawrence 2007)

[3] Refer to Jones et al. (2013) and Jang et al. (2013) for details

[4] Benzene source for model is areally distributed based on LNAPL distribution; refer to Jang et al. (2013) for details

[5] There are no designated building numbers within the Hadnot Point landfill; location of sources based on Installation Restoration Program Site 82 history and contaminant analyses (Faye et al. 2010) and model calibration (Jones et al. 2013)

[6] Source concentration values vary by model layer; refer to Table A12 and Jones et al. (2013) and Jang et al. (2013) for details

Areal distributions of reconstructed TCE concentrations for model layers 1, 3, and 5 for four periods—January 1951, January 1968, November 1984, and June 2008—are shown in Figure A19. Model layers 1, 3, and 5 represent major water-bearing units in the study area and are correlated with the Brewster Boulevard aquifer system, the Tarawa Terrace aquifer, and the Upper Castle Hayne aquifer, respectively (Table A11). Water-supply wells in the study area were open to water-bearing units corresponding to model layers 3 and 5. The specific simulation dates noted above were selected to show typical historical reconstruction results because (1) January 1951 represents an early time period after the onset of pumping, (2) January 1968 represents the start of the core period for the epidemiological studies, (3) November 1984 represents the month prior to the shutdown of many of the contaminated water-supply wells, and (4) June 2008 represents the end of the historical reconstruction simulation and a time when all contaminated water-supply wells had been removed from service for more than 20 years. Viewed synoptically, the maps in Figure A19 illustrate a progression in the areal distribution of TCE by model layer at the HPIA from the early onset of pumping (January 1951) to substantial impact of TCE on water-supply wells (January 1968 and November 1984), to dilution and reduction in the TCE concentration at the end of the historical reconstruction simulation (June 2008) because of the cessation of pumping of historically contaminated HPIA water-supply wells. Larger-scale maps showing additional HPIA details such as building identifications are provided in Appendix A4.

Summary statistics for reconstructed (simulated) TCE concentrations at HPIA water-supply wells HP-602, HP-608, and HP-634 are listed in Table A14. Maximum reconstructed TCE concentrations range from 50 µg/L at water-supply well HP-608 to more than 650 µg/L at water-supply wells HP-602 and HP-634. During the core period of interest to the epidemiological studies (1968–1985), TCE concentrations at all HPIA water-supply wells listed in Table A14 exceeded the current MCL for TCE (5 µg/L) by factors ranging from about 5 to more than 130. Reconstructed concentrations exceeded the current MCL for TCE at HPIA water-supply wells for durations ranging from 283 months (about 24 years) to 390 months (about 33 years).

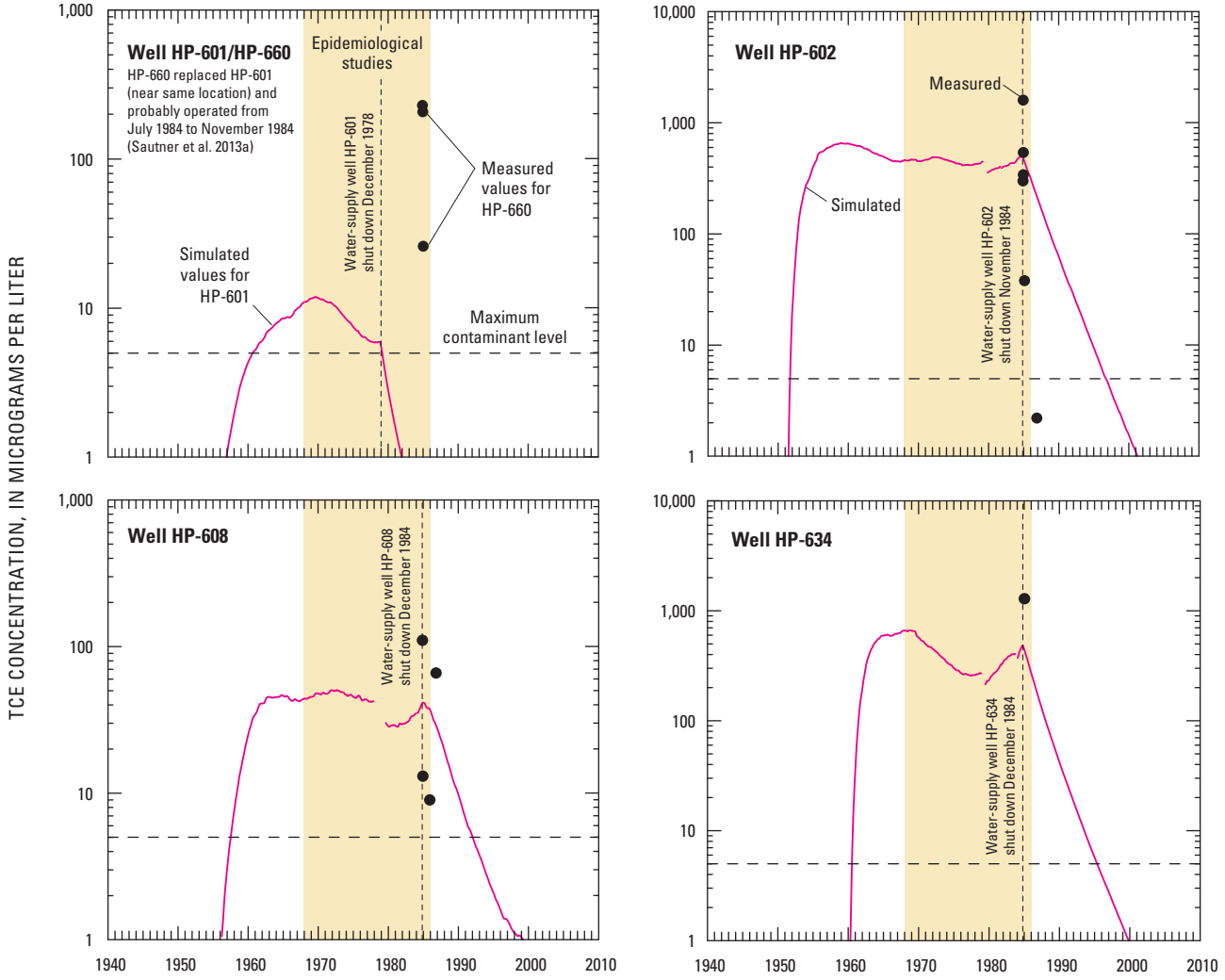


Figure A18. Reconstructed (simulated) and measured concentrations of trichloroethylene (TCE) at selected water-supply wells within the Hadnot Point Industrial Area, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. Groundwater-flow simulation using MODFLOW (Harbaugh 2005) and contaminant fate and transport simulation using MT3DMS (Zheng and Wang 1999). (See Figure A13 for well locations.)

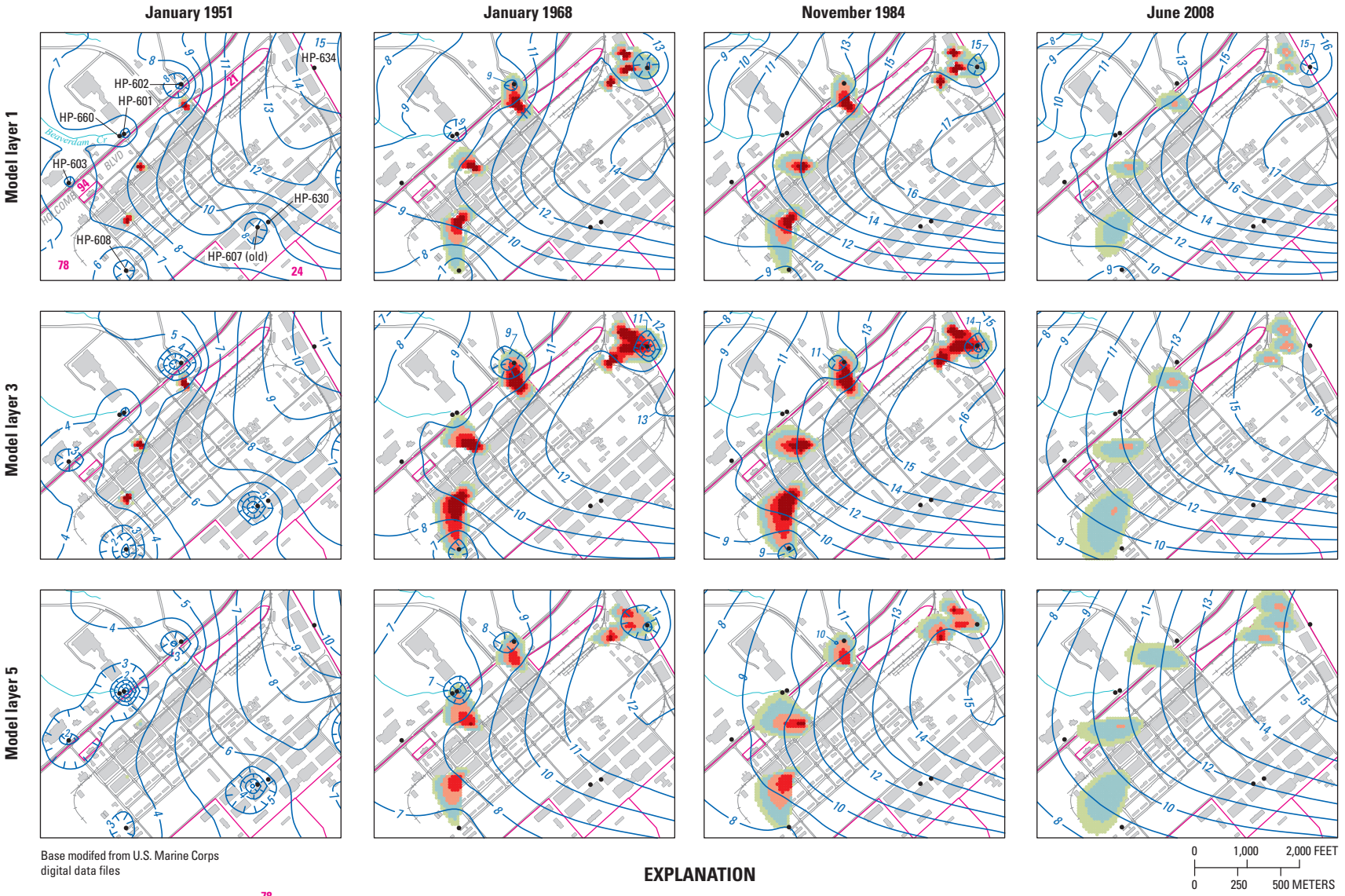


Figure A19. Reconstructed (simulated) water levels and distribution of trichloroethylene (TCE) within the Hadnot Point Industrial Area fate and transport model subdomain, model layers 1, 3, and 5, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1951, January 1968, November 1984, and June 2008. (See Figure A13 for location and building numbers; see Appendix A4 for more detailed maps and results.)

Table A14. Summary statistics for reconstructed contaminant concentrations at selected water-supply wells and the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.[1,2]

[MCL, maximum contaminant level; TCE, trichloroethylene; PCE, tetrachloroethylene; VC, vinyl chloride; 1,2-tDCE, *trans*-1,2-dichloroethylene; N/A, not applicable; µg/L, microgram per liter]

Water-supply identification (contaminant)	Reconstructed (simulated) concentration, in micrograms per liter				[2]Duration in months exceeding MCL (month and year first exceeding MCL)	Date well stopped pumping in model
	[3]July 1942–June 1996			Range during health study period of interest (January 1968–February 1985)		
	Maximum (date of maximum)	Mean	Standard deviation			
[4]Hadnot Point Industrial Area (HPIA)						
HP-602 (TCE)	658 (Jan. 1959)	359	222	357–499	390 (Oct. 1951)	Dec. 1984
HP-608 (TCE)	50 (Sept. 1972)	25	20	28–50	307 (Aug. 1957)	Dec. 1984
HP-634 (TCE)	659 (Oct. 1968)	391	170	212–659	283 (Aug. 1960)	Dec. 1984
HP-602 (benzene)	236 (Nov. 1984)	53	65	48–236	309 (July 1958)	Dec. 1984
HP-603 (benzene)	179 (May 1996)	29	43	6–129	345 (Aug. 1967)	June 1996
HP-608 (benzene)	11 (Sept. 1979)	4	4	6–11	201 (June 1966)	Dec. 1984
[4]Hadnot Point landfill (HPLF)						
HP-651 (PCE)	353 (Dec. 1982)	249	122	[5]0–353	142 (Apr. 1973)	Feb. 1985
HP-651 (TCE)	7,135 (Dec. 1978)	5,831	2,071	[5]1–7,135	150 (Aug. 1972)	Feb. 1985
HP-651 (1,2-tDCE)	4,037 (Dec. 1984)	3,284	572	[5]69–4,037	150 (Aug. 1972)	Feb. 1985
HP-651 (VC)	660 (Nov. 1984)	391	173	[5]8–660	151 (July 1972)	Feb. 1985
[6]Hadnot Point water treatment plant (HPWTP)						
HPWTP (PCE)	39 (Nov. 1983)	4	8	0–39	114 (Aug. 1974)	N/A
HPWTP (TCE)	783 (Nov. 1983)	107	180	0–783	374 (Aug. 1953)	N/A
HPWTP (1,2-tDCE)	435 (Nov. 1983)	53	95	0–435	128 (Nov. 1972)	N/A
HPWTP (VC)	67 (Nov. 1983)	6	13	0–67	144 (Nov. 1972)	N/A
HPWTP (benzene)	12 (Apr. 1984)	2	3	0–12	63 (Jan. 1979)	N/A

[1] For periods of time when concentrations are equal to or exceed the current MCLs for TCE, PCE, and benzene; non-rounded concentration values used to calculate statistics

[2] Current MCLs are as follows: vinyl chloride, 2 µg/L; PCE, TCE, and benzene, 5 µg/L; 1,2-tDCE, 100 µg/L (see Table A3)

[3] Statistics are computed solely for periods of operation

[4] See Appendix A3 for complete listing

[5] Water-supply well HP-651 did not start pumping until July 1972; values shown represent dates of July 1972–February 1985

[6] Finished-water concentrations; see Appendix A7 for complete listing

Benzene Concentrations in Groundwater

Benzene contamination of groundwater within the HPIA occurred primarily as a result of operations in and around the HPFF and Building 1115 areas. The HPFF area, designated as IRP site 22 under the CERCLA program, and UST Building 1115, regulated under the RCRA program (Figures A12 and A13), are interconnected by an underground fuel pipeline. Benzene occurs as free product (or "floating LNAPL") in vicinity of the HPFF, Building 1115, and IRP site 94/Building 1613 areas and as dissolved-phase benzene contamination in the vicinity of Building 1601 (Faye et al. 2010, 2012). Figure A9 shows the location of the HPFF, fuel lines from the HPFF to other areas within the HPIA, the distribution of benzene sample data, and the general location of historical areas of free product measured in wells. Of the BTEX components of fuel, benzene is a known human carcinogen (NTP 2011) and is of special interest to the ATSDR health studies (the current MCL for benzene is 5 µg/L). Because benzene occurs as both free product and dissolved phase within the HPIA, three modeling approaches were necessary to reconstruct benzene concentrations in groundwater: (1) estimation of the volume of fuel loss and mass of LNAPL in the subsurface using site data and the model TechNAPLVol, (2) simulation of the dissolution of benzene from LNAPL and the subsequent fate and transport of dissolved benzene using the model TechFlowMP at the HPFF, and in Building 1115 and Building 1613 areas, and (3) simulation of the fate and transport of dissolved-phase benzene in groundwater in the Building 1601 area using the model MT3DMS.

Data on the thickness of floating product or "free" LNAPLs at the HPIA have been collected since 1988. During the period 1988–1999, a total of 373 observations were recorded, with 96 of those measurements indicating free LNAPL (Jang et al. 2013). Previous investigations, listed in Table A15, have documented fuel losses based on inventory losses (Water and Air Research, Inc. 1983; O'Brien and Gere Engineers, Inc. 1988, 1990; CH2M HILL, Inc. 2001) and have estimated volumes of subsurface LNAPL by using an analytical modeling approach (CH2M HILL, Inc. 2001; Catlin Engineers and Scientists 2010[45]). Documented inventory losses have ranged from 20,000 gal to 50,000 gal. Modeling estimates of subsurface LNAPL have indicated a range of

[45] Draft report by Baker Environmental, Inc., contained in UST Management Web Portal File #01185, p. 526–562.

Table A15. Estimates of fuel loss, free product in the subsurface, and fuel recovery at the Hadnot Point Industrial Area fuel farm, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[USMCB, U.S. Marine Corps Base; HPFF, Hadnot Point fuel farm; ATSDR, Agency for Toxic Substances and Disease Registry]

Type of estimate	Volume, in gallons	Reference
Fuel-loss estimates		
USMC documentation of known release from underground fuel line in 1979	20,000–50,000	Water and Air Research, Inc. (1983)
USMC documentation of known fuel releases and inventory losses during 1979–1987	23,150–33,150	O'Brien and Gere Engineers, Inc. (1988, 1990), CH2M HILL (2001)
Model-derived estimates		
[1]SpillCAD™ model estimate of free product (LNAPL) in the subsurface using free product measurements collected during 1988–1995	830,324–1,061,901	UST Management Web Portal Files (2010–2012)[2]
Order-of-magnitude estimate of total fuel in the subsurface based on available documentation as of 2001 (specific methodology not described)	400,000–1,100,000	CH2M HILL (2001)
Fuel recovery estimate		
Reported total fuel recovery from HPFF/Building 1115 area remediation systems as of July 2010	414,118	[3]USMCB Camp Lejeune (July 2010)

[1] SpillCAD™ was developed by Environmental Systems & Technologies (1993)

[2] Draft report by Baker Environmental, Inc., contained in UST Management Web Portal File #01185, p. 526–562

[3] From information presented at the ATSDR-DON Data Mining & Discovery Technical Work Group Meeting, USMCB Camp Lejeune, July 21–22, 2010

830,324 gal (1988–1991 data) to 1,061,901 gal (1992–1995 data) using the SpillCAD™ model (ES&T 1993; Catlin Engineers and Scientists 2010). An order of magnitude approach for quantifying fuel in the subsurface resulted in estimates ranging from 400,000 gal to 1,100,000 gal (CH2M HILL, Inc. 2001). Most recently (July 2010), USMCB Camp Lejeune estimated total fuel recovery from the HPFF/Building 1115 area remediation systems to be 414,118 gal (Table A15).

The ATSDR volume estimates of LNAPL in the subsurface at the HPFF and in the vicinity of Buildings 1115 and 1613 are based on using measured LNAPL thickness in wells (373 observations, 96 of which indicated free LNAPL) for 1988–1999. With the aforementioned data, three computational methods were used to quantify and estimate LNAPL volumes: (1) a semi-analytical solution described in Farr et al. (1990), (2) numerical integration of the semi-analytical equation (Farr et al. 1990, Equation 6) in a three-dimensional porous medium domain using the "apparent" LNAPL thickness from well data, and (3) numerical integration in a three-dimensional porous medium using the "actual" LNAPL thickness from soil data. Results from the three methods are referred to as Scheme 1, Scheme 2, and Scheme 3, respectively, in Table A16. The three methods for LNAPL volume estimation are contained in the model code TechNAPLVol. Data and parameters used to calculate total floating LNAPL volume and LNAPL volume in the subsurface included the following (Jang et al. 2013):

- Measured LNAPL thickness data in wells,
- LNAPL and water densities,
- Gas-water, gas-LNAPL, and LNAPL-water displacement pressures,
- Surface tensions between the aforementioned phases, and
- Soil coefficients for the Brooks-Corey equation (Brooks and Corey 1964, 1966) in a three-dimensional domain.

Because of uncertainty and variability of soil parameters, seven cases for each solution method were analyzed whereby entry pressures and the Brooks-Corey equation coefficients (Brooks and Corey 1964, 1966) were varied (Jang et al. 2013). Results of the ATSDR volume estimates are listed in Table A16 showing the minimum, maximum, and mean LNAPL volume estimates based on the solution methodology (semi-analytical or numerical integration) for each volume estimate. LNAPL volumes in the subsurface range from 939,000 gal to 1,618,000 gal (depending on the method of estimation); the means range from 1,174,000 gal to 1,348,000 gal. It should be noted that the estimates listed in Table A16 are based on the assumption of fresh gasoline (Farr et al. 1990). For aged gasoline, values listed in Table A16 increase about 20 percent; for specific estimates using aged gasoline, refer to Jang et al. (2013).

Table A16. Estimated volumes of light nonaqueous phase liquid in the subsurface, using semi-analytical solutions and numerical integration, Hadnot Point Industrial Area fuel farm, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.[1]

[1]Method and model (scheme number)	[2]Light nonaqueous phase liquid (LNAPL) volume, in gallons		
	Minimum	Maximum	Mean
[3]Analytical solution using depth of LNAPL in wells; TechNAPLVol model; (Scheme 1)	939,000	1,408,000	1,174,000
Numerical integration of three-dimensional domain using LNAPL depth in wells (apparent thickness); TechNAPLVol model; (Scheme 2)	939,000	1,409,000	1,174,000
Numerical integration of three-dimensional domain using LNAPL depth in soil (actual thickness); TechNAPLVol model; (Scheme 3)	1,079,000	1,618,000	1,348,000

[1] Results listed are a summary of multiple simulation scenarios. Refer to Jang et al. (2013) for details and descriptions of each scheme; see Jang et al. (2013, Tables S7.6 and S7.7) for full range of results and seven different simulation scenarios; also see Jang et al. (2013, Figure S7.12)

[2] Volumes reported are for fresh gasoline; for aged gasoline, minimum volumes increase about 20 percent

[3] Analytical solution derived by Farr et al. (1990)

The LNAPL source area characterized using the Tech-NAPLVol model served as input to the three-dimensional finite-element model, TechFlowMP (Jang and Aral 2005, 2007), which was used to reconstruct benzene concentrations in groundwater and at historically operated water-supply wells within the HPIA contaminant fate and transport subdomain (Figure A13). Additionally, the three-dimensional finite-difference model, MT3DMS (Zheng and Wang 1999; Zheng 2010), was used to reconstruct benzene concentrations within the HPIA subdomain where the benzene source was characterized as dissolved-phase benzene in the vicinity of Building 1601 (Figure A9, Figure A13, Table A13). Within the HPIA, concentrations of benzene greater than detection limits were determined in water samples collected from water-supply wells HP-602 and HP-608. Benzene concentrations were below detection limits in water samples collected from well HP-603 (Table A5). A comprehensive summary of analyses for BTEX in water samples collected from Hadnot Point and Holcomb Boulevard water-supply wells is provided in Faye et al. (2010).

Figure A20 shows reconstructed (simulated) benzene concentrations in water-supply wells HP-602, HP-603, and HP-608. Reconstructed (simulated) monthly mean benzene concentrations in these water-supply wells also are listed in Appendix A3 for the entire historical reconstruction period (January 1942–June 2008). The maximum reconstructed groundwater concentration of benzene in water-supply well HP-602 was 236 µg/L during November 1984 (Table A14, Figure A20, Appendix A3). This well was permanently taken out of service on November 30, 1984, because of benzene contamination (Camp Lejeune Water Document CLW #4913). By comparison, the maximum measured concentration at water-supply well HP-602 when it was in continuous

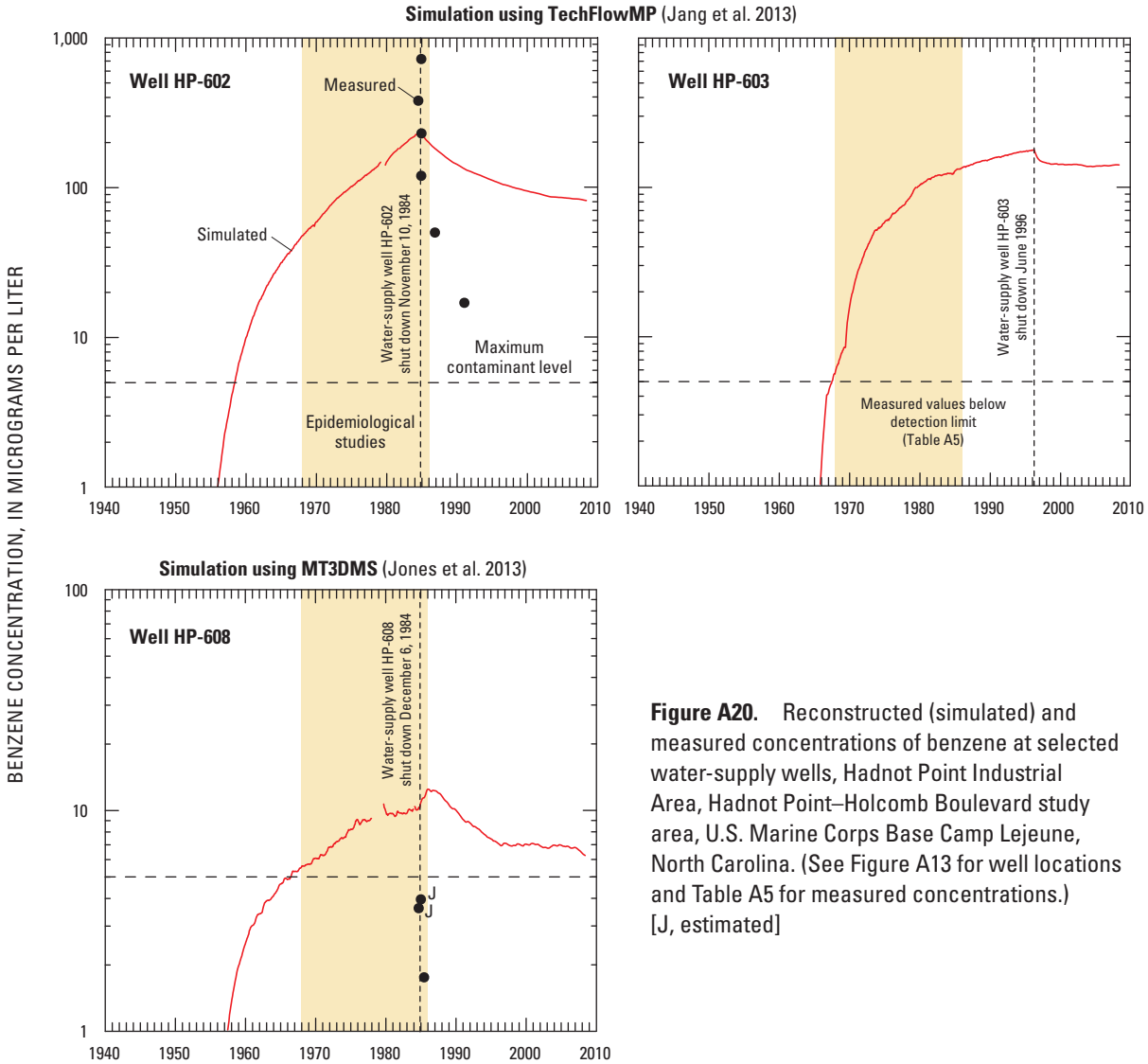


Figure A20. Reconstructed (simulated) and measured concentrations of benzene at selected water-supply wells, Hadnot Point Industrial Area, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. (See Figure A13 for well locations and Table A5 for measured concentrations.) [J, estimated]

service was 380 µg/L during July 1984 (Table A5),[46] and the reconstructed benzene concentration for July 1984 is 231 µg/L (Appendix A3). During November 1984, 32 water-supply wells provided water to the HPWTP. The reconstructed combined flow rate for all wells was 417,012 cubic feet per day (ft^3/d), whereas the corresponding flow rate for well HP-602 was 10,012 ft^3/d. Comparison of the combined flow rate for all water-supply wells to the flow rate for well HP-602 for November 1984 indicates that the benzene contribution from water-supply well HP-602 to the finished water benzene concentration at the HPWTP is substantially reduced by dilution, both under actual and simulated operating conditions. Additional discussion and results pertinent to measured and reconstructed finished-water concentrations are presented in this report in the section on Computation of Finished-Water Concentrations—Hadnot Point Water Treatment Plant.

Simulated (reconstructed) benzene concentrations in water-supply wells HP-602 and HP-603 (Figure A20, Appendix A3) indicate approximately the same range of concentrations during the core period of interest (1968–1985) to the epidemiological studies. Reconstructed benzene concentrations for well HP-602 are in reasonable agreement with field data. However, reconstructed benzene concentrations for water-supply well HP-603 are inconsistent with field data (Figure A20, Table A5). Potential explanations for the apparent discrepancy between simulated results and field data at water-supply well HP-603 are presented in the Discussion section of this report. To assess factors that may provide some explanation for this discrepancy, variations in source area, location, strength, and release date were tested using a sensitivity analysis (see report section on Sensitivity Analysis). In addition, the contribution of water-supply well HP-603 to benzene finished-water concentrations was also tested using a sensitivity analysis.

The areal distributions of reconstructed benzene concentrations for model layers 1, 3, and 5 for four periods—January 1951, January 1968, November 1984, and June 2008—are shown in Figure A21. As previously noted, model layers 1, 3, and 5 represent major water-bearing units in the study area and are correlated with the Brewster Boulevard aquifer system, the Tarawa Terrace aquifer, and the Upper Castle Hayne aquifer, respectively (Table A11). Benzene characterized as an LNAPL occurred near the water table at depths corresponding to model layer 1; water-supply wells HP-602, HP-603, and HP-608 were open to water-bearing units corresponding to model layers 3 and 5. Viewed synoptically, the maps in Figure A21 illustrate a progression in the areal distribution of benzene by model layer at the HPIA from the early onset of pumping (January 1951) to benzene affecting water-supply wells (January 1968 and November 1984). After contaminated water-supply wells (e.g., HP-602) were taken out of service, a substantial volume of free-product (LNAPL) benzene still remained near the water table and in the shallow subsurface, thereby providing an infinite benzene source to the underlying aquifers. This condition resulted in increased benzene concentrations and areal distributions of benzene in the subsurface and model layers 1, 3, and 5 as seen in Figure A21 for June 2008. Additionally, the ATSDR benzene analyses did not simulate remediation of benzene (removal of LNAPL) as this was not a goal of the ATSDR water-modeling effort, so there is no reduction in LNAPL volume between November 1984 and June 2008 as seen in Figure A21. Larger-scale maps of benzene concentrations in groundwater showing additional HPIA details such as building identifications are provided in Appendix A5.

[46] A benzene concentration of 720 µg/L was measured on December 10, 1984 (Table A5). At that time, well HP-602 was reported as out of service; sampling protocol and methodology are not available.

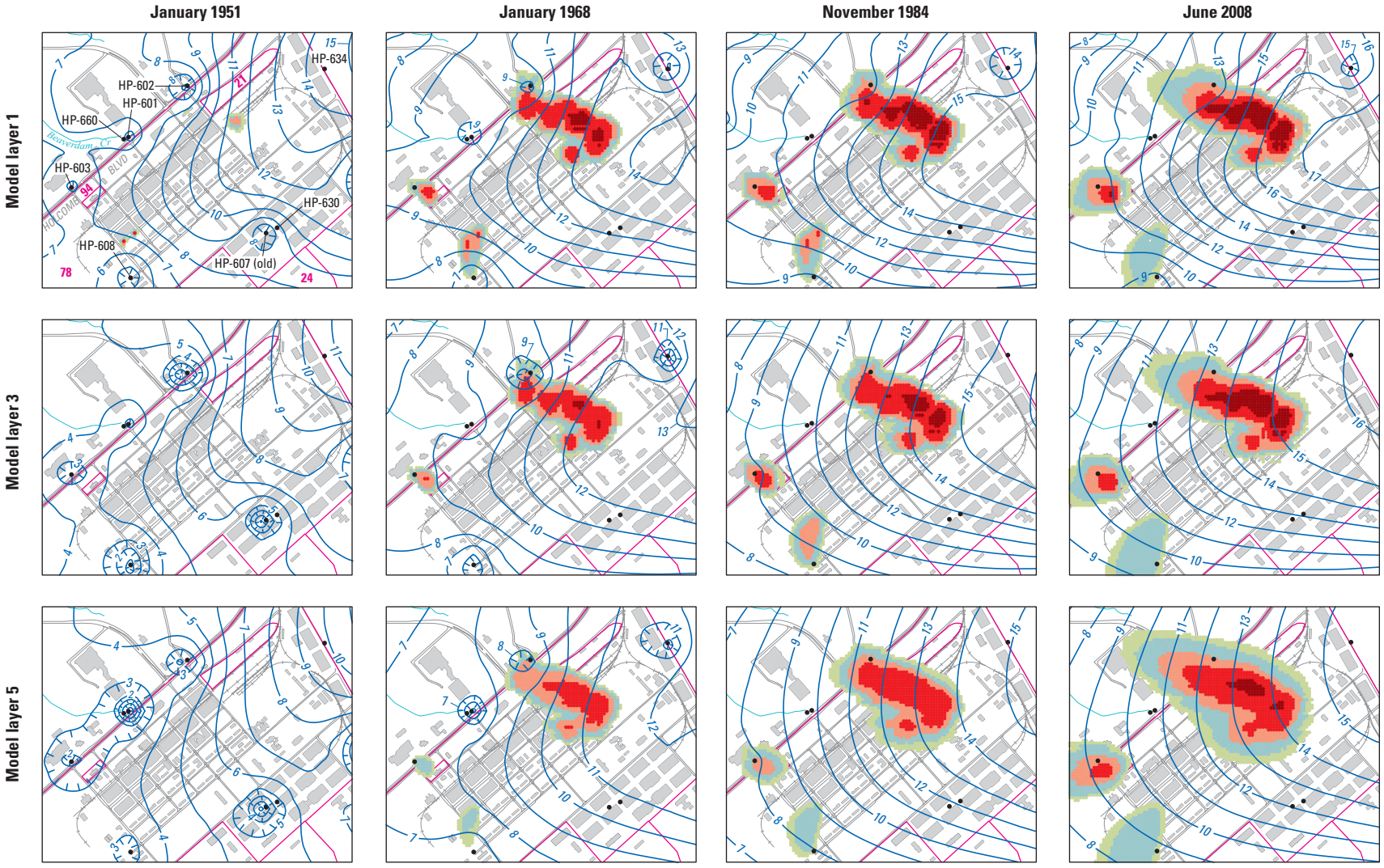


Figure A21. Reconstructed (simulated) water levels and distribution of benzene, Hadnot Point Industrial Area fate and transport model subdomain, model layers 1, 3, and 5, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1951, January 1968, November 1984, and June 2008. (See Figure A13 for location and building numbers; see Appendix A5 for more detailed maps and results.)

Simulation of Contaminant Fate and Transport—Hadnot Point Landfill Area

The area designated as the Hadnot Point landfill (HPLF) contains IRP sites 3, 6, 10, 74, and 82; one AST/UST site (tanks S889 and S891); and 13 water-supply wells. All are included within the ATSDR contaminant fate and transport model subdomain for the HPLF area (Figures A12 and A14). Descriptions and site histories for IRP and AST/UST sites are contained in Faye et al. (2010, 2012). Detailed water-supply well operational histories are provided in Sautner et al. (2013a).

Trichloroethylene (TCE) Concentrations in Groundwater

Two TCE sources within IRP Sites 6 and 82 were identified for inclusion in contaminant fate and transport model simulations of the HPLF (Tables A7 and A8). The areas of highest contaminant concentrations and corresponding model source locations are shown in Figures A10 and A14, respectively. Well HP-651 was the primary water-supply well affected by groundwater contamination at the HPLF. For historical reconstruction and modeling purposes, the two TCE sources were introduced to the HPLF model during January 1948 (Table A13). Specific details pertinent to representation of the TCE sources in the contaminant fate and transport model are presented in Jones et al. (2013).

Figure A22 shows the reconstructed (simulated) TCE concentrations at water-supply well HP-651, located to the east of the TCE contaminant sources and the HPLF (Figure A14). Monthly reconstructed results for water-supply well HP-651 also are listed in Appendix A3. Historical reconstruction results for the HPLF should be interpreted as monthly mean concentrations of TCE dissolved in groundwater. The reconstructed concentrations at water-supply well HP-651 are based on groundwater flow from the model cell coincident with the location of water-supply well HP-651 because this well is open to the Upper Castle Hayne aquifer, River Bend and Lower units, which are correlated solely with model layer 5 (Table A11; refer to Jones et al. [2013] for details). As previously noted, observation data at water-supply wells are limited, and in the case of HP-651, three of the five water-quality samples were obtained between January 16 and February 4, 1985, and range from 3,200 µg/L to 18,900 µg/L (Table A4). Given the data measurement limitations, substantial variation in concentration range within a 1-month period, and interpretive constraints, the reconstructed (simulated) TCE concentrations shown in Figure A22 (and listed in Appendix A3) are in reasonable agreement with observed data and "real world" conditions.

The areal distributions of reconstructed TCE concentrations for model layers 1, 3, and 5 for four periods—January 1968, June 1978, November 1984, and June 2008—are shown in Figure A23. Model layers 1, 3, and 5 represent major water-bearing units in the study area and are correlated with the Brewster Boulevard aquifer system, the Tarawa Terrace aquifer, and the Upper Castle Hayne aquifer, respectively (Table A11). The TCE source occurring within the fate and transport model

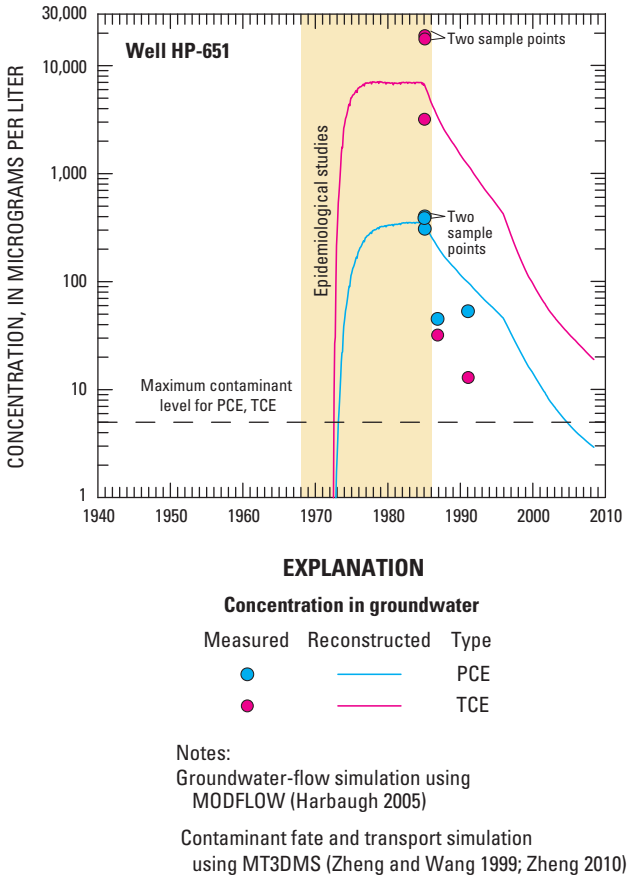


Figure A22. Reconstructed (simulated) and measured concentrations of tetrachloroethylene (PCE) and trichloroethylene (TCE) at water-supply well HP-651, Hadnot Point landfill area, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. (See Figure A14 for well location and Table A4 for measured data.)

subdomain representing the HPLF was assigned to model layers 1–7 (Table A12). Viewed synoptically, the maps in Figure A23 illustrate a progression in the vertical (by model layer) and areal distribution of TCE within the HPLF area. January 1968 coincides with the start of the core period for the epidemiological studies, but a time prior to the onset of pumping at well HP-651. By January 1968, TCE contamination within the HPLF area had migrated vertically downward to the Upper Castle Hayne aquifer, corresponding to model layer 5 (Table A11 and Figure A23). June 1978 and November 1984 represent periods of substantial impact of water-supply well HP-651 on groundwater flow and the migration of TCE within the HPLF area. In the model, water-supply well HP-651 is pumping 100 percent from the Upper Castle Hayne aquifer (layer 5), and this effect is seen by the large cone of depression centered at, and migration of TCE to, well HP-651 during June 1978 and November 1984 (Figure A23). Reduction in TCE concentrations began when well HP-651 was taken out of service during February 1985 (Camp Lejeune Water Document CLW #4913; Sautner et al. 2013a). By June 2008, a shift in the center of mass of the TCE plume in a northwesterly direction from well HP-651 is clearly seen in Figure A23. This shift in the center of mass of TCE is primarily caused by the

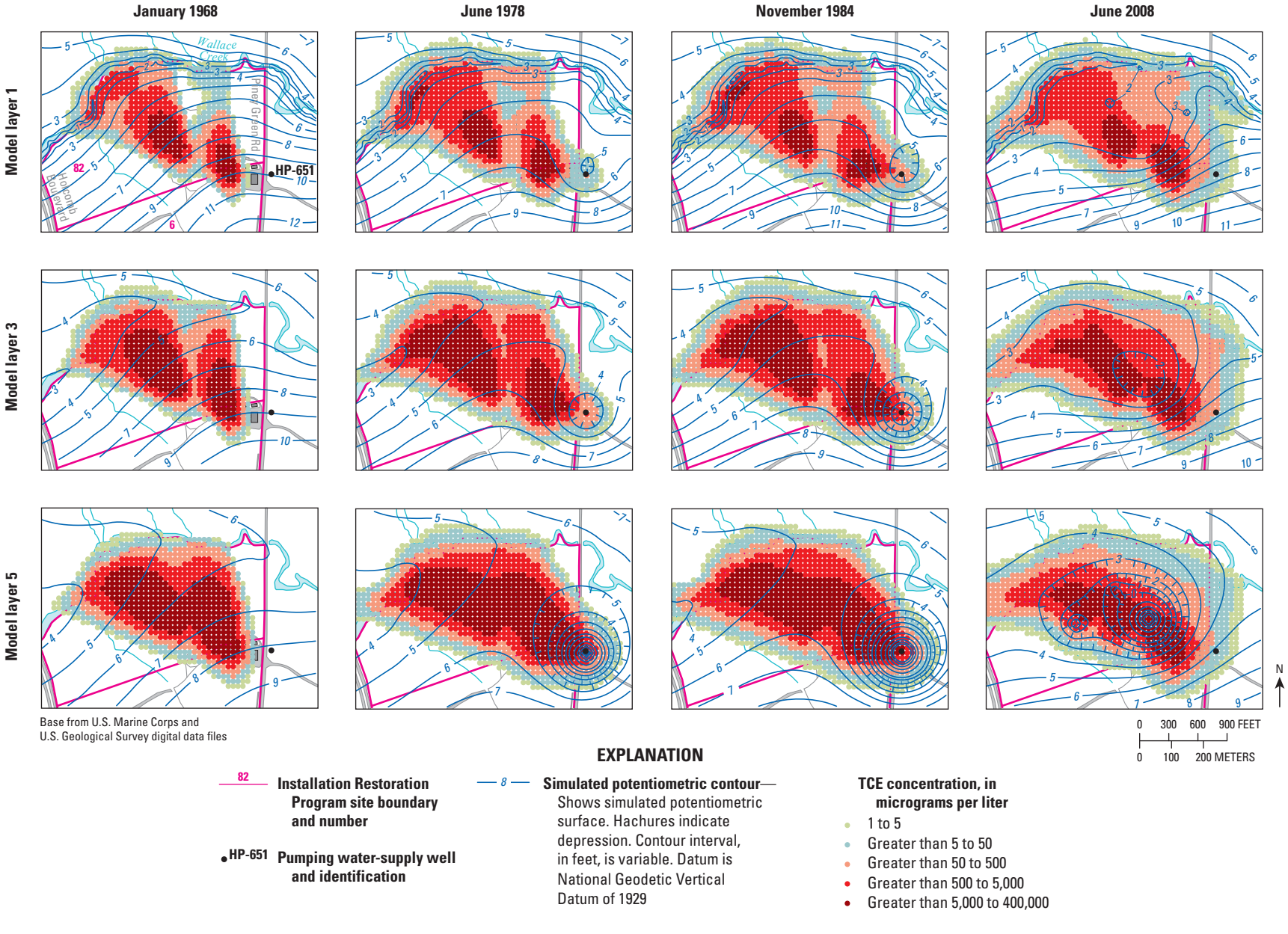


Figure A23. Reconstructed (simulated) water levels and distribution of trichloroethylene (TCE), Hadnot Point landfill area fate and transport model subdomain, model layers 1, 3, and 5, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1968, June 1978, November 1984, and June 2008. (See Figure A14 for location; see Appendix A6 for more detailed maps and results.)

influence of Wallace Creek (Figure A14 and Appendix A6) on local groundwater flow and is more pronounced in model layers 1 and 3. Note, remediation extraction well operations began during October 1996[47] and pumped from model layer 5. Larger-scale maps showing additional HPLF area details such as remediation well locations are provided in Appendix A6.

Summary statistics for reconstructed (simulated) TCE concentrations at water-supply well HP-651 are listed in Table A14 (simulated historical monthly mean concentrations are listed in Appendix A3). Maximum reconstructed TCE concentration was simulated as 7,135 µg/L during December 1978. After the onset of pumping at water-supply well HP-651 (July 1972), TCE concentrations during the period of interest to the ATSDR health studies substantially exceeded the current MCL for TCE (5 µg/L) by factors ranging from about 1 to more than 1,400. The current MCL for TCE was first exceeded at water-supply well HP-651 during August 1972 and exceeded the MCL for 150 months (about 13 years). For specific data and operational information on water-supply well HP-651, refer to Sautner et al. (2013a); for detailed analyses and discussions pertinent to the fate and transport of TCE within the HPLF area, refer to Jones et al. (2013).

Tetrachloroethylene (PCE) Concentrations in Groundwater

At the HPLF, two PCE sources within IRP Sites 6 and 82 were identified for inclusion in contaminant fate and transport model simulations (Tables A7 and A8). The source locations are shown in Figure A14. Water-supply well HP-651 was the primary water-supply well affected by groundwater contamination within the HPLF area (Figure A10). Measured concentrations from water-quality sampling of the well on January 16 and February 4, 1985, indicate PCE concentrations substantially exceeded the current MCL for PCE of 5 µg/L (Table A4). However, the measured PCE concentrations are more than an order of magnitude lower in value than corresponding TCE concentrations measured during the same period of January–February 1985. This is evidence, therefore, that TCE was not a degradation by-product of PCE and that PCE should be characterized and modeled as a different contaminant source within the HPLF area—described in Jones et al. (2013).[48] For historical reconstruction and modeling purposes, the two PCE sources (locations shown in Figure A14) were assigned to HPLF model layers 1–5 (Table A12) and were introduced during January 1948 (Table A13). Specific details pertinent to representation of the PCE sources in the contaminant fate and transport model are presented in Jones et al. (2013).

Figure A22 shows the reconstructed (simulated) PCE concentrations at water-supply well HP-651, located to the east of the PCE contaminant sources within the HPLF area (Figures A10 and A14). Monthly reconstructed results for water-supply well HP-651 also are listed in Appendix A3. As with results obtained for the HPIA, historical reconstruction results for the HPLF area also should be interpreted to represent monthly mean concentrations of PCE dissolved in groundwater at the aforementioned water-supply well. Water-supply well HP-651 is modeled as withdrawing water solely from model layer 5, which is correlated with the Upper Castle Hayne aquifer—River Bend and Lower Units (Table A11; Jones et al. 2013). As previously noted, observation data at water-supply wells are limited, and in the case of HP-651, three of the five water-quality samples were obtained between January 16 and February 4, 1985. Unlike the TCE water-quality sample data, PCE values are relatively consistent, ranging in value from 307 µg/L to 400 µg/L (Table A4). The reconstructed (simulated) PCE concentrations shown in Figure A22 (and listed in Appendix A3) provide good agreement with observed data.

The areal distributions of reconstructed PCE concentrations for model layers 1, 3, and 5 for four periods—January 1968, June 1978, November 1984, and June 2008—are shown in Figure A24. Viewed synoptically, the maps in Figure A24 illustrate a progression in the vertical (by model layer) and areal distribution of PCE within the HPLF area. In the model, water-supply well HP-651 is pumping 100 percent from the Upper Castle Hayne aquifer (layer 5), and this effect is seen by the large cone of depression centered at, and migration of PCE to, well HP-651 during June 1978 and November 1984. The effect of water-supply well HP-651 pumping from model layer 5 also is seen in model layer 3 and, to a lesser degree, model layer 1 when compared with January 1968 historical reconstruction results. Like TCE, reduction in PCE concentrations began when well HP-651 was taken out of service during February 1985 (Camp Lejeune Water Document CLW #4913; Sautner et al. 2013a). By June 2008, a shift in the center of mass of the PCE plume in a northwesterly direction from well HP-651 is clearly seen in Figure A24. This shift in the center of mass is primarily caused by the influence of Wallace Creek (Figure A14 and Appendix A6) on local groundwater flow as it is more pronounced in model layers 1 and 3. Shallow and deep remediation extraction wells began operating during October 1996. Comparisons of the vertical and areal distributions of PCE (Figure A24) with those of TCE (Figure A23) clearly indicate the substantially lower concentrations of PCE in all model layers and the substantially reduced areas of dispersion of PCE within each of the model layers. Larger-scale maps of the vertical and areal distributions of PCE showing additional HPLF area details are provided in Appendix A6.

Summary statistics for reconstructed PCE concentrations at water-supply well HP-651 are listed in Table A14 (simulated historical monthly mean concentrations are listed in Appendix A3). Maximum reconstructed PCE concentration was estimated to be 353 µg/L during December 1982. After the onset of pumping at water-supply well HP-651 (July 1972), PCE concentrations during the period of interest to the ATSDR health studies exceeded the current MCL for PCE (5 µg/L) by a factor of more than 70. At water-supply well HP-651, the current MCL for PCE was first exceeded during April 1973 and exceeded the MCL for 142 months (about 12 years). For specific data and operational information on water-supply well HP-651, refer to Sautner et al. (2013a); for detailed analyses and discussions pertinent to the fate and transport of PCE within the HPLF area, refer to Jones et al. (2013).

[47] Refer to Faye et al. (2010, p. C46–C51) for details and location of remediation extraction wells.

[48] As documented in Lawrence (2007) and Jang and Aral (2008b), under anaerobic biodegradation, PCE transforms (degrades) to TCE, 1,2-cDCE or 1,2-tDCE, VC, and ethene.

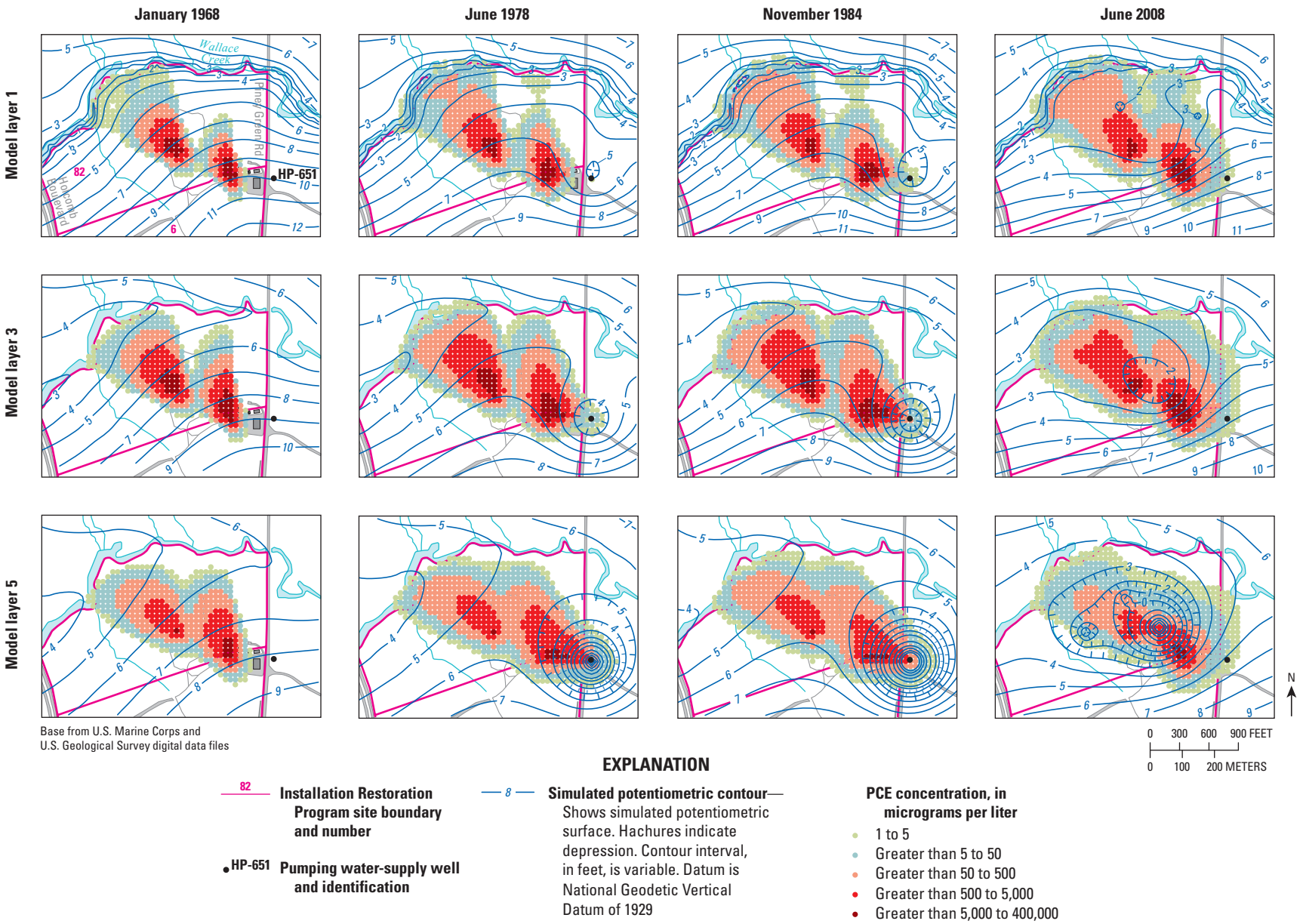


Figure A24. Reconstructed (simulated) water levels and distribution of tetrachloroethylene (PCE), Hadnot Point landfill area fate and transport model subdomain, model layers 1, 3, and 5, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1968, June 1978, November 1984, and June 2008. (See Figure A14 for location; see Appendix A6 for more detailed maps and results.)

Linear Control Model Methodology to Reconstruct Concentrations at Water-Supply Well HP-651

An alternative and simpler computational method, Linear Control Model (LCM) methodology, which is a linear state-space representation of a contaminated groundwater aquifer system, was developed to reconstruct contaminant concentrations in water-supply wells and compare results with the MODFLOW-MT3DMS numerical modeling approach. (See previous discussion in the section Linear Control Model Methodology to Reconstruct Water-Supply Concentrations.) Deactivation of water-supply well HP-651 (Figure A5) presented an opportunity to test and apply the LCM because there were sufficient, although limited, observation data once the well was secured and taken out of service on February 4, 1985 (Camp Lejeune Water Document CLW #4913; Sautner et al. 2013a). Measured data for PCE, TCE, 1,2-tDCE, and VC are listed in Table A4 and are also shown graphically in Figure A25. Reconstructed historical monthly concentrations at water-supply well HP-651, derived using the LCM, are shown in Figure A25 for PCE, TCE, 1,2-tDCE, and VC. For

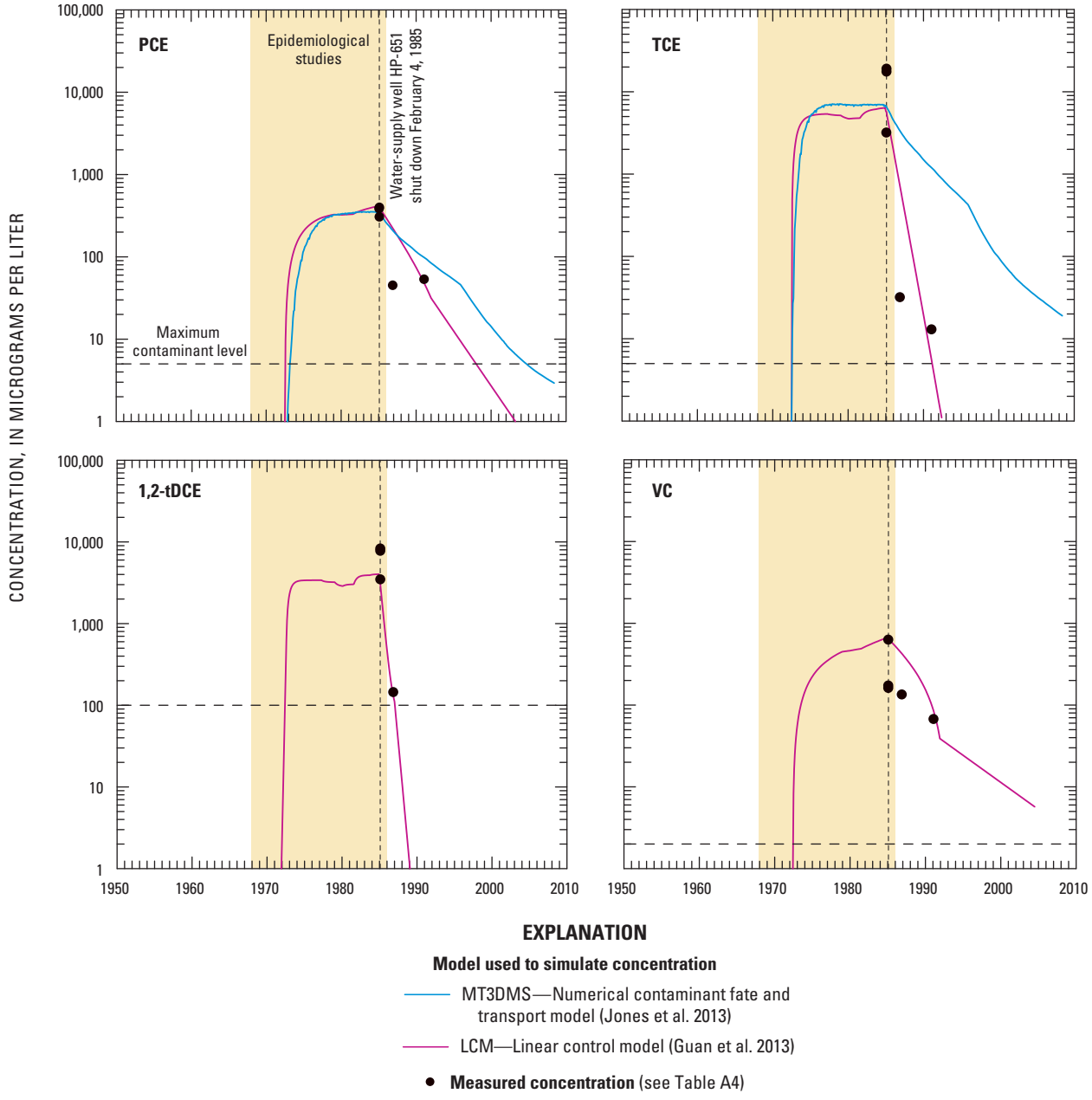


Figure A25. Reconstructed (simulated) concentrations of tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at water-supply well HP-651 using numerical (MT3DMS) and linear control methodology (TechControl) models, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. (See Figure A14 for well location.)

PCE and TCE, corresponding concentrations reconstructed (simulated) using the numerical contaminant fate and transport model MT3DMS (Zheng and Wang 1999; Zheng 2010) also are shown for comparison. The results shown in Figure A25 demonstrate very good agreement between the LCM results, the numerical contaminant fate and transport model (MT3DMS) results, and observation data for water-supply well HP-651. Corresponding monthly historical concentrations for 1,2-tDCE and VC derived from the LCM analyses also are listed in Appendix A3. Thus, the application of the LCM to a contaminated water-supply well such as HP-651 demonstrates that historical contaminant concentrations can be reconstructed using a simpler modeling approach; results are reliable when compared with field data and historical reconstruction results from a numerical contaminant fate and transport model (MT3DMS). Details on the development of the LCM methodology and application to water-supply well HP-651 are presented in Guan et al. (2013).

Estimates of Contaminant Mass in Groundwater

Estimates of subsurface contaminant mass pertinent to fate and transport in groundwater were previously discussed and are listed in Table A6. Results of simulated contaminant mass in groundwater for calibrated fate and transport models (MT3DMS) for the HPIA and HPLF areas for dissolved contaminants (TCE, PCE, and benzene) are shown in Figure A26 and are listed in Table A17. In these mass balance graphs, positive-valued plots indicate mass added to the aquifer (from contaminant sources), and the negative-valued plots indicate mass removed from the aquifer. At the HPIA, for TCE, most mass (by volume) was removed through biodegradation; the least amount of mass was removed through pumping of water-supply wells. For the HPLF area, most mass was removed by sorption until remediation activities were initiated around 1996. Then, most of the mass in the aquifer was removed through pumping of remediation extraction wells. Very little dissolved benzene was added to the aquifer, when compared to the other contaminants. This is consistent with results obtained from the historical reconstruction analyses of LNAPL and dissolved benzene using the TechFlowMP model (Jang et al. 2013) wherein less than 2 percent of the benzene dissolved into groundwater from the LNAPL source. Furthermore, similar to the plots shown in Figure A26 where pumping removes the least mass (prior to the onset of remediation extraction-well pumping), the TechFlowMP benzene LNAPL simulations show that only 0.005 percent of the dissolved benzene mass is removed by pumping (Jang et al. 2013).

Quantitative results for mass balance terms obtained from contaminant fate and transport simulations using MT3DMS are listed in Table A17. Results are listed for the core period of interest to the ATSDR health studies (January 1968–December 1985) and for the end of the simulation period (June 2008). The mass in the aquifer should approximately equal the mass contributed by the sources minus the mass removed through by biodegradation, supply wells, and drains (in the case of the HPLF area). For example, during December 1985 for the HPLF area, the TCE mass in the aquifer is simulated as 2,254 kilograms (kg), which is about equal to the mass contributed by the contaminant source (4,501 kg) minus the total mass removed through biodegradation (1,438 kg), supply wells (686 kg), and drains (125 kg) or 2,252 kg. At the HPIA, during the period January 1968–December 1985, 3.3 kg of TCE were removed by water-supply wells[49] near the Building 1601 area, and 26 kg were removed by water-supply wells near the Building 900 area. This TCE mass, which was dissolved in groundwater, was the raw water source for contaminated finished water supplied by the HPWTP to base housing and other facilities and intermittently supplied to the Holcomb Boulevard water-distribution system. Of note, in the HPLF area, 686 kg of TCE were removed by water-supply well HP-651 during the core period of interest to the ATSDR health studies (January 1968–December 1985), which is more than 20 times more than the mass removed by HPIA water-supply wells (about 30 kg) operating near Buildings 1601 and 900.

[49] The figure of 3.3 kg is arrived at by computing the difference in mass removed by supply wells between January 1968 (2.5 kg) and December 1985 (5.8) for Building 1601.

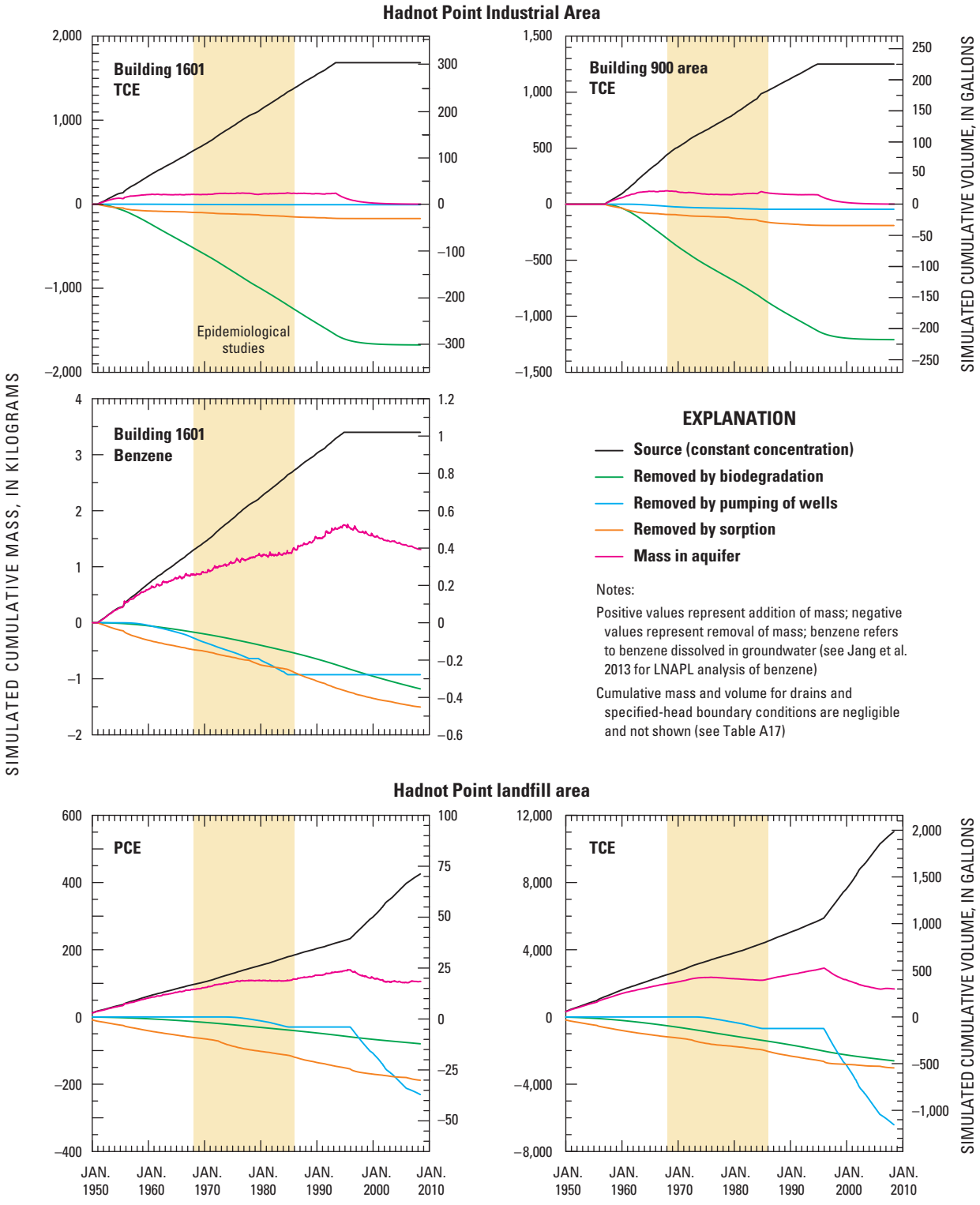


Figure A26. Reconstructed (simulated) cumulative mass balance and volumes of tetrachloroethylene (PCE), trichloroethylene (TCE), and benzene in groundwater, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Table A17. Reconstructed (simulated) cumulative mass balance and volumes of tetrachloroethylene (PCE), trichloroethylene (TCE), and dissolved benzene, derived from contaminant fate and transport simulations using MT3DMS, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[kg, kilogram; gal, gallon]

Mass term	Simulated cumulative mass and volume					
	January 1968		December 1985		June 2008	
	kg	gal	kg	gal	kg	gal
Hadnot Point Industrial Area (HPIA) fate and transport subdomain (see Figure A13)						
Building 1601—Trichloroethylene (TCE)						
Source	637	115	1,379	249	1,684	304
Removed by biodegradation	520	94	1,248	225	1,675	302
Removed by wells	2.5	0.5	5.8	1.1	5.8	1.1
Removed by sorption	98	18	151	27	171	31
Mass in aquifer[1]	117	21	130	23	0.9	0.2
Building 1601—Benzene						
Source	1.3	0.4	2.7	0.8	3.4	1.0
Removed by biodegradation	0.2	0.1	0.5	0.2	1.2	0.4
Removed by wells	0.3	0.1	0.9	0.3	0.9	0.3
Removed by sorption	0.5	0.1	0.9	0.3	1.5	0.5
Mass in aquifer[1]	0.9	0.3	1.3	0.4	1.3	0.4
Building 900—Trichloroethylene (TCE)						
Source	441	80	1,012	183	1,251	226
Removed by biodegradation	305	55	873	158	1,209	218
Removed by wells	19	3	45	8	45	8
Removed by sorption	91	17	160	29	190	34
Mass in aquifer[1]	120	22	101	18	0.9	0.2
Hadnot Point landfill (HPLF) area fate and transport subdomain (see Figure A14)						
Tetrachloroethylene (PCE)						
Source	97	16	184	30	426	69
Removed by biodegradation	14	2	41	7	80	13
Removed by wells	0	0	30	5	231	38
Removed by sorption	61	10	119	19	188	31
Removed by drains	0	0	1	0.2	5	0.9
Mass in aquifer[1]	83	13	113	18	106	17
Trichloroethylene (TCE)						
Source	2,514	454	4,501	812	11,031	1,990
Removed by biodegradation	520	94	1,438	259	2,611	471
Removed by wells	0.0	0.0	686	124	6,414	1,157
Removed by sorption	1,180	213	2,043	369	3,030	547
Removed by drains	7	1	125	23	331	60
Mass in aquifer[1]	1985	358	2,254	407	1,666	301

[1] Mass in aquifer includes sorbed and dissolved

Computation of Finished-Water Concentrations—Hadnot Point Water Treatment Plant

Using reconstructed (simulated) water-supply well concentrations previously discussed (Figures A18, A20, A22, A25, and Appendix A3), monthly mean concentrations of PCE, TCE, 1,2-tDCE, VC, and benzene were estimated for finished water at the HPWTP. These estimates were computed using a materials mass balance model (simple mixing) to compute the flow-weighted mean concentrations of VOCs as described earlier in the section on Computation of Contaminated Finished-Water Concentrations.

Reconstructed (simulated) monthly mean concentrations of PCE, TCE, 1,2-tDCE, VC, and benzene in finished water delivered by the HPWTP and measured concentrations in finished water of VOCs are shown in Figure A27. The current MCL for each contaminant (Table A3) also is shown. Monthly reconstructed concentrations at the HPWTP for the entire historical period (1942–2008) are listed in Appendix A7. Because the range in values for reconstructed and measured concentrations span several orders of magnitude, Figure A27 is plotted using a logarithmic ordinate (y-axis). Of note in Figure A27 is the effect of the contribution of contaminated groundwater when pumping began at water-supply well HP-651 (July 1972). TCE concentrations in finished water at the HPWTP ranged from about 10 to 30 µg/L for the period 1955–1972, prior to the onset of pumping from water-supply well HP-651 (Figure A27, Appendix A7). Subsequent to the onset of pumping of water-supply well HP-651 during July 1972, finished-water concentrations increased to a maximum computed value of 783 µg/L during November 1983 (Table A18 and Appendix A7). Measured concentrations of PCE, TCE, 1,2-tDCE, VC, and benzene and historical reconstruction (simulated) results for the HPWTP are listed in Table A18. Given the limited number of measured finished-water concentration data and their substantial variations, there is reasonable agreement between measured finished-water concentrations and historical reconstruction results for the HPWTP.

Table A18. Selected measured and reconstructed (simulated) concentrations of tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter; J, estimated]

Contaminant	[1]Measured data		[2]Reconstructed (simulated)		[2]Reconstructed (maximum value)	
	Sample date	Concentration, in µg/L	Simulation date	Concentration, in µg/L	Simulation date	Concentration, in µg/L
PCE	5/27/1982[3]	15	May 1982	21	Nov. 1983	39
	7/27/1982[4]	100	July 1982	27		
	12/4/1984[6]	3.9J	Nov. 1984	31		
	2/5/1985[7]	7.5J	Jan. 1985	16		
TCE	5/27/1982[3]	1,400	May 1982	438	Nov. 1983	783
	7/27/1982[5]	19	Aug. 1982	670		
	7/27/1982[6]	21	Aug. 1982	670		
	12/4/1984[5]	46	Nov. 1984	639		
	12/4/1984[6]	200	Nov. 1984	639		
	12/12/1984[6]	2.3J	Dec. 1984	43		
	12/19/1984	1.2	Dec. 1984	43		
	2/5/1985[7]	429	Jan. 1985	324		
1,2-tDCE	12/4/1984[6]	83	Nov. 1984	358	Nov. 1983	435
	12/4/1984[5]	15	Dec. 1984	26		
	12/12/1984[6]	2.3J	Dec. 1984	26		
	2/5/1985[7]	150	Jan. 1985	163		
VC	2/5/1985[7]	2.9J	Jan. 1985	31	Nov. 1983	67
Benzene	11/19/1985[7,8,9]	2,500	Nov. 1985	3	Apr. 1984	12
	12/10/1985[7]	38	Dec. 1985	3		
	12/18/1985[7]	1.0	Dec. 1985	3		

[1] Data from Faye et al. (2010, Tables C11 and C12)

[2] Simulation results represent the last day of each month (e.g., May 31); results reported for simulation month nearest the sample date; refer to Appendix A7 for complete listing of reconstructed finished-water concentrations

[3] Water sample collected at Building NH-1; data reported as unreliable

[4] Water sample collected at Building FC-530

[5] Untreated water

[6] Treated water

[7] Treatment status unknown

[8] Laboratory analysis noted with: "Sample appears to have been contaminated with benzene, toluene, and methyl chloride" (JTC Environmental Consultants 1985)

[9] Data noted with: "Not Representative" (U.S. Marine Corp Base Camp Lejeune Water Document CLW #1356)

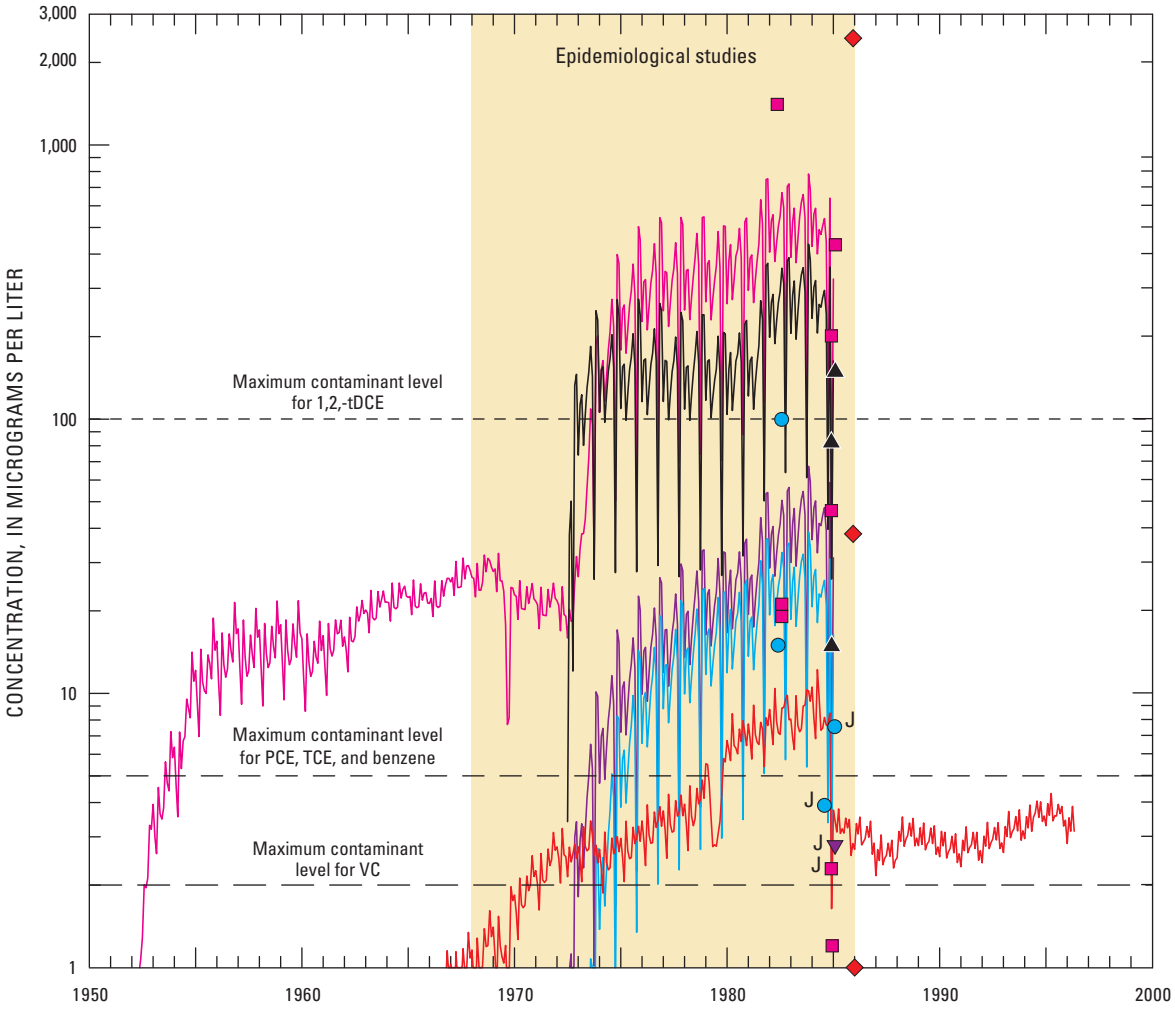


Figure A27. Reconstructed (simulated) finished-water concentrations of tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, and measured concentrations, Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. (Note: See Appendix A7 for monthly mean finished-water concentration and Table A3 for detailed list of current maximum contaminant levels.) [J, estimated; LCM, linear control model; LNAPL, light nonaqueous phase liquid]

Intermittent Transfers of Finished Water from Hadnot Point to Holcomb Boulevard

During the period June 1972–December 1985, the Hadnot Point and Holcomb Boulevard water-distribution systems were intermittently interconnected during dry spring and summer months. During these periods, contaminated Hadnot Point finished water (Figure A27) was transferred to and distributed within the uncontaminated Holcomb Boulevard water-distribution system. The interconnection of the two water-distribution systems was primarily accomplished by operating booster pump 742, although on rare occasions, the valve at Marston Pavilion (near Wallace Creek) also was opened (Figure A1). Operational records indicating booster pump 742 operations and Marston Pavilion valve openings are only partially documented. Interconnection information and data that are available were obtained from the USMCB Camp Lejeune water utility log books (Camp Lejeune Water Documents CLW #7023–CLW #8735). These data, representing the number of interconnection events, are shown graphically in Figure A28. Note, all contaminated Hadnot Point water-supply wells were taken out of service after February 1985 (Sautner et al. 2013a).

Because of the interconnection of the Hadnot Point and Holcomb Boulevard water-distribution systems, a more complex analysis was necessary (compared to the simple mixing-model approach described by Equations A1 and A2) to determine the concentration of finished water in the Holcomb Boulevard water-distribution system (Figure A15) during periods of interconnection.[50] This required the application of the EPANET 2 water-distribution system model (Rossman 2000) and extended period simulation (EPS). The EPANET 2 water-distribution system model was calibrated for the Holcomb Boulevard water-distribution system using field data collected by the ATSDR water-modeling team; field data represented operational conditions during 2004 (Sautner et al. 2005, 2007, 2013b). EPSs were used to reconstruct water-distribution system flow and mass transport patterns during discrete interconnection events (Figure A28) when booster pump 742 (Figure A1) was intermittently operated, resulting in the transfer of contaminated finished water from the Hadnot Point water-distribution system to the "uncontaminated" Holcomb Boulevard water-distribution system. Pipelines represented in the water-distribution system network models

[50] See section on Computation of Contaminated Finished-Water Concentrations.

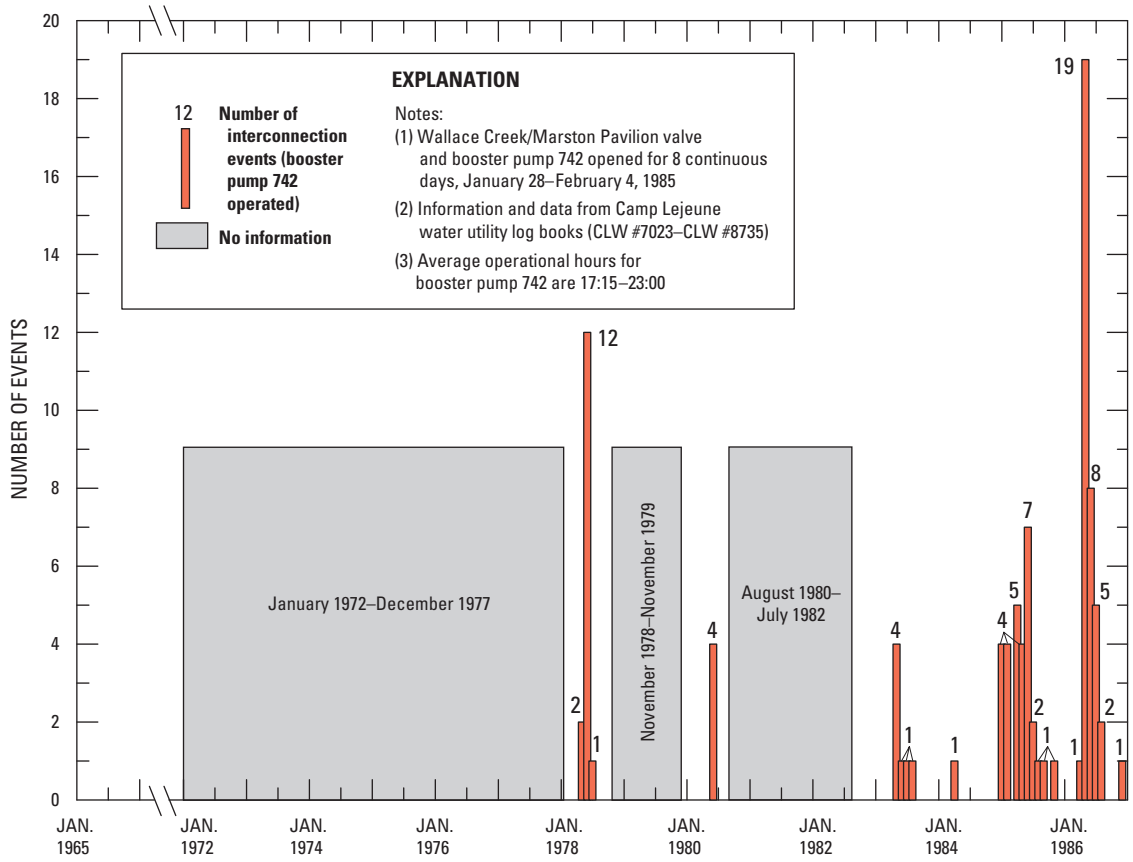


Figure A28. Number of interconnection events when Hadnot Point finished water was transferred to the Holcomb Boulevard water-distribution system, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, 1972–1986.

are coincident with locations of streets within the HPHB study area (Figure A1) (e.g., see Maslia et al. [2009b, Figure I3].) The network representation of the "real world" Hadnot Point and Holcomb Boulevard water-distribution systems was simplified by representing the Hadnot Point water-distribution system as an infinite reservoir on the upstream side of booster pump 742; this allowed for shorter EPANET 2 model run-times. To simulate the estimated percentage of Hadnot Point contaminated water at locations throughout Holcomb Boulevard, 100 units (e.g., 100 µg/L) of a conservative tracer[51] were placed in the model's reservoir location, which represented finished (contaminated) Hadnot Point water that would have been transferred to the Holcomb Boulevard water-distribution system through booster pump 742. For the 8-day period, January 28–February 4, 1985, the bypass valve at Marston Pavilion (Figure A1) was documented to have been open, thereby allowing finished (contaminated) Hadnot Point water to flow freely through the bypass valve to the Holcomb Boulevard water-distribution system.

Because information pertaining to times when interconnection events occurred is limited, and for some years unknown (e.g., 1972–1977, Figure A28), a Markov process (Ross 1997) was applied using available information to estimate the probability and number of monthly interconnection events that occurred during the months of April–August for years 1972–1985.[52] Table A19 lists the number of recorded interconnection events and the number of events predicted by using a Markov Chain analysis for the period 1972–1985. Details of the Markov process are provided in Sautner et al. (2013b).

Using the Markov Chain analysis when data were unavailable or unknown, EPANET 2 EPSs were conducted for each month when water transfers occurred by operating booster pump 742 (interconnection event). Note, for the 8-day period of January 28–February 4, 1985, the HBWTP was shut down (Camp Lejeune Water Documents CLW #8109 and #8117). During this period, all Holcomb Boulevard family housing areas were continuously supplied with contaminated Hadnot Point finished water. Results for each Holcomb Boulevard housing area for 1972–1985 are listed in Table A20.[53] Results should be interpreted as monthly mean concentrations for a specific housing area assuming a source (Hadnot Point

[51] A conservative tracer is a chemical compound whose concentration does not change due to biological or chemical processes.

[52] A Markov process analyzes the tendency of one event to be followed by another event based on the sequence of events. Using this analysis, one can generate a new sequence of random but related events, which will look similar to the original. A stream of events is called a Markov Chain.

[53] Holcomb Boulevard housing areas and their designations for which results are provided are Paradise Point (PP), Midway Park (MP), Berkeley Manor (BM), and Watkins Village (WV); see Figure A1 for locations.

Table A19. Number of recorded and predicted interconnection events when Hadnot Point finished water was transferred to the Holcomb Boulevard water-distribution system, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, 1972–1985.

[Rec., recorded; Pred., predicted; N/A, not applicable; —, data not available]

Year	April		May		June		July		August	
	[1] Rec.	[2] Pred.	Rec.	Pred.	Rec.	Pred.	Rec.	Pred.	Rec.	Pred.
1972[3]	N/A	N/A	N/A	N/A	—	0	—	0	—	0
1973	—	0	—	0	—	1	—	0	—	0
1974	—	0	—	0	—	0	—	0	—	0
1975	—	0	—	0	—	0	—	0	—	0
1976	—	0	—	0	—	1	—	0	—	0
1977	—	1	—	1	—	1	—	1	—	1
1978	0	0	3	2	12	3	1	1	0	2
1979	—	1	—	1	—	2	—	1	—	1
1980	0	0	0	1	4	2	0	1	—	2
1981	—	16	—	3	—	3	—	1	—	1
1982	—	2	—	5	—	2	—	2	0	1
1983	0	1	4	4	1	7	1	2	1	2
1984	1	1	0	3	0	3	0	2	0	2
1985[4]	5	5	4	3	7	5	2	2	1	1

[1] Recorded values obtained from Camp Lejeune water utility log books (U.S. Marine Corps Base Camp Lejeune Water Documents CLW #7025–CLW #8735)

[2] Predicted interconnection events derived from application of Markov Chain analysis; refer to Sautner et al. (2013b)

[3] Prior to June 1972, the Hadnot Point water treatment plant (WTP) supplied all of the finished water to Holcomb Boulevard family housing areas

[4] For the period of January 28–February 4, 1985, booster pump 742 operated continuously due to shut down of Holcomb Boulevard WTP; this continuous event is not included in the Markov Chain analysis

Table A20. Reconstructed (simulated) monthly mean percentage of finished Hadnot Point water treatment plant water transferred through Booster Pump 742 and distributed to Holcomb Boulevard family housing areas during interconnection events, U.S. Marine Corps Base Camp Lejeune, North Carolina, 1972–1985.[1,2]

[Values in percent; PP, Paradise Point; MP, Midway Park; BM, Berkeley Manor; WV, Watkins Village; —, not applicable]

Month	[2]1972				1973				1974				1975				1976			
	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV
Jan.	100	100	100	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Feb.	100	100	100	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Mar.	100	100	100	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Apr.	100	100	100	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
May	100	100	100	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
June	100	100	100	—	0	1	1	—	0	0	0	—	0	0	0	—	0	1	1	—
July	6	1	2	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Aug.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Sept.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Oct.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Nov.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Dec.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—

Month	1977				1978				1979				1980				1981			
	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV
Jan.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Feb.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mar.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Apr.	0	1	1	—	0	0	0	0	0	1	1	1	0	0	0	0	0	1	15	11
May	0	0	1	—	0	1	2	1	0	0	1	1	0	0	0	0	0	1	4	3
June	0	0	1	—	1	7	15	11	0	1	2	1	0	2	4	3	0	1	3	2
July	0	1	1	—	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	1
Aug.	0	1	1	—	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	1
Sept.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oct.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nov.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dec.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Month	1982				1983				1984				[4]1985				1986			
	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV
Jan.	0	0	0	0	0	0	0	0	0	0	0	0	10	10	10	10				
Feb.	0	0	0	0	0	0	0	0	0	0	0	0	20	16	17	17				
Mar.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Apr.	0	1	2	2	0	0	0	0	0	0	1	1	0	1	5	4				
May	0	1	4	3	0	1	3	2	0	0	0	0	0	2	4	3				
June	0	1	2	1	0	0	0	0	0	0	0	0	1	3	7	6				
July	0	1	2	1	0	0	0	0	0	0	0	0	0	0	1	1				
Aug.	0	0	1	1	0	0	1	1	0	0	0	0	3	1	1	1				
Sept.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Oct.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Nov.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1				
Dec.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				

[1] Based on a concentration of 100 micrograms per liter of a dissolved conservative contaminant in Hadnot Point finished water being transferred through Booster Pump 742. To obtain a specific concentration for Holcomb Boulevard family housing area, multiply concentration of Hadnot Point finished water by percent (in decimal form) for month of interest

[2] Monthly percentages rounded to nearest whole number

[3] Values for January–June 1972 represent Hadnot Point finished water without any mixing (dilution) with Holcomb Boulevard water treatment plant (WTP) finished water because the Holcomb Boulevard WTP came online after June 1972 (Scott A. Brewer, U.S. Marine Corps Base Camp Lejeune, written communication, September 29, 2005)

[4] Watkins Village housing was not built and occupied until about 1978 (Faye et al. 2010) and the first documented interconnection occurs during May 1978 (U.S. Marine Corps Base Camp Lejeune Water Documents CLW #7023, #7031, and #7033)

[5] For period of January 28–February 4, 1985, booster pump 742 operated continuously owing to the shutdown of the Holcomb Boulevard water treatment plant; this continuous event is not included in the Markov Chain analysis

finished water) concentration of 100 units (100 µg/L). Knowing a specific reconstructed finished-water concentration at the HPWTP, the resulting finished-water concentration at a specific Holcomb Boulevard housing area was calculated for the period July 1972–February 1985. This result was determined by multiplying the reconstructed finished-water concentration at the HPWTP with the percentage of Hadnot Point finished water at each Holcomb Boulevard housing area (Table A20). For example, the reconstructed (simulated) finished water TCE concentration at the HPWTP for May 1982 was 438 µg/L (Table A18). Based on the percentage of Hadnot Point water distributed to the Paradise Point, Midway Park, Berkeley Manor, and Watkins Village housing areas of 0, 1, 4, and 3 percent, respectively (Table A20, May 1982), the resulting concentrations of TCE (rounded) would be 0 µg/L for Paradise Point, 4 µg/L for Midway Park, 18 µg/L for Berkeley Manor, and 13 µg/L for Watkins Village. Using this process, specific values for PCE, TCE, 1,2-tDCE, VC, and benzene concentrations in finished water distributed to the Holcomb Boulevard housing areas were computed and are listed in Appendix A8 (Tables A8.1–A8.5, respectively) for each month, January 1972–December 1985. For selected months when concentrations are non-zero for any of the Holcomb Boulevard housing areas, a summary listing of Appendix A8 results is provided as Table A21. Note, of the five contaminants of concern to the ATSDR health studies (PCE, TCE, 1,2-tDCE, VC, and benzene), only TCE and VC exceed their current MCLs (5 µg/L and 2 µg/L, respectively) in finished water distributed to Holcomb Boulevard family housing areas. This is due to very low concentrations of PCE, 1,2-tDCE, and benzene in Hadnot Point finished water when it mixes with uncontaminated finished water in the Holcomb Boulevard water-distribution system. TCE is the predominant contaminant of concern for the Holcomb Boulevard housing area and exceeds the current MCL by factors of about 2–12 during intermittent water transfers occurring during the period July 1972–February 1985 (Table A21).[54]

Spatial distributions of TCE within Holcomb Boulevard housing areas for three time periods—June 1978, May 1982, and February 1985—are shown in Figure A29. These historical reconstruction results were obtained using the EPANET 2 water-distribution system model previously discussed for interconnection events (see Sautner et al. [2013b] for detailed discussion). The Holcomb Boulevard reconstructed finished-water mean TCE concentrations for the Berkeley Manor and Watkins Village housing areas during June 1978 are 51 µg/L and 38 µg/L, respectively.[55] For May 1982, the Berkeley Manor and Watkins Village housing areas show reconstructed mean TCE concentrations of 20 µg/L and 13 µg/L, respectively. During the 8-day period of January 28–February 4, 1985 (represented by the February 1985 map in Figure A29), when the HBWTP was shut down, the reconstructed mean TCE concentrations in all housing areas exceeded 50 µg/L with the exception of the northernmost extent of Paradise Point and a small area to the north of the Marston Pavilion valve. Overall, during intermittent transfers of contaminated Hadnot Point finished water, the Paradise Point family housing area shows the lowest reconstructed mean TCE concentrations, whereas Berkeley Manor followed by Watkins Village show the greatest reconstructed mean TCE concentrations (except for the pipeline that directly connects booster pump 742 to the Holcomb Boulevard water-distribution system along Holcomb Boulevard). Spatial distribution maps for the other contaminants of concern (similar to Figure A29) are provided in Sautner et al. (2013b), although reconstructed concentrations for the other contaminants of concern (PCE, 1,2-tDCE, VC, and benzene) rarely equaled or exceeded their current MCLs during interconnection periods of interest to the ATSDR health study (Table A21). Selected calibrated model input files for the distribution of contaminants within the Holcomb Boulevard water-distribution system for use with the EPANET 2 (Rossman 2000) model code are provided on the CD-ROM that accompanies this report.

[54] Values for January–June 1972 represent Hadnot Point finished water without any mixing (dilution) with HBWTP finished water because the HBWTP came online during June 1972 (Scott A. Brewer, USMCB Camp Lejeune, written communication, September 29, 2005).

[55] Refer also to Table A21 and Appendix Table A8.2.

Table A21. Reconstructed (simulated) mean concentrations of tetrachloroethylene, trichloroethylene, *trans*-1,2-dichloroethylene, vinyl chloride, and benzene in finished water distributed to Holcomb Boulevard family housing areas for selected months, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, 1972–1985.[1,2]

[µg/L, microgram per liter; PP, Paradise Point; MP, Midway Park; BM, Berkeley Manor; WV, Watkins Village; —, not applicable]

Month Year	Concentration, in µg/L				Month Year	Concentration, in µg/L				Month Year	Concentration, in µg/L			
	PP	MP	BM	[3]WV		PP	MP	BM	[3]WV		PP	MP	BM	[3]WV
Tetrachloroethylene (PCE)[4]														
June 1978	0	1	2	2	May 1982	0	0	1	1	Jan. 1985[5]	2	2	2	2
June 1980	0	0	1	1	June 1982	0	0	1	0	Feb. 1985[5]	3	3	3	3
Apr. 1981	0	0	2	1	July 1982	0	0	1	0					
May 1981	0	0	1	0	May 1983	0	0	1	0					
Trichloroethylene (TCE)[4]														
Jan. 1972	22	22	22	—	May 1978	0	2	6	4	Apr. 1982	0	3	9	7
Feb. 1972	21	21	21	—	June 1978	3	23	51	38	May 1982	1	6	20	13
Mar. 1972	17	17	17	—	July 1978	0	0	1	1	June 1982	0	4	10	7
Apr. 1972	24	24	24	—	Apr. 1979	0	1	2	1	July 1982	0	4	12	8
May 1972	19	19	19	—	May 1979	0	1	3	2	Aug. 1982	1	3	6	4
June 1972	19	19	19	—	June 1979	0	2	6	4	May 1983	1	5	14	10
July 1972	1	0	0	—	July 1979	0	1	4	2	June 1983	0	0	2	2
June 1973	0	0	1	—	Aug. 1979	0	2	5	3	July 1983	0	0	3	2
June 1976	1	2	3	—	June 1980	2	8	17	13	Aug. 1983	0	2	5	3
Apr. 1977	0	1	2	—	Apr. 1981	0	4	39	28	Apr. 1984	0	2	5	3
May 1977	1	1	3	—	May 1981	0	4	13	10	Jan. 1985[5]	34	31	32	34
June 1977	1	2	3	—	June 1981	0	4	10	7	Feb. 1985[5]	66	53	54	56
July 1977	1	2	3	—	July 1981	0	2	4	3					
Aug. 1977	1	2	4	—	Aug. 1981	0	2	6	4					
***Trans*-1,2-dichloroethylene (1,2-tDCE)[4]**														
June 1973	0	1	1	—	June 1979	0	1	3	2	June 1982	0	2	6	4
June 1976	0	1	2	—	July 1979	0	0	1	1	July 1982	0	2	6	4
Apr. 1977	0	1	1	—	Aug. 1979	0	1	2	1	Aug. 1982	0	2	3	2
May 1977	0	1	1	—	June 1980	1	3	7	5	May 1983	0	3	8	5
June 1977	0	1	1	—	Apr. 1981	0	2	16	12	June 1983	0	0	1	1
July 1977	0	1	2	—	May 1981	0	2	6	4	July 1983	0	0	2	1
Aug. 1977	0	1	2	—	June 1981	0	2	4	3	Aug. 1983	0	1	3	2
May 1978	0	1	3	2	July 1981	0	1	2	1	Apr. 1984	0	1	2	2
June 1978	2	10	22	17	Aug. 1981	0	1	3	2	Jan. 1985[5]	17	16	16	17
Apr. 1979	0	1	1	1	Apr. 1982	0	2	4	3	Feb. 1985[5]	33	27	27	27
May 1979	0	0	1	1	May 1982	0	3	10	7					
Vinyl chloride (VC)[4]														
June 1978	0	1	3	2	June 1981	0	0	1	0	July 1982	0	0	1	1
June 1980	0	1	1	1	Apr. 1982	0	0	1	0	May 1983	0	0	1	1
Apr. 1981	0	0	3	2	May 1982	0	0	1	1	Jan. 1985[5]	3	3	3	3
May 1981	0	0	1	1	June 1982	0	0	1	1	Feb. 1985[5]	6	5	5	5
Benzene[4]														
Jan. 1972	3	3	3	—	Apr. 1972	3	3	3	—	June 1978	0	0	1	0
Feb. 1972	3	3	3	—	May 1972	3	3	3	—	Apr. 1981	0	0	1	1
Mar. 1972	2	2	2	—	June 1972	3	3	3	—	Feb. 1985[5]	1	1	1	1

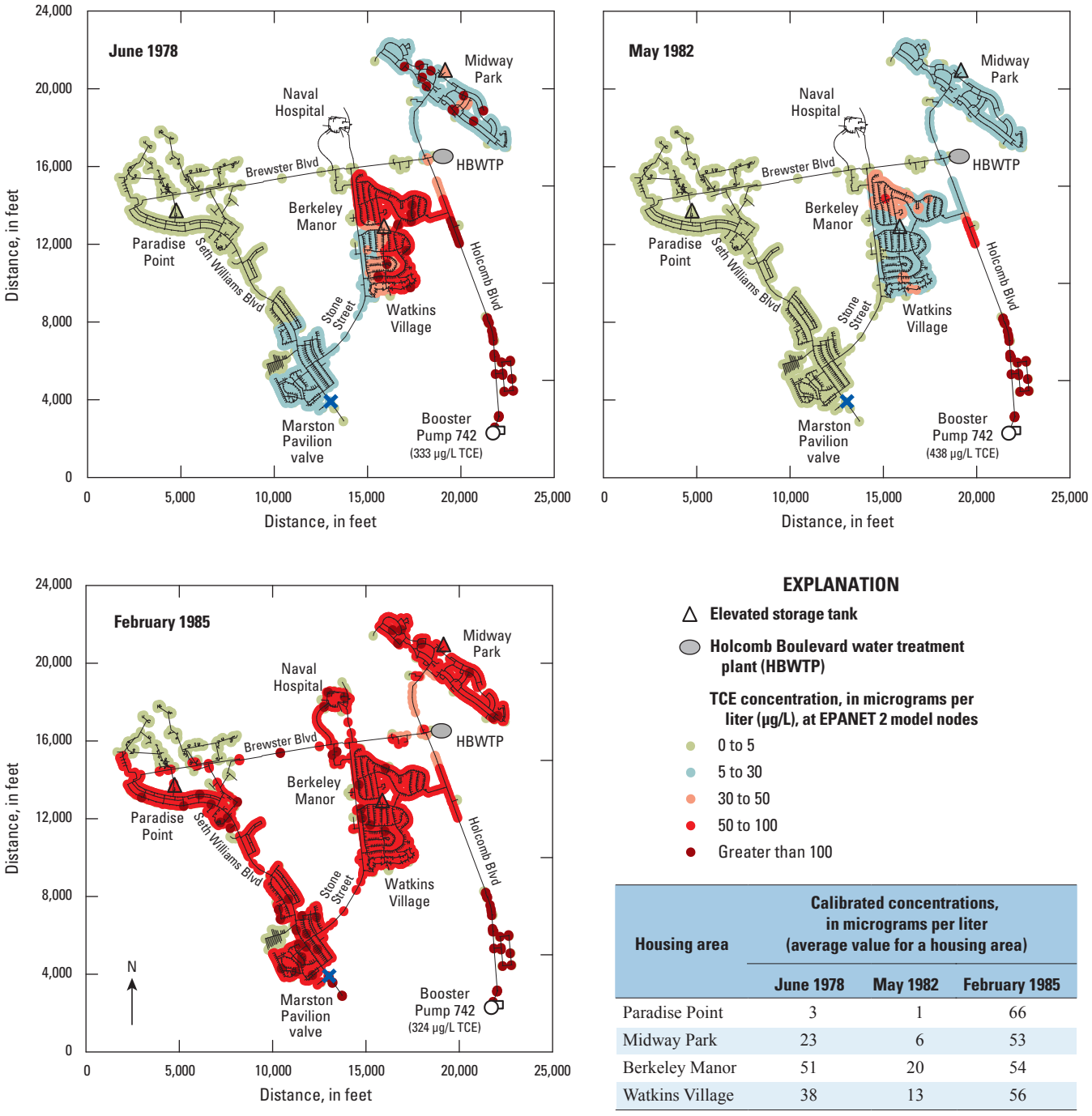
[1] See Appendix A8 (Tables A8.1–A8.5) for complete monthly listing, January 1972–December 1985

[2] Values for January–June 1972 represent Hadnot Point finished water without any mixing (dilution) with Holcomb Boulevard water treatment plant (WTP) finished water because the Holcomb Boulevard WTP came online after June 1972 (Scott A. Brewer, U.S. Marine Corps Base Camp Lejeune, written communication, September 29, 2005)

[3] Watkins Village housing was not built and occupied until about 1978 (Faye et al. 2010), and the first documented interconnection occurs during May 1978 (U.S. Marine Corps Base Camp Lejeune Water Documents CLW #7023, #7031, and #7033)

[4] Current maximum contaminant level (MCL) for PCE, TCE, and benzene is 5 µg/L; current MCL for 1,2-tDCE is 100 µg/L; current MCL for VC is 2 µg/L; see Table A3

[5] For the 8-day period January 28–February 4, 1985, the Holcomb Boulevard water treatment plant was shut down, and contaminated Hadnot Point finished water was continuously provided to Holcomb Boulevard family housing areas



Housing area	Calibrated concentrations, in micrograms per liter (average value for a housing area)		
	June 1978	May 1982	February 1985
Paradise Point	3	1	66
Midway Park	23	6	53
Berkeley Manor	51	20	54
Watkins Village	38	13	56

Figure A29. Reconstructed (simulated) distribution of trichloroethylene (TCE) contamination within the Holcomb Boulevard water treatment plant service area resulting from supply of contaminated Hadnot Point finished water, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, June 1978, May 1982, and February 1985. (See Figure A1 for location.)

Sensitivity Analysis

Best modeling practice requires that evaluations be conducted to ascertain confidence in models and model results by assessing parameter sensitivity, variability, and uncertainty associated with the modeling process and with the outcomes attributed to models (ASTM 1994; Saltelli et al. 2000). There are numerous methods for characterizing a model's sensitivity and uncertainty based on variations of calibrated parameter values (ASTM 1994; Cullen and Frey 1999; Salltelli et al. 2000; Tung and Yen 2005; Hill and Tiedeman 2007). These methods are generally classified into two groups: (1) sensitivity analysis, wherein calibrated model parameter values are varied either manually or through some automated method, and (2) probabilistic uncertainty analysis, wherein probabilistic methods are used to characterize and quantify the input and output parameter variation and uncertainty.

The purpose of this report section is to summarize the characterization of model output sensitivity (e.g., simulated water levels, finished-water concentrations) due to model input parameter variability by reporting on a series of sensitivity analyses conducted by using calibrated model-input parameter values.[56] Some of the sensitivity analyses reported herein were conducted to explore certain model-input parameter value assignments (e.g., horizontal hydraulic conductivity [K_{xx}] or historical monthly pumping [$Q_{monthly}$]) and some sensitivity analyses were conducted to explore specific scenarios viewed as important in model conceptualization (e.g., contaminant source-release date or cell-size discretization). The sensitivity analyses conducted as part of the historical reconstruction process are shown in Figure A30 and are categorized by the type of parameter being varied (physical or numerical) and by the type of simulation model for which the parameter sensitivity is tested (groundwater flow, contaminant fate and transport, or water-distribution system). Additionally, the figures or tables in this report where results of the sensitivity analysis are found are provided in Figure A30. The specific types of sensitivity analysis conducted are summarized below and described in subsequent sections of this report.

[56] Probabilistic uncertainty analysis is described and discussed in the Uncertainty Analysis section of this report.

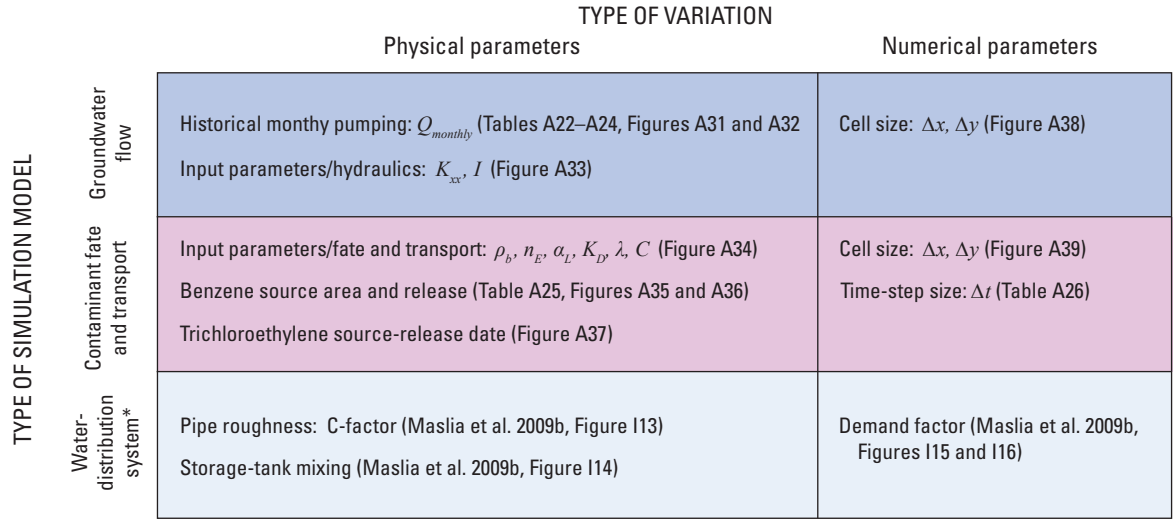


Figure A30. Types of sensitivity analyses applied to model parameters, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune.

1. **Statistical analysis of historical monthly pumping:** monthly water-supply well pumping rates ($Q_{monthly}$) were varied by using a statistical analysis to assess the variation of the calibrated water-supply well monthly pumpage on finished-water concentrations of TCE at the HPWTP.

2. **Groundwater-flow model parameters**: groundwater-flow model parameters of horizontal hydraulic conductivity (K_{xx}) and infiltration (I) were varied to assess the sensitivity of calibrated parameter-value variation on simulated water levels, groundwater velocities, and reconstructed contaminant concentrations.

3. **Fate and transport model parameters:** fate and transport parameters of source concentration (C), bulk density (ρ_b), porosity (n_E), longitudinal dispersivity (α_L), distribution coefficient (K_D), and biodegradation rate (λ) were varied to assess the sensitivity of calibrated parameter-value variation on PCE and TCE concentrations in groundwater and in finished water at the HPWTP.

4. **Benzene source-area and source-release variation:** sensitivity analyses were conducted to assess the effects of varying contaminant-source area size, location, and release date on reconstructed benzene concentrations at water-supply well HP-603 and at the HPWTP.

5. **Trichloroethylene source-release-date variation:** sensitivity analyses were conducted to assess the effects of varying the calibrated TCE source-release date (9 years after UST system installation and 7 years after site development for the HPLF area) on reconstructed TCE finished-water concentrations at the HPWTP.

6. **Finite-difference grid cell-size variation:** the finite-difference cell size of 50 ft per side (used in the calibrated groundwater-flow and contaminant fate and transport HPIA and HPLF subdomain model areas) was reduced to 25 ft and 12.5 ft per side to assess the sensitivity of varying a numerical parameter on water levels in supply wells (25-ft cell size), on TCE concentration at water-supply well HP-651 (25-ft and 12.5-ft cell sizes), and on computed contaminant mass in water-supply well HP-651 (25-ft and 12.5-ft cell sizes).

7. **Time-step size variation:** the calibrated model time step of a calendar month (e.g., 31 days for January) was reduced to 1 day to assess the sensitivity of time-step variation on simulated concentrations of PCE and TCE at water-supply well HP-651 during the period November 1984–January 1985.

8. **Water-distribution system parameters:** water-distribution system model-calibrated parameters of pipe roughness (C-factor), storage-tank mixing model type, and demand factor were varied to assess the effects of varying these model parameters on the calibrated EPANET 2 water-distribution system model used to reconstruct contaminant concentrations in the Holcomb Boulevard family housing areas during intermittent periods of water transfers from Hadnot Point to Holcomb Boulevard (1972–1985). These sensitivity analyses are described in detail in Maslia et al. (2009b) as part of the Tarawa Terrace study area historical reconstruction effort and are not presented in this report. Figure A30 provides specific information as to associated figures in Maslia et al. (2009b) that are pertinent to the water-distribution system model sensitivity analysis.

For the sensitivity analyses conducted for the HPHB study area, a model-input parameter (e.g., K_{xx}, $Q_{monthly}$) was adjusted or varied from its calibrated value, and the effect of this variation was then assessed on model output parameter values (e.g., water-supply well concentration). This particular sensitivity analysis method is referred to as one-at-a-time (OAT) designs or experiments, and details can be found in Saltelli et al. (2000). The aforementioned physical and numerical parameters were varied from their respective calibrated values (e.g., Table A12) using the OAT sensitivity analysis method (and a variation on the OAT sensitivity analysis method by grouping several parameters together). The corresponding effects of this variation on the change in reconstructed concentrations of contaminants of concern (e.g., PCE, TCE, benzene) at selected water-supply wells and in finished water at the HPWTP are presented and summarized below. Details of the sensitivity analyses summarized in this report section are described in Suárez-Soto et al. (2013), Guan et al. (2013), Jones et al. (2013), Jang et al. (2013), and Sautner et al. (2013b).

Statistical Analysis of Historical Pumping Variation

Pumping schedules (Figures A6 and A7) that were derived on a monthly basis for water-supply wells for present-day period (1998–2008) and the historical reconstruction period (1942–1998) are described in Telci et al. (2013). Because historical pumping records are incomplete—monthly data are only available from 1980 through 2008 (Table A22)—the calibrated HPHB study area models are based on uncertain and variable pumping rates. The sensitivity of the calibrated models to variations in calibrated pumping rates was assessed using a statistical analysis approach by developing a procedure for analyzing historical pumping schedule variation using available Hadnot Point and Holcomb Boulevard pumpage data (Table A22).[57] Results of the statistical analysis were then used to assess variation of contaminant concentrations in HPWTP finished water. The statistical analysis procedure applied to the HPHB study area is similar to the procedure applied to the TT study area reported by Maslia et al. (2009b).

[57] Numerous data sources were used to assemble the data listed in Table A22; data sources are listed in Sautner et al. (2013a, Table S1.1).

Table A22. Historical record of total monthly raw water (groundwater) delivered to water treatment plants, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[—, data not available]

Year	[1]Monthly groundwater pumping demand ($Q_{monthly}$), in cubic feet per day												Annual total	Annual monthly mean (Q_{mean})
	January	February	March	April	May	June	July	August	September	October	November	December		
Hadnot Point water treatment plant														
1980	463,699	543,859	490,478	476,905	433,091	452,371	504,467	431,581	426,797	396,406	463,693	450,197	5,533,545	461,129
1981	475,497	459,470	469,572	459,817	473,333	457,847	508,426	427,916	438,098	—	—	—	4,169,975	463,331
1983	432,750	418,038	—	395,637	403,120	447,883	458,386	465,868	413,688	—	417,734	478,085	4,331,189	433,119
1984	490,112	481,291	449,188	463,738	494,972	512,772	480,702	496,830	462,232	485,140	417,012	430,128	5,664,117	472,010
1987	425,441	554,774	465,726	458,221	439,680	486,628	453,673	504,894	562,670	634,745	602,360	587,578	6,176,391	514,699
1988	539,742	449,323	431,676	401,113	442,358	413,670	423,108	460,818	439,711	430,223	430,612	477,425	5,339,778	444,982
1995	411,240	432,648	428,877	413,296	411,809	431,828	416,631	399,248	384,064	403,323	422,096	421,857	4,976,917	414,743
1996	412,258	—	428,209	424,476	443,888	406,171	376,173	388,282	384,889	369,178	402,312	410,869	4,446,704	404,246
1997	397,186	409,063	428,770	407,748	406,730	403,439	399,287	395,302	406,407	374,159	—	397,199	4,425,289	402,299
1998	373,124	380,784	412,383	418,434	428,614	453,498	433,522	431,551	414,780	373,771	386,644	418,821	4,925,926	410,494
1999	409,878	378,793	380,502	386,845	394,189	413,920	395,186	400,649	428,393	—	—	—	3,588,355	398,706
2000	—	408,219	407,575	393,146	425,354	452,460	407,018	513,510	420,760	397,044	418,184	398,096	4,641,366	421,942
2001	412,732	405,043	421,719	411,990	406,755	420,158	402,585	415,621	400,926	391,132	412,948	382,818	4,884,428	407,036
2002	405,074	398,196	387,803	396,737	412,180	408,800	441,499	443,781	437,666	406,492	405,734	406,712	4,950,674	412,556
2003	431,995	421,409	366,746	343,733	341,972	376,845	389,424	392,991	379,189	369,187	375,495	369,588	4,558,575	379,881
2004	402,590	373,596	370,407	345,493	339,251	356,829	347,600	353,633	323,035	336,056	332,361	320,950	4,201,799	350,150
2005	345,047	369,388	342,153	344,713	328,897	346,594	363,956	357,147	339,901	330,924	339,526	343,020	4,151,266	345,939
2006	346,539	348,687	369,881	342,427	341,903	349,931	337,000	388,631	353,977	337,138	314,430	318,285	4,148,829	345,736
2007	336,431	317,730	315,857	302,457	301,885	316,310	321,536	341,675	326,341	304,429	315,696	314,041	3,814,388	317,866
2008	321,204	312,213	316,042	316,756	292,101	295,688	323,046	332,533	297,573	282,846	326,011	328,708	3,744,721	312,060

Table A22. Historical record of total monthly raw water (groundwater) delivered to water treatment plants, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[—, data not available]

Year	[1]Monthly groundwater pumping demand ($Q_{monthly}$), in cubic feet per day												Annual total	Annual monthly mean (Q_{mean})
	January	February	March	April	May	June	July	August	September	October	November	December		
Holcomb Boulevard water treatment plant														
1980	116,738	114,587	114,120	121,382	142,741	163,286	145,375	183,660	178,303	146,376	127,148	108,165	1,661,881	138,490
1981	133,676	125,072	112,361	259,492	167,398	207,851	144,750	150,783	173,139	—	—	—	1,474,522	163,836
1983	140,869	181,992	—	151,821	211,026	231,651	193,160	199,839	151,692	—	139,531	135,380	1,736,960	173,696
1984	127,738	151,986	162,258	147,303	177,562	215,858	190,555	188,265	168,237	148,217	139,513	132,383	1,949,876	162,490
1987	118,799	66,950	241,725	276,576	351,239	407,129	412,163	337,587	273,644	170,848	184,314	169,705	3,010,679	250,890
1988	251,867	334,561	300,337	295,225	307,724	366,405	312,239	286,848	269,955	266,628	267,303	267,663	3,526,755	293,896
1995	305,400	349,236	299,677	362,871	379,355	339,700	362,718	414,858	339,375	321,066	298,197	300,548	4,073,002	339,417
1996	320,117	—	330,652	320,602	346,052	348,630	337,345	346,767	334,977	278,112	266,488	267,581	3,497,323	317,938
1997	286,210	302,963	304,744	340,783	302,372	306,008	296,008	300,993	278,853	255,796	—	249,129	3,223,859	293,078
1998	261,289	254,370	274,075	266,688	293,619	331,835	296,469	300,410	293,808	252,234	254,969	263,515	3,343,281	278,607
1999	274,317	250,260	254,821	287,703	289,953	335,520	351,830	382,732	325,606	—	—	—	2,752,741	305,860
2000	296,844	295,540	305,094	296,606	342,973	361,085	332,740	334,861	291,740	285,408	278,604	268,392	3,689,885	307,490
2001	280,738	260,104	279,526	307,630	290,639	303,357	296,603	252,669	228,692	214,393	207,098	205,234	3,126,683	260,557
2002	217,804	209,606	198,516	230,572	227,615	231,481	215,454	223,022	204,696	195,609	198,066	214,255	2,566,698	213,891
2003	247,055	187,945	189,330	215,203	222,776	228,371	236,101	233,635	215,765	212,694	219,967	200,348	2,609,192	217,433
2004	217,425	222,500	222,181	217,953	245,045	229,218	215,420	216,442	206,897	211,888	204,656	194,648	2,604,272	217,023
2005	201,569	210,556	205,872	212,325	213,121	221,273	228,141	253,018	242,118	210,055	191,974	179,408	2,569,431	214,119
2006	168,912	170,409	180,564	204,041	189,184	194,233	204,980	197,696	200,481	175,717	174,587	150,680	2,211,483	184,290
2007	171,361	205,472	193,820	191,435	199,839	214,740	211,578	269,013	259,568	272,510	227,774	201,957	2,619,065	218,255
2008	211,142	204,527	202,306	196,092	208,727	260,592	221,832	240,332	219,677	201,465	183,784	157,704	2,508,180	209,015

[1] Refer to Sautner et al. (2013a, Table S1.1) for data sources

Historical records for total groundwater withdrawals that supplied raw water to the HPWTP and HBWTP are incomplete for the period covering model simulation for Hadnot Point (1942–2008) and for Holcomb Boulevard (1972–2008). However, nearly complete monthly pumping records are available for years 1980–2008, with complete daily pumpage records available for years 1998–2008. Using historical monthly pumpage data, ratios of monthly groundwater pumping rates ($Q_{monthly}$) to annual monthly mean pumping rates (Q_{mean}) were computed, and these ratios ($Q_{monthly} / Q_{mean}$) are listed in Table A23 for the HPWTP and HBWTP. The $Q_{monthly} / Q_{mean}$ ratios were computed by dividing total monthly raw water delivered to the HPWTP and HBWTP ($Q_{monthly}$; monthly entries listed in Table A22) by the annual mean pumping rates (Q_{mean}; entries from last column in Table A22). Statistical analyses are summarized in Table A24 using the $Q_{monthly} / Q_{mean}$ ratios listed in Table A23 for the HPWTP and HBWTP. The $Q_{monthly} / Q_{mean}$ ratios and monthly mean values also are shown graphically in Figure A31. The results of the statistical analysis indicate that pumping demand is higher in spring and summer for the HBWTP service area. This is consistent with the observed higher demand conditions during these months that required additional water supply, which has been documented by the intermittent transfer of finished water from Hadnot Point to Holcomb Boulevard during the period 1972–1980 (previously discussed in the section on Intermittent Transfers of Finished Water from Hadnot Point to Holcomb Boulevard). Note that during the 12-month period shown in Figure A31, the mean value of raw-water delivery to the HPWTP and HBWTP (mean value of groundwater pumping demand) is indicated by a value for the ratio $Q_{monthly} / Q_{mean}$ of 1.0. For the HPWTP, during the months of January–March and June–August, the annual monthly mean is exceeded; during the remaining months of the year, the $Q_{monthly} / Q_{mean}$ ratios are equal to or less than the annual monthly mean (see Table A23 for specific values). For the HBWTP, during the months of April–September, the annual monthly mean is exceeded; during the remaining months of the year, the $Q_{monthly} / Q_{mean}$ ratios are less than the annual monthly mean.

Results of the statistical analysis listed in Table A23 and shown in Figure A31 were used to generate total pumping demand for each stress period in which pumping occurred (stress periods 7 [July 1942] through 798 [June 2008]). For the groundwater flow and contaminant fate and transport simulations, the total pumpage demand during months of data availability reflects the pumpage demand data listed in Table A22 (annual total). For all other monthly stress periods, the historically reconstructed monthly pumpage demand (Telci et al. 2013) was multiplied by the $Q_{monthly} / Q_{mean}$ ratios for each month of the year. This schedule was characterized with statistical properties of a mean and standard deviation based on the analyses of ratios listed in Table A24 and shown in Figure A31. Results of the reconstructed finished-water concentrations for PCE and TCE at the HPWTP—based on the statistical methodology applied to monthly pumpage variation—are shown in Figure A32. In these graphs, the calibrated PCE and TCE finished-water concentrations are those derived during the historical reconstruction process, previously discussed (e.g., Figure A27); concentration values are located on the left ordinate (y-axes). The range of variation, which is represented by differences between maximum and minimum simulated concentrations for a specific month, is computed by applying the $Q_{monthly} / Q_{mean}$ ratios (Figure A31) to historical monthly pumpage. These variations in concentrations for PCE and TCE are values located on the right ordinate (y- axes) of graphs in Figure A32. Overall, it appears from the results of the statistical analysis of historical pumping variation that finished-water concentrations are not very sensitive to monthly pumpage variation within the HPIA and HPLF model subdomain areas. The maximum range of variation for PCE (maximum minus minimum concentrations) is less than or equal to the MCL for PCE (5 µg/L). The maximum range of variation for TCE occurs solely during the onset of pumping at water-supply well HP-651 and is about 100 µg/L. Model sensitivity owing to monthly pumpage variation because of data uncertainty and possibly measurement error is well within the accuracy needed for the epidemiological studies when compared to the maximum reconstructed TCE concentration of about 800 µg/L. Furthermore, results shown in Figure A32 indicate that variation in reconstructed finished-water concentrations due to monthly water-supply well operation variations is substantially less than reconstructed finished-water concentrations and measured data variation.

Table A23. Ratios of historical monthly groundwater pumping rates to annual monthly mean pumping rates, ($Q_{monthly}/Q_{mean}$), for water treatment plants, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[—, data not available]

Year	[1]Ratio of monthly groundwater pumping rate to annual monthly mean pumping rate ($Q_{monthly}/Q_{mean}$)											
	January	February	March	April	May	June	July	August	September	October	November	December
Hadnot Point water treatment plant												
1980	1.006	1.179	1.064	1.034	0.939	0.981	1.094	0.936	0.926	0.860	1.006	0.976
1981	1.026	0.992	1.013	0.992	1.022	0.988	1.097	0.924	0.946	—	—	—
1983	0.999	0.965	—	0.913	0.931	1.034	1.058	1.076	0.955	—	0.964	1.104
1984	1.038	1.020	0.952	0.982	1.049	1.086	1.018	1.053	0.979	1.028	0.883	0.911
1987	0.827	1.078	0.905	0.890	0.854	0.945	0.881	0.981	1.093	1.233	1.170	1.142
1988	1.213	1.010	0.970	0.901	0.994	0.930	0.951	1.036	0.988	0.967	0.968	1.073
1995	0.992	1.043	1.034	0.997	0.993	1.041	1.005	0.963	0.926	0.972	1.018	1.017
1996	1.020	—	1.059	1.050	1.098	1.005	0.931	0.961	0.952	0.913	0.995	1.016
1997	0.987	1.017	1.066	1.014	1.011	1.003	0.993	0.983	1.010	0.930	—	0.987
1998	0.909	0.928	1.005	1.019	1.044	1.105	1.056	1.051	1.010	0.911	0.942	1.020
1999	1.028	0.950	0.954	0.970	0.989	1.038	0.991	1.005	1.074	—	—	—
2000	—	0.967	0.966	0.932	1.008	1.072	0.965	1.217	0.997	0.941	0.991	0.943
2001	1.014	0.995	1.036	1.012	0.999	1.032	0.989	1.021	0.985	0.961	1.015	0.941
2002	0.982	0.965	0.940	0.962	0.999	0.991	1.070	1.076	1.061	0.985	0.983	0.986
2003	1.137	1.109	0.965	0.905	0.900	0.992	1.025	1.035	0.998	0.972	0.988	0.973
2004	1.150	1.067	1.058	0.987	0.969	1.019	0.993	1.010	0.923	0.960	0.949	0.917
2005	0.997	1.068	0.989	0.996	0.951	1.002	1.052	1.032	0.983	0.957	0.981	0.992
2006	1.002	1.009	1.070	0.990	0.989	1.012	0.975	1.124	1.024	0.975	0.909	0.921
2007	1.058	1.000	0.994	0.952	0.950	0.995	1.012	1.075	1.027	0.958	0.993	0.988
2008	1.029	1.000	1.013	1.015	0.936	0.948	1.035	1.066	0.954	0.906	1.045	1.053
Holcomb Boulevard water treatment plant												
1980	0.843	0.827	0.824	0.876	1.031	1.179	1.050	1.326	1.287	1.057	0.918	0.781
1981	0.816	0.763	0.686	1.584	1.022	1.269	0.884	0.920	1.057	—	—	—
1983	0.811	1.048	—	0.874	1.215	1.334	1.112	1.151	0.873	—	0.803	0.779
1984	0.786	0.935	0.999	0.907	1.093	1.328	1.173	1.159	1.035	0.912	0.859	0.815
1987	0.474	0.267	0.963	1.102	1.400	1.623	1.643	1.346	1.091	0.681	0.735	0.676
1988	0.857	1.138	1.022	1.005	1.047	1.247	1.062	0.976	0.919	0.907	0.910	0.911
1995	0.900	1.029	0.883	1.069	1.118	1.001	1.069	1.222	1.000	0.946	0.879	0.885
1996	1.007	—	1.040	1.008	1.088	1.097	1.061	1.091	1.054	0.875	0.838	0.842
1997	0.977	1.034	1.040	1.163	1.032	1.044	1.010	1.027	0.951	0.873	—	0.850
1998	0.938	0.913	0.984	0.957	1.054	1.191	1.064	1.078	1.055	0.905	0.915	0.946
1999	0.897	0.818	0.833	0.941	0.948	1.097	1.150	1.251	1.065	—	—	—
2000	0.965	0.961	0.992	0.965	1.115	1.174	1.082	1.089	0.949	0.928	0.906	0.873
2001	1.077	0.998	1.073	1.181	1.115	1.164	1.138	0.970	0.878	0.823	0.795	0.788
2002	1.018	0.980	0.928	1.078	1.064	1.082	1.007	1.043	0.957	0.915	0.926	1.002
2003	1.136	0.864	0.871	0.990	1.025	1.050	1.086	1.075	0.992	0.978	1.012	0.921
2004	1.002	1.025	1.024	1.004	1.129	1.056	0.993	0.997	0.953	0.976	0.943	0.897
2005	0.941	0.983	0.961	0.992	0.995	1.033	1.065	1.182	1.131	0.981	0.897	0.838
2006	0.917	0.925	0.980	1.107	1.027	1.054	1.112	1.073	1.088	0.953	0.947	0.818
2007	0.785	0.941	0.888	0.877	0.916	0.984	0.969	1.233	1.189	1.249	1.044	0.925
2008	1.010	0.979	0.968	0.938	0.999	1.247	1.061	1.150	1.051	0.964	0.879	0.755

[1] Ratios of $Q_{monthly}/Q_{mean}$ computed by dividing monthly total raw water delivered to treatment plant ($Q_{monthly}$) by annual monthly mean (Q_{mean}) listed in Table A22

Table A24. Statistical analyses of ratios of historical monthly groundwater pumping rates to annual monthly mean pumping rates, ($Q_{monthly}/Q_{mean}$), for water treatment plants, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.[1]

Month	[2]Ratio of monthly groundwater pumping rate to mean annual monthly pumping rate							
	Hadnot Point				Holcomb Boulevard			
	Mean	Standard deviation	Minimum	Maximum	Mean	Standard deviation	Minimum	Maximum
January	1.022	0.083	0.827	1.213	0.908	0.141	0.474	1.136
February	1.019	0.061	0.928	1.179	0.917	0.181	0.267	1.138
March	1.003	0.049	0.905	1.070	0.945	0.095	0.686	1.073
April	0.976	0.047	0.890	1.050	1.031	0.159	0.874	1.584
May	0.981	0.055	0.854	1.098	1.072	0.103	0.916	1.400
June	1.011	0.045	0.930	1.105	1.163	0.151	0.984	1.623
July	1.010	0.055	0.881	1.097	1.090	0.146	0.884	1.643
August	1.031	0.068	0.924	1.217	1.118	0.117	0.920	1.346
September	0.991	0.049	0.923	1.093	1.029	0.102	0.873	1.288
October	0.966	0.079	0.860	1.233	0.937	0.114	0.681	1.249
November	0.988	0.061	0.884	1.170	0.894	0.076	0.735	1.044
December	0.998	0.064	0.911	1.142	0.850	0.079	0.676	1.002

[1] Statistical analyses based on pumpage data 1980–2008; refer to Sautner et al. (2013a, Table S1.1) for data sources

[2] Ratios of $Q_{monthly}/Q_{mean}$ computed by dividing monthly total raw water delivered to water treatment plant ($Q_{monthly}$) by annual monthly mean (Q_{mean}) listed in Table A22

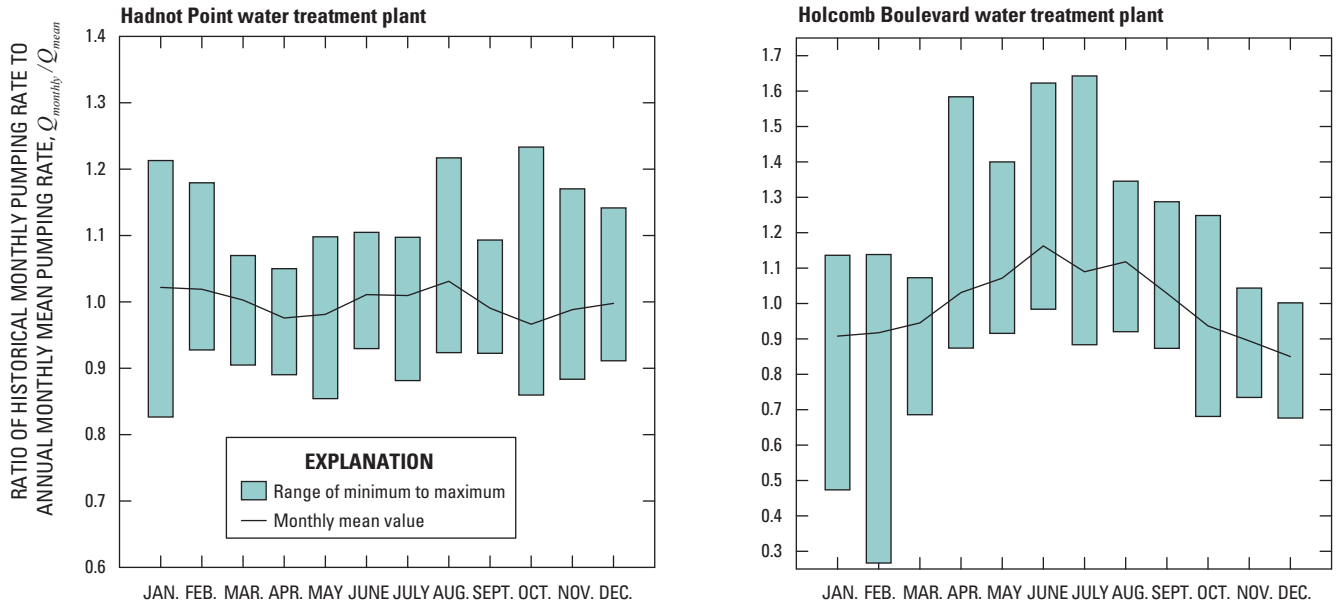


Figure A31. Results of statistical analysis of ratios of historical monthly pumping ($Q_{monthly}$) to annual monthly mean pumping (Q_{mean}) for water treatment plants, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. (See Sautner et al. 2013a, Table S1.1 for historical pumpage data sources.)

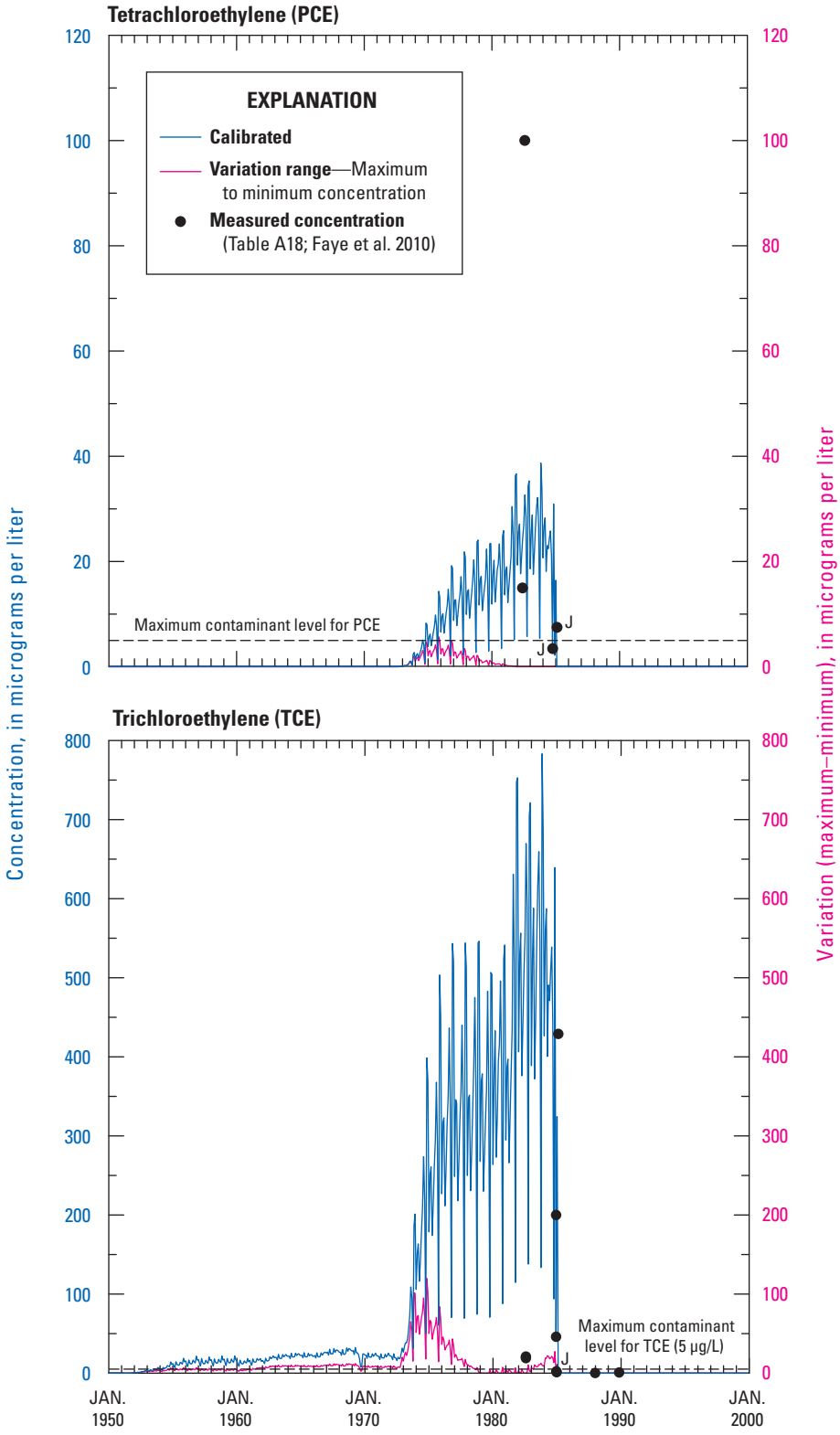


Figure A32. Concentrations and variations of tetrachloroethylene (PCE) and trichloroethylene (TCE) in finished water at the Hadnot Point water treatment plant derived from calibrated water-supply well pumpage and statistical analysis of water-supply well pumpage variation, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. [J, estimated]

Groundwater-Flow Model Parameters

For the HPIA and HPLF model subdomain areas (Figures A12), groundwater-flow model parameters K_{xx} and I were varied by using the OAT sensitivity analysis because as reported in Suárez-Soto et al. (2013), calibrated water levels were deemed to be most sensitive to variations in calibrated values of K_{xx} and I. Results for simulated concentrations of PCE and TCE in finished water at the HPWTP are shown in Figure A33.[58] In conducting the sensitivity analyses, groundwater-flow model parameters were varied from calibrated values (Table A12), and then results were extracted to provide a global range of finished-water concentration values. Results shown in graphs of Figure A33 represent upper and lower limits (global range) of the sensitivity analyses, along with the calibrated concentrations previously discussed (Figure A27). Results represent monthly mean concentrations in finished water at the HPWTP when reconstructed concentrations equaled or exceeded 1 µg/L. Also shown in Figure A33 are reported water-quality data from sampling events (Faye et al. 2010). Model codes used to derive the sensitivity analyses results shown in Figure A33 are MODFLOW, MT3DMS, and the mixing model for the HPWTP. Results of the sensitivity analyses showing concentrations in finished water at the HPWTP indicate concentration variations of about an order of magnitude (about a factor of 10) or less. By comparison, water-quality data shown indicate variations ranging from about 1 µg/L to more than 1,000 µg/L, or nearly 3 orders of magnitude (Figure A33).

[58] Results of the OAT sensitivity analysis at selected water-supply wells (e.g., HP-602, HP-634, HP-651) are provided in Suárez-Soto et al. (2013) and Jones et al. (2013).

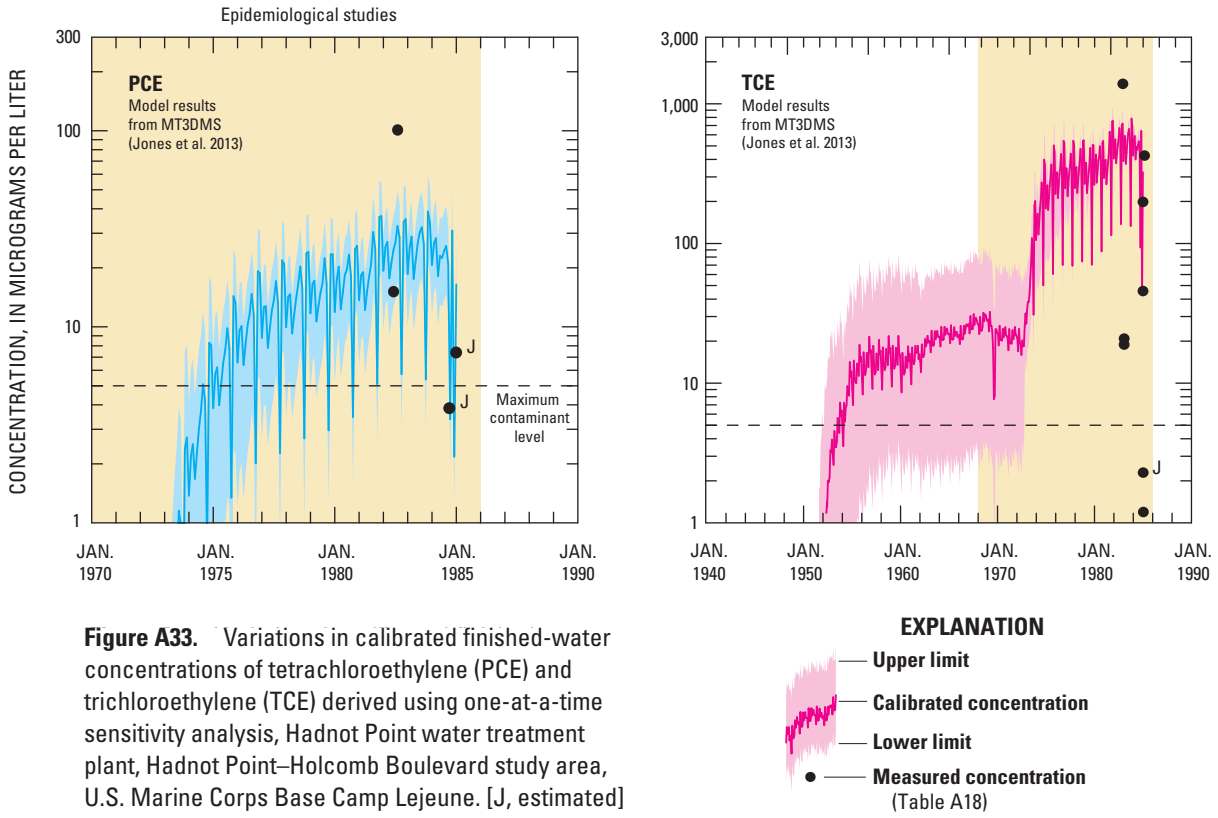


Figure A33. Variations in calibrated finished-water concentrations of tetrachloroethylene (PCE) and trichloroethylene (TCE) derived using one-at-a-time sensitivity analysis, Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune. [J, estimated]

Hydraulic, Fate, and Transport Model Parameters

Contaminant fate and transport model parameters for source concentration (C), bulk density (ρ_b), porosity (n_E), longitudinal dispersivity (α_L), distribution coefficient (K_D), and biodegradation rate (λ) were varied to assess the sensitivity of calibrated parameter-value variation on PCE and TCE concentrations in groundwater and in finished water at the HPWTP. Because simulation of the migration of contaminants requires values for specific discharge (and hence groundwater velocity) derived from the groundwater-flow model, horizontal hydraulic conductivity (K_{xx}) for model layer 3[59] and steady-state (predevelopment) long-term infiltration (I) were also varied for the contaminant fate and transport model parameter sensitivity analyses. Three different scenarios were constructed to explore parameter sensitivity. In each scenario, the minimum and maximum finished water PCE and TCE concentrations at the HPWTP were computed for each month of the historical simulations. Calibrated model parameter values that were varied for each scenario are listed below:

- Scenario 1: K_{xx}, C, n_E, and α_L;
- Scenario 2: K_{xx}, I, C, K_D, and λ; and
- Scenario 3: K_{xx}, I, C, n_E, α_L, K_D, and λ.

[59] Sensitivity analyses on K_{xx} using the groundwater-flow model indicated that the most sensitive model layer to K_{xx} variation was model layer 3. Therefore, for the analysis scenarios where hydraulic, fate, and transport parameters were varied in combination, K_{xx} for model layer 3 was chosen to be varied. Refer to Suárez-Soto et al. (2013) for details.

For hydraulic parameters (K_{xx} and I), values of variation were determined from the sensitivity analyses conducted on the predevelopment (steady-state) model described in Suárez-Soto et al. (2013) and ranged from 0.1 to 10 times the calibrated K_{xx} values for model layer 3 and from about 0.6 to 1.3 times the calibrated I values. (All calibrated values are listed in Table A12.) For fate and transport parameters (C, n_E, α_L, K_D, and λ), a minimum value (e.g., 2.5 percentile) and a maximum value (e.g., 97.5 percentile) were chosen from probability density functions (PDFs) used to describe each parameter (Jones et al. 2013). Two contaminant fate and transport simulations for each of the aforementioned scenarios were conducted—one simulation using the minimum PDF value (2.5 percentile) for a parameter and one simulation using the maximum PDF value (97.5 percentile) for each parameter.

Results of the contaminant fate and transport model sensitivity analysis for scenarios 1, 2, and 3 are shown in Figure A34 for PCE and TCE finished-water concentrations at the HPWTP. Variations about the calibrated reconstructed concentrations (monthly mean) are generally about an order of magnitude (a factor of about 10). For scenarios 1 and 2, variations in finished-water concentrations are about the same. For scenario 3, when variations in all hydraulic, fate, and transport parameters are included (K_{xx}, I, C, n_E, α_L, K_D, and λ), variations in finished-water concentrations from calibrated values increase. For calibrated TCE finished-water concentrations of about 20 µg/L or less (prior to July 1972), there is a greater variation when compared to TCE concentrations simulated subsequent to the onset of pumping at water-supply well HP-651 (July 1972).

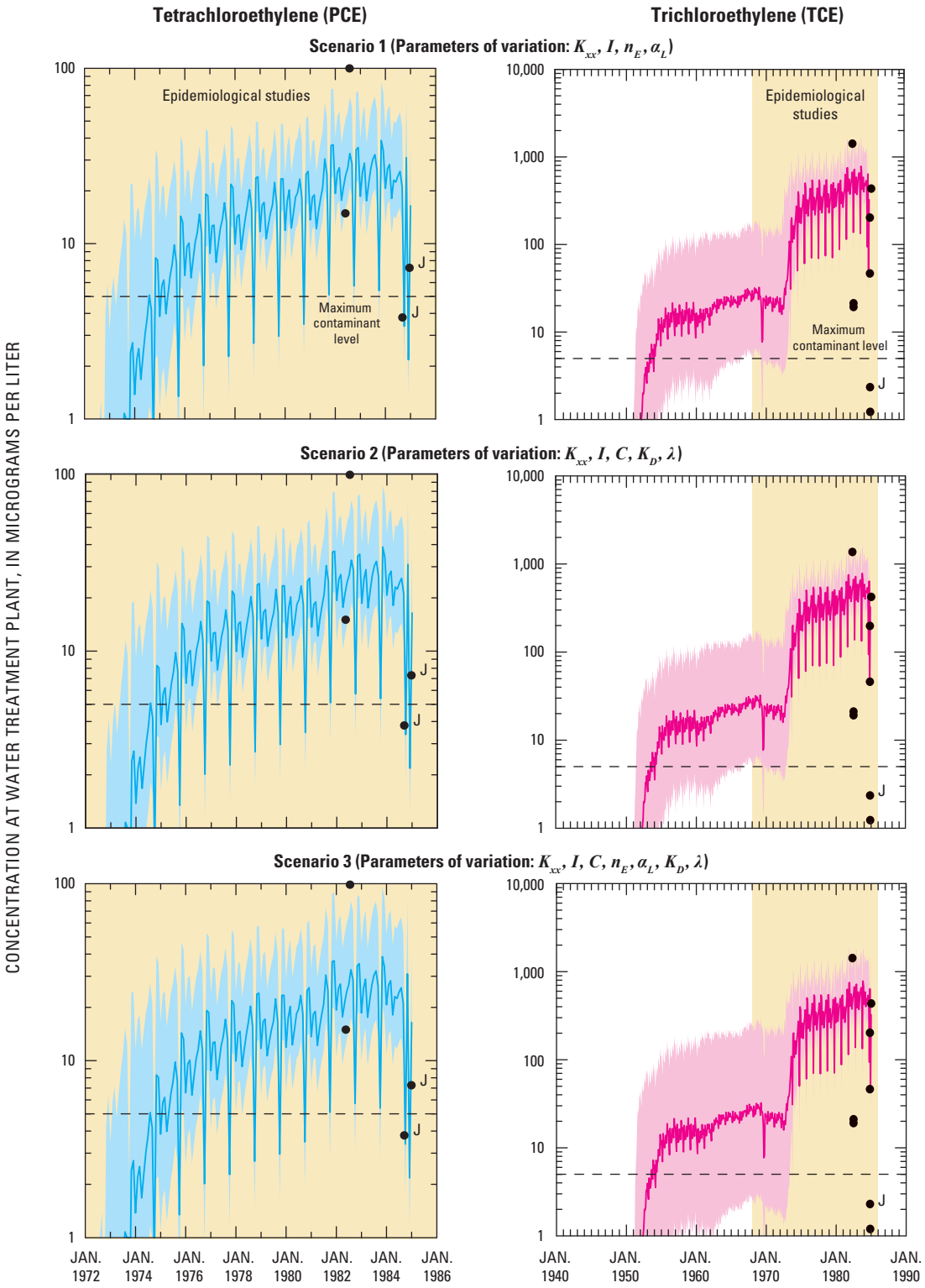


Figure A34. Concentrations of tetrachloroethylene (PCE) and trichloroethylene (TCE) in finished water at the Hadnot Point water treatment plant derived from model calibration and hydraulic, fate, and transport model parameter sensitivity analysis, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. [K_{xx}, horizontal hydraulic conductivity; I, infiltration; C, source concentration; n_E, porosity; α_L, longitudinal dispersivity; K_D, distribution coefficient; λ, biodegradation rate; J, estimated]

Benzene Source-Area and Source-Release Sensitivity Analysis

As previously discussed, simulated results for water-supply well HP-602 provide reasonable agreement with field data, whereas simulated results for water-supply well HP-603 are inconsistent with field data (Figure A20). Therefore, sensitivity analyses were conducted to assess the effect of varying contaminant-source area size, location, and release date on reconstructed benzene concentrations at water-supply well HP-603 and at the HPWTP. Additionally, the sensitivity analysis included assessing the effect of the contribution of benzene-contaminated groundwater from well HP-603 on benzene concentrations in finished water at the HPWTP. Benzene is documented as occurring as free-phase LNAPL in the vicinity of Building 1613 (Faye et al. 2012; also see Figure A13 for location of Building 1613). To simplify sensitivity analyses simulations, MT3DMS was used to simulate the dissolved-phase benzene rather than using the more complex (and computationally expensive) TechFlowMP that simulates the dissolution of free-phase benzene into dissolved-phase benzene. Figure A35 shows results for an MT3DMS source area of one cell, four cells, and a source-area location change of about 150 ft (downgradient from the calibrated location). Figure A35 also shows calibrated results obtained using TechFlowMP. Results indicate that varying model source area and location provides some improvement between reconstructed benzene concentrations in water-supply well HP-603 and field data (Table A5) for the scenario where the contaminant source is assigned to one model cell.

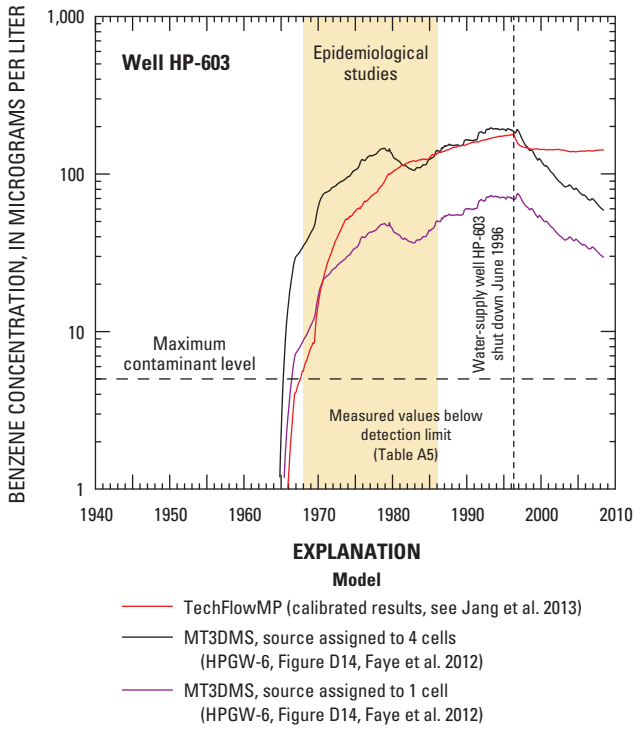


Figure A35. Effect of contaminant-source area variation at Building 1613 on simulated concentrations of benzene at water-supply well HP-603, Hadnot Point Industrial Area, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. (See Figure A13 for well and building location.)

Sensitivity analysis results for varying assigned source concentration value (from a calibrated value of 17,000 µg/L) and source-release date (from the calibrated release date of January 1, 1964) are listed in Table A25. These results indicate a small improvement in reconstructed benzene concentrations at well HP-603 compared to calibrated results (Figure A20) and field data (Table A5). Perhaps more important, however, in the context of the overall project is that the effect of these contaminant-source variations on finished-water benzene concentrations at the HPWTP is minimal (Figure A36). To assess the contribution of reconstructed (simulated) benzene-contaminated groundwater from water-supply well HP-603 to finished-water concentrations at the HPWTP, the mixing-model results were derived by removing the flow and contaminant mass contribution from well HP-603. Reconstructed benzene concentration results shown in Figure A36 indicate that the contribution from benzene-contaminated water-supply well HP-603 to finished-water concentrations at the HPWTP was minimal. The effects of varying the source-release date (from January 1964 to January 1976) on benzene concentrations at the HPWTP also are shown in Figure 36 and are listed in Table A25. These results also indicate very little model sensitivity (at water-supply well HP-603 and the HPWTP) to changes in benzene source-release dates.

Table A25. Reconstructed (simulated) concentrations of benzene at water-supply well HP-603 and at the Hadnot Point water treatment plant for varying source concentrations of benzene and release dates at Building 1613, Hadnot Point Industrial Area, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.[1]

[µg/L, microgram per liter; HPWTP, Hadnot Point water treatment plant; LNAPL, light nonaqueous phase liquid]

[3]Release date	[2]Source concentration, in micrograms per liter					
	17,000		15,000		10,000	
	Reconstructed benzene concentration (maximum value), in micrograms per liter					
	[4]Well HP-603	[5]HPWTP	Well HP-603	HPWTP	Well HP-603	HPWTP
1964	196	12	173	11	115	7
1968	193	12	170	11	114	7
1972	189	11	167	10	111	6
1976	182	11	161	10	107	6

[1] All results shown are derived by using MT3DMS for dissolved-phase benzene in groundwater. Calibrated values for 1964 and 17,000 µg/L at well HP-603 and at the HPWTP are 125 µg/L and 12 µg/L, respectively, derived using TechFlowMP to simulate free-phase LNAPL (Appendix A3; Jang and Aral 2013)

[2] Source location is Building 1613 (see Figure A13 for building location; see Faye et al. 2012, Figure D14 for details on benzene contamination at Building 1613)

[3] All release dates begin on January 1 of year listed

[4] See Figure A13 for location

[5] HPWTP, maximum computed finished-water concentrations at the Hadnot Point WTP (see Figure A12 for location); mixing model used to compute finished water concentrations of benzene (see text for details on mixing-model approach)

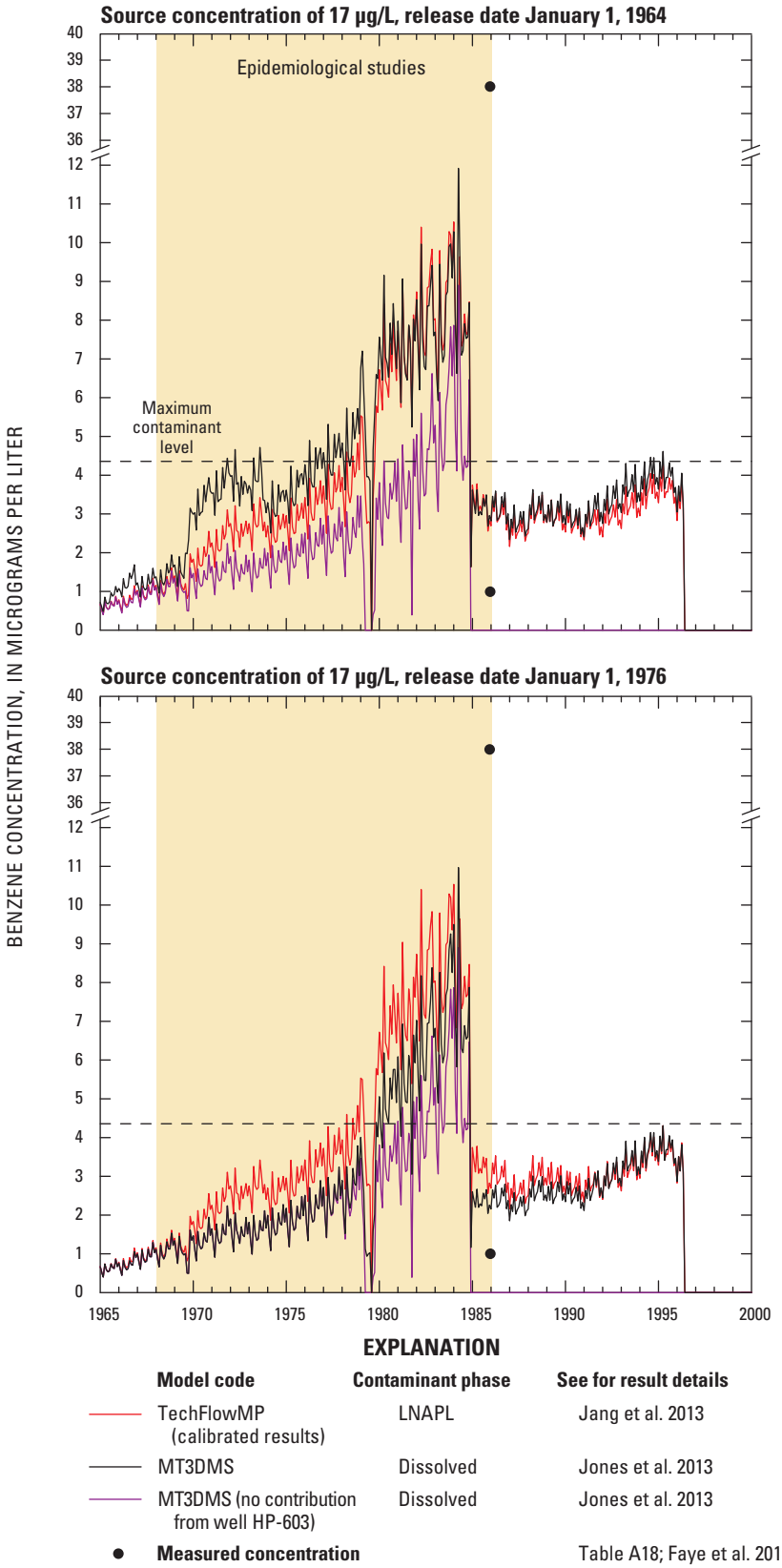


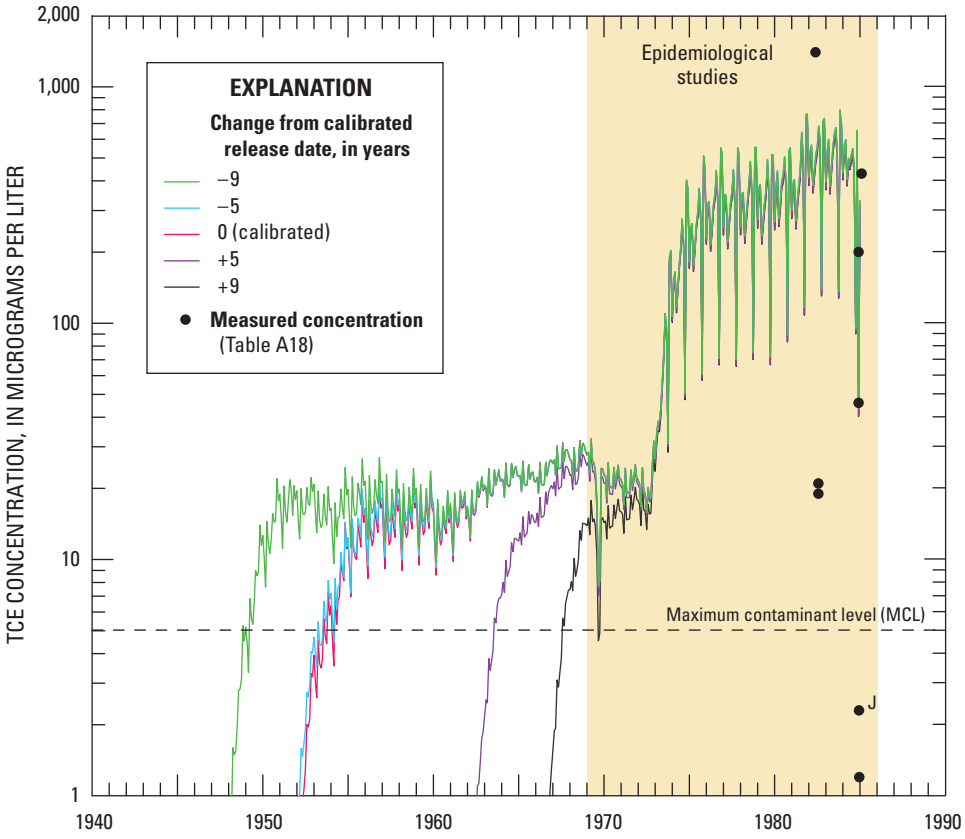
Figure A36. Variations in reconstructed (simulated) benzene concentrations in finished water based on variations in benzene concentrations at water-supply well HP-603 and source-release dates, Hadnot Point water treatment plant, U.S. Marine Corps Base Camp Lejeune, North Carolina. (See Figure A13 for well location.) [LNAPL, light nonaqueous phase liquid]

Trichloroethylene Source-Release-Date Sensitivity Analysis

Historical records delineating the timing and volume of inadvertent releases of solvents during routine operations, from leaking UST systems, or from disposal of solvent waste, spent dry cleaning filters, or other materials were not available for the HPHB study area. For modeling purposes, a median source-release date of 9 years from the date of UST system installation or site development (in the case of the HPLF area) was used in the contaminant fate and transport models (Jones et al. [2013] and Jang et al. [2013]). This source-release date formulation is consistent with empirical data indicating that the median timeframe for leak development in UST systems (typically in piping and joint components) is 9 years from installation date (USEPA 1986, 1987; Gangadharan et al. 1987). UST systems were not the source of contaminants in the HPLF area. However, given the lack of historical information, a similar source-release time frame, in this case 7 years from site development, was applied to HPLF-area sources within the model (Jones et al. 2013). The shorter source-release time frame acknowledges that landfill disposal likely encompassed a range of contained and uncontained source materials, in contrast to the engineered tank and piping system sources discussed previously.

To assess the effect of source-release-date variation on TCE concentrations in finished water at the HPWTP, a sensitivity analysis was conducted whereby the source-release date was modified from the calibrated source-release date. For example, a decrease of 5 years from the calibrated median of 9 years indicates a source-release date of 4 years from the estimated installation date for a UST system. Conversely, an increase of 5 years from the calibrated median of 9 years indicates a source-release date of 14 years from the estimated UST installation date.

Four sensitivity analysis simulations were conducted using the HPIA and HPLF area TCE contaminant source-release dates (Table A13). For these sensitivity analyses, the calibrated source-release date (9 years for suspected UST system sources and 7 years for HPLF area sources) was decreased by 5 and 9 years and increased by 5 and 9 years (7 years for the HPLF area sources) (Figure A37). In the case of the HPLF area sources, the calibrated source-release date was decreased by 7 years, to coincide with Base development in 1941. Results indicate that reconstructed TCE concentrations of finished-water for the HPWTP at the start of the epidemiological studies (January 1968) display little variation, except for a source-release-date increase of 9 years. The maximum reconstructed TCE concentration during the time frame (1968–1985) of the epidemiological studies varies by about 5 percent or less from the calibrated maximum value of 783 µg/L (Figure A37). Decreasing the source-release date by 9 years from its calibrated value (Figure A37) implies that contaminant leakage in the HPLF area would have started during or immediately following the onset of construction (1941/1942) of USMCB Camp Lejeune, which is not an unrealistic scenario given landfill-construction technologies that existed during the 1940s and 1950s. Results from this scenario indicate that the MCL for TCE in finished water at the HPWTP would have been exceeded during November 1948, compared to the calibrated exceedance date of August 1953. Variations in source-release dates of ±9 years show MCL exceedance-date variations of about 5 years earlier to 14 years later than the calibrated TCE MCL exceedance date (August 1953). In terms of historical reconstruction results of interest to the ATSDR epidemiological studies (finished-water concentrations of TCE during the period 1968–1985), the variation (and uncertainty due to a lack of data) in source-release dates does not appear to have a substantial effect.



[1]Change from calibrated release date, in years	First month exceeding MCL	Concentration at start of epidemiological study (January 1968), in micrograms per liter	Maximum concentration during epidemiological study period (January 1968–December 1985), in micrograms per liter
−9	November 1948	26	800
−5	April 1953	26	798
0 (calibrated)	August 1953	27	783
+5	August 1963	23	748
+9	August 1967	7	740

[1]Calibrated release date varies by source location (Table A13)

Note:
−9 years means 9 years earlier than calibrated-source release date
+9 years means 9 years after calibrated-source release date

Figure A37. Reconstructed (simulated) finished-water concentrations of trichloroethylene (TCE) derived from variations in contaminant-source release dates, Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. [J, estimated]

Finite-Difference Grid Cell-Size Variation

A sensitivity analysis was conducted to determine if the finite-difference cell size of 50 ft per side, which was used for the calibrated groundwater-flow and contaminant fate and transport models in the HPIA and HPLF subdomain areas (Figure A12), was appropriate in terms of simulating the water levels and contaminant concentrations in a pumping well when compared to a smaller cell size. For this analysis, refined model grids—within the HPIA and HPLF subdomain areas—consisting of smaller cell sizes were used in the areas containing water-supply wells and contaminant sources. The cell dimensions of the refined grid were 25 ft along each cell side for groundwater flow (see Suárez-Soto et al. [2013] for maps showing 25-ft-cell grid locations for the HPIA and HPLF subdomain model areas). Water levels simulated using the refined model grid (25-ft cells) were compared to water levels simulated using the calibrated model grid (50-ft cells) in wells HP-602 for the HPIA model subdomain and HP-651 for the HPLF model subdomain. Comparisons were made for January 1968 and November 1984 for water-supply well HP-602 and for July 1972 and November 1984 for well HP-651 (Figure A38).

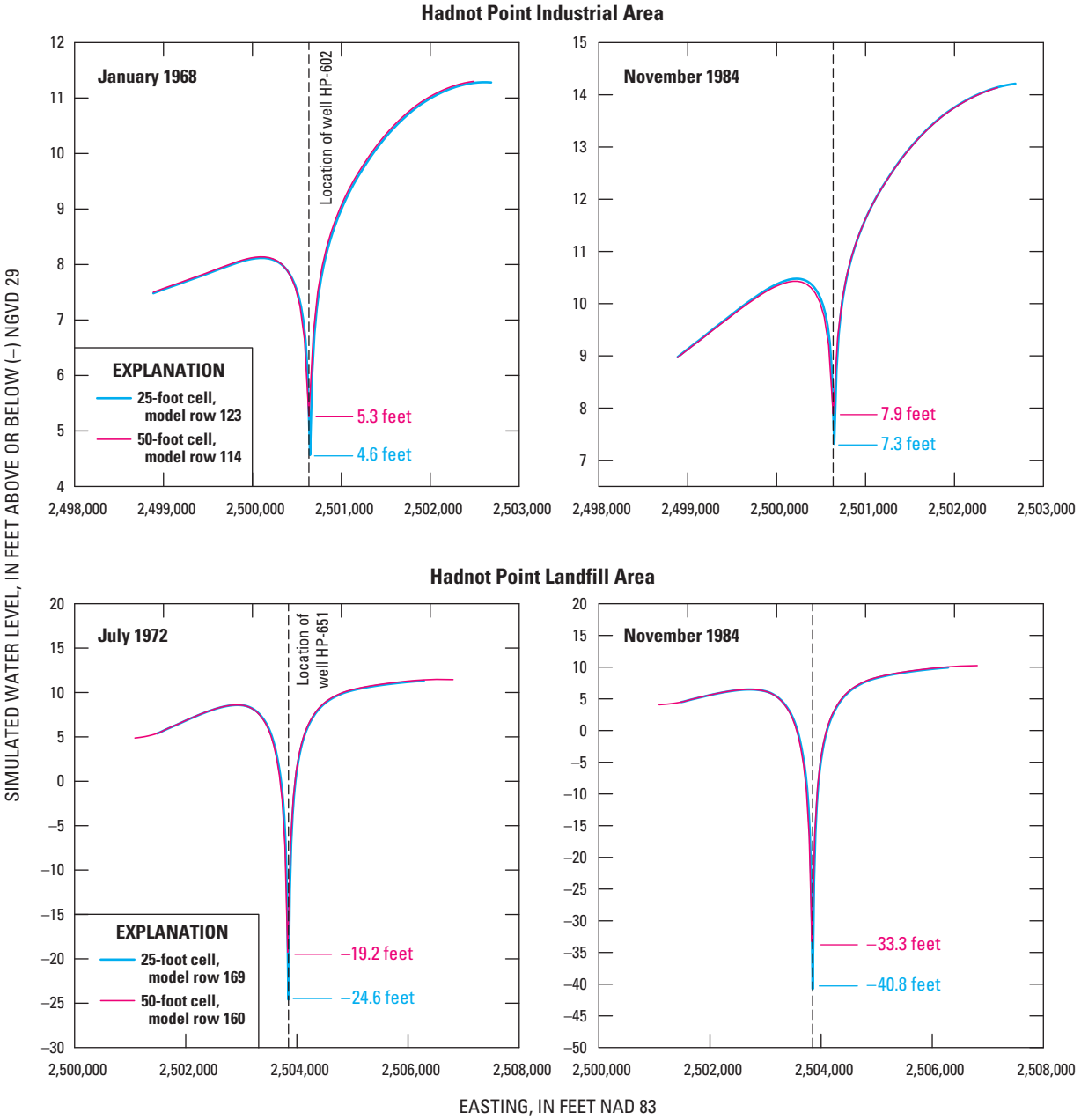


Figure A38. Simulated water levels along designated model row containing water-supply wells HP-602 and HP-651 using finite-difference cell dimensions of 50 feet per side and 25 feet per side, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

The graphs show little difference in water levels simulated using the refined and calibrated model grids (50-ft and 25-ft cells, respectively). For example, during January 1968, the simulated water level in well HP-602 using the calibrated model grid was 5.3 ft; for the refined model grid, the simulated water level was 4.6 ft. Sensitivity to a 50-percent reduction in cell dimension (75-percent reduction in cell area) throughout the model subdomain areas is apparent only at cells where pumpage is assigned. The difference in simulated water levels at these cells is small compared to total simulated drawdown. Simulated differences, with a maximum of 7.5 ft in the HPLF area for November 1984 (Figure A38) are within the transient model calibration ranges.

Contaminant fate and transport simulations can exhibit numerical instabilities related to spatial discretization (finite-difference grid cell size), which in turn can affect simulated concentrations and computed contaminant mass. The Peclet number (P_e) provides a criterion for controlling numerical oscillations due to spatial discretization when its value is less than or equal to 2 (Daus and Friend 1985; Zheng and Bennett 2002). The Peclet number is physically interpreted as the ratio of advective (V) to dispersive (D) transport terms and is defined as

$$P_e = \frac{V \Delta l}{D}, \qquad \text{(A3)}$$

where

P_e = Peclet number [L^0];
V = simulated groundwater-flow velocity [LT^{-1}];
Δl = a characteristic length [L]; and
D = dispersion coefficient [L^2T^{-1}]. [60]

In a one-dimensional, uniform flow field, Equation A3 reduces to:

$$P_e = \frac{\Delta l}{\alpha_L}, \qquad \text{(A4)}$$

where α_L is the aquifer dispersivity in feet. Using the finite-difference cell dimension assigned to the HPIA and HPLF area fate and transport model subdomains of 50 ft, the calibrated α_L value of 25 ft (Table A12), and substituting into Equation A4, yields a P_e value of 2, thereby satisfying the aforementioned criterion for controlling oscillations due to spatial discretization. Because of aquifer heterogeneity and water-supply well operations, the flow field in the HPHB study area is not uniform and is three dimensional. Therefore, a more robust analysis for evaluating P_e (Equation A3) is presented.

[60] L represents length units; T represents time units; L^0 indicates a dimensionless variable.

In a three-dimensional groundwater-flow system, the dispersion coefficient (D) in Equation A3 is represented by a dispersion tensor and contains nine terms (Zheng and Bennett 2002):

$$\boldsymbol{D} = \begin{pmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{zx} & D_{zy} & D_{zz} \end{pmatrix}, \qquad \text{(A5)}$$

where $\boldsymbol{D}$ is the dispersion tensor. The dispersion tensor components (e.g., D_{xx}, D_{xy}) are defined in terms of groundwater velocity ($\boldsymbol{V}$) and its directional components (V_x, V_y, and V_z), horizontal, transverse, and vertical dispersivity (α_L, α_T, and α_V; e.g., Table A12), and the effective molecular diffusion coefficient (D^*, Table A12). If the axes of the computational grid are aligned with the principal directions of groundwater velocity or the cross-terms of $\boldsymbol{D}$ are assumed to be negligible (and approaching zero), then equation A5 reduces to a diagonal matrix containing only the diagonal terms of $\boldsymbol{D}$ such that (Zheng and Bennett 2002),

$$\boldsymbol{D} = \begin{pmatrix} D_{xx} & 0 & 0 \\ 0 & D_{yy} & 0 \\ 0 & 0 & D_{zz} \end{pmatrix}, \qquad \text{(A6)}$$

where:

$$D_{xx} = \alpha_L \frac{V_x^2}{|V|} + \alpha_T \frac{V_y^2}{|V|} + \alpha_V \frac{V_z^2}{|V|} + D^*, \qquad \text{(A7a)}$$

$$D_{yy} = \alpha_L \frac{V_y^2}{|V|} + \alpha_T \frac{V_x^2}{|V|} + \alpha_V \frac{V_z^2}{|V|} + D^*, \qquad \text{(A7b)}$$

$$D_{zz} = \alpha_L \frac{V_z^2}{|V|} + \alpha_T \frac{V_x^2}{|V|} + \alpha_V \frac{V_y^2}{|V|} + D^*, \text{ and} \qquad \text{(A7c)}$$

$$|V| = \sqrt{V_x^2 + V_y^2 + V_z^2}. \qquad \text{(A7d)}$$

Equation A3 can now be solved using the diagonal terms of the dispersivity tensor (Equation A6) to define a Peclet number corresponding to each directional axis, as follows:

$$P_{ex} = \frac{V_x \Delta x}{D_{xx}}, \quad \text{(A8a)}$$

$$P_{ey} = \frac{V_y \Delta y}{D_{yy}}, \quad \text{(A8b)}$$

$$P_{ez} = \frac{V_z \Delta z}{D_{zz}}. \quad \text{(A8c)}$$

In Equation A8a–c, Δx, Δy, and Δz correspond to the finite-difference cell dimensions along rows, columns, and model layers, respectively for the HPIA and HPLF contaminant fate and transport model subdomain areas.

To compute the Peclet numbers defined in Equation A8a–c, the directional values of velocity and the diagonal terms of the dispersion tensor were extracted from the MT3DMS contaminant fate and transport model code for specific finite-difference cells and simulation months of interest to the ATSDR epidemiological studies. For the HPIA, the cell nearest water-supply well HP-608 (Figure A13) was used to compute Equation A8 terms for conditions during January 1968 (start of health studies) and November 1984 (month prior to cessation of pumping of water-supply well HP-608). For the HPLF area, the cell nearest water-supply well HP-651 (Figure A14) was used to compute Equation A8 terms for conditions during June 1972 (start of operations of the well) and November 1984. Peclet number calculations for the calibrated HPIA and HPLF contaminant fate and transport subdomain model locations are listed in Table A26 along with values for components of velocity and the dispersion tensor.

For water-supply well HP-608 (HPIA subdomain model), results indicate that the computed Peclet numbers are below or somewhat higher than 2, the criterion indicated by Daus and Frind (1985) for controlling numerical oscillations. However, as the Peclet numbers were computed for a cell directly impacted by water-supply well HP-608, cells further distant from the well, would have substantially lower velocities, thereby meeting the Peclet criterion. For water-supply well HP-651 (HPLF subdomain model), results indicate that the computed Peclet numbers are greater than 6 for the horizontal Peclet number component (P_{ex}) and less than 1 for the transverse and vertical Peclet number components (P_{ey} and P_{ez}, respectively). These results imply that the flow field near water-supply well HP-651 is an advective-dominated flow field, principally because HP-651 was the only major water-supply well in the area and it was withdrawing groundwater solely from one zone—model layer 5. If the finite difference grid is refined whereby cell dimensions are reduced to 25 ft per side or 12.5 ft per side in the areal discretization (Δx and Δy) the resulting Peclet numbers in the vicinity of the aforementioned water-supply wells would approximately be reduced by corresponding factors of 2 and 4, respectively.

Table A26. Results of Peclet number calculations for the Hadnot Point Industrial Area (HPIA) and Hadnot Point landfill (HPLF) area contaminant fate and transport subdomain models.

Simulation month and year (Stress period)	Cell dimensions (ft)			Velocity (ft/d)			Dispersion (ft²/d)			Peclet number (Equation A8)		
	Δx	Δy	Δz	V_x	V_y	V_z	D_{xx}	D_{yy}	D_{zz}	P_{ex}	P_{ey}	P_{ez}
Hadnot Point Industrial Area, water-supply well HP-608[1]												
Jan. 1968 (313)	50.0	50.0	33.6	12.9	0.7	–0.7	223	37.5	0.7	2.9	0.1	3.5
Nov. 1984 (515)	50.0	50.0	33.6	5.1	–0.1	–0.04	133	20.4	0.4	1.9	0.3	2.9
Hadnot Point landfill (HPLF) area, water-supply well HP-651[2]												
June 1972 (367)	50.0	50.0	57.2	–16.5	–0.05	0.0	126	47.6	1.1	6.6	0.1	0.0
Nov. 1984 (515)	50.0	50.0	57.2	–23.0	–0.3	0.02	176	64.5	1.6	6.6	0.2	0.8

[1]See Figure A13 for well location; HPIA subdomain model cell location: row 184, column 114, layer 3

[2]See Figure A14 for well location; HPLF subdomain model cell location: row160, column 166, layer 5

To further assess the propensity for numerical oscillations because of inappropriate spatial discretization (resulting in Peclet numbers greater than 2 in the vicinity of water-supply well HP-651), descriptions of model simulations conducted using the aforementioned refined cell dimensions (25 ft and 12.5 ft per side) for the HPLF contaminant fate and transport subdomain model are presented below.

Contaminant fate and transport simulations were conducted using reduced finite-difference grid cell sizes of 25 ft and 12.5 ft per side. This grid refinement would effectively yield a reduction in the Peclet number by a factor of 2 to 4. Results of the contaminant fate and transport simulations for the HPLF subdomain area for TCE concentrations in water-supply well HP-651 are shown in Figure A39. The three concentration plots in the graph represent simulated TCE concentrations in well HP-651 that result from using finite-difference grid cell sizes of 50, 25, and 12.5 ft per side (the 50-ft cell size represents the calibrated model). These results indicate approximately the same results from the onset of pumping during July 1972 to cessation of pumping during February 1985, a period of interest to the ATSDR health studies. Additionally, simulated concentrations at water-supply well HP-651 are similar using the three different cell sizes (50 ft, 25 ft, and 12.5 ft) and range from about 7,100 µg/L to 9,200 µg/L (Figure A39). By comparison, measured data range in value from 3,200 µg/L to 18,900 µg/L for the period January 16–February 4, 1985 (Table A4). Thus, sensitvity analysis results for variations in finite-difference cell sizes demonstrate that concentrations simulated by the HPHB study area contaminant fate and transport models were most likely unaffected by numerical oscillations caused by inappropriate (too large) spatial (cell size) discretization.

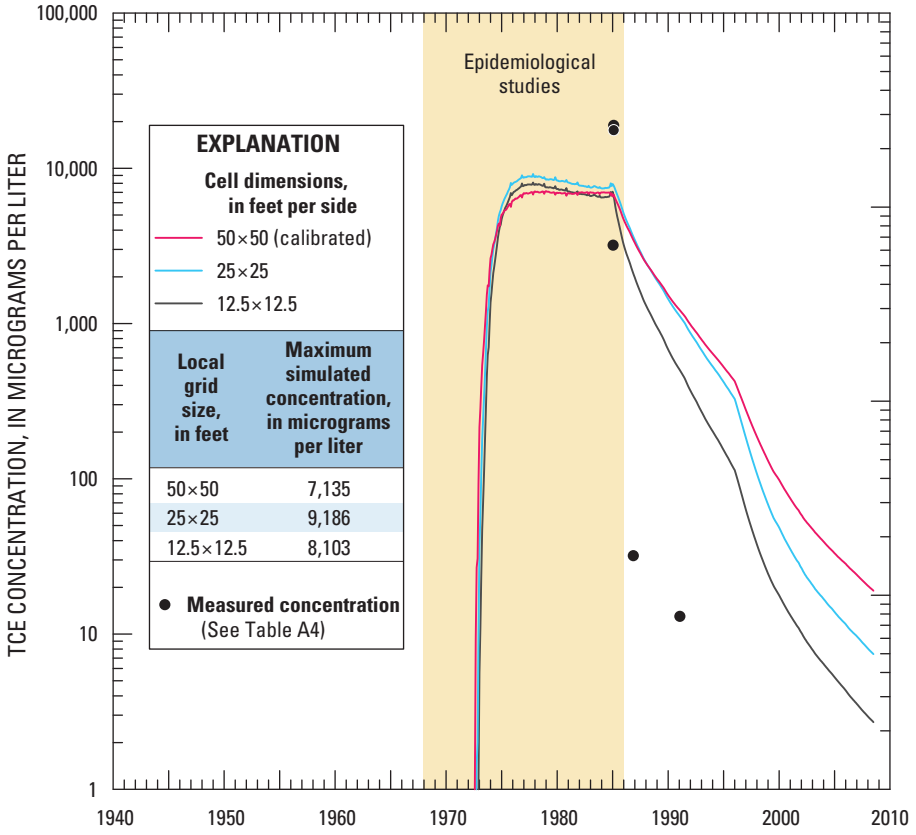


Figure A39. Simulated concentrations of trichloroethylene (TCE) in water-supply well HP-651 using finite-difference cell dimensions of 50, 25, and 12.5 feet per side, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. (See Figure A13 for well location.)

Time-Step Size Variation

When conducting fate and transport simulations, numerical instability related to inappropriate temporal discretization (i.e., time-step size) is minimized when the Courant number (C_N) equals 1 or less (Daus and Frind 1985; Zheng and Bennett 2002). The Courant number is defined as

$$C_N = \frac{V \Delta t}{\Delta l}, \quad \text{(A9)}$$

where

C_N = Courant number [L^0];
V = simulated groundwater-flow velocity [LT^{-1}];
Δt = stress-period length or time-step size [T]; and
Δl = a characteristic length [L].

For the application of the MT3DMS model to the HPIA and HPLF area contaminant fate and transport subdomain models, C_N was set to a maximum value of 1.[61]

The characteristic length of finite-difference numerical models is typically related to grid cell dimensions. The MODFLOW and MT3DMS models applied to the HPHB study area fate and transport model subdomains are uniform at 50 ft per side. Therefore, the characteristic length, Δl, becomes the length of the cell side or the distance between two adjacent cell centroids (50 ft). For the HPHB study area groundwater-flow and contaminant fate and transport models, the stress periods were equal to the number of days in a month (i.e., 28, 29, 30, or 31). Except in the immediate vicinity of water-supply wells, groundwater-flow velocities ranged from 0.01 to 0.6 ft/d for the HPIA model subdomain area and from 0.01 to 1 ft/d for the HPLF model subdomain area. Thus, applying Equation A7 to each subdomain area yields the following values for Courant numbers:

HPIA subdomain area (Figures A12 and A13):

$$\frac{0.01 \times 28}{50} \le C_N \le \frac{0.6 \times 31}{50}$$
$$0.006 \le C_N \le 0.4, \quad \text{(A10)}$$

and for the HPLF subdomain area (Figures A12 and A14):

$$\frac{0.01 \times 28}{50} \le C_N \le \frac{1.0 \times 31}{50}$$
$$0.006 \le C_N \le 0.6. \quad \text{(A11)}$$

This demonstrates that for the HPHB study area, even when using time steps as large as a month, the Courant number was less than 1 throughout the subdomain model areas except in the immediate vicinity of operating water-supply wells.

In the immediate vicinity of operating water-supply wells, velocities were simulated as high as 18 ft/d near HP-608 in the HPIA area and as high as 10 ft/d near HP-651 in the HPLF area. Substituting these values of velocity into Equation A7 results in maximum-value Courant numbers of about 11 and 6 for the HPIA and HPLF fate and transport model subdomain areas, respectively; these Courant numbers—exceeding a value of 1—could be indicative of numerical oscillations leading to inaccurate simulated concentrations. However, MT3DMS decreases Δt (increases the number of transport time steps) to maintain a C_N value of 1. To further assess the effect of numerical oscillations caused by an inappropriate time discretization (that is, too large of a time step),

[61] With the current model code version of MT3DMS applied to the HPHB study area, the Courant condition is automatically checked at every cell in the computational grid by the MT3DMS code to assure that $C_N \le 1$ for every stress period. If the Courant condition is not met, MT3DMS increases the number of transport time steps within a stress period, thus reducing the value of Δt in Equation A7. In most cases, the stress period was discretized by MT3DMS into about 2–5 transport time steps to comply with a Courant condition of 1.

contaminant fate and transport simulations were conducted by assigning 1-day stress periods ($\Delta t = 1$) to the calibrated contaminant fate and transport model for the HPLF subdomain area from November 1, 1984, to January 31, 1985. Pumpage assigned to these months in the calibrated model was assigned to every day of each respective month for the time-step sensitivity analysis. Comparisons of calibrated (30- and 31-day time steps) and simulated (1-day time step) concentrations of PCE and TCE for the days of November 30, 1984, December 31, 1984, and January 31, 1985 for water-supply well HP-651 are listed in Table A27. These results show that the relative absolute difference in simulated PCE and TCE concentrations at water-supply well HP-651 between the 1-day time step and the 30- and 31-day time steps is typically less than 0.2 percent and never exceeds 0.25 percent. Thus, PCE and TCE concentrations simulated by the HPHB study area contaminant fate and transport models were most likely unaffected by numerical oscillations caused by inappropriate temporal discretization.

Table A27. Simulated tetrachloroethylene and trichloroethylene concentrations at water-supply well HP-651, November 1984–January 1985, using 1-day stress periods and 30- or 31-day stress periods (calibrated model), Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter; Δt, time of stress period]

Contaminant	Simulated elapsed time, in days	Date	[1]Simulated concentration, in µg/L		[2]Absolute relative difference, in percent
			Δt=1 day	Δt=30 or 31 days	
Tetrachloroethylene (PCE)	15,675	Nov. 30, 1984	348.557	347.777	0.22
	15,706	Dec. 31, 1984	337.01	336.601	0.12
	15,737	Jan. 31, 1985	343.498	343.105	0.11
Trichloroethylene (TCE)	15,675	Nov. 30, 1984	6,910.40	6,894.63	0.23
	15,706	Dec. 31, 1984	6,589.20	6,582.72	0.10
	15,737	Jan. 31, 1985	6,779.30	6,772.31	0.10

[1] Simulated PCE and TCE concentrations for $\Delta t = 30$ or $\Delta t = 31$ days are from the calibrated fate and transport model for the Hadnot Point landfill (HPLF) subdomain area, described in Jones et al. (2013)

[2] Absolute relative difference ($|R_C|$) of simulated PCE and TCE concentrations are water-supply wells defined as:

$$|R_C| = \frac{C_{\text{cal}} - C_{\Delta t=1}}{C_{\Delta t=1}} \times 100\% ,$$

where

C_{cal} is the calibrated PCE or TCE concentration simulated using a time-step size of 30 or 31 days, and

$C_{\Delta t=1}$ is the PCE or TCE concentration simulated using a time-step size of 1 day

Uncertainty Analysis

Variability and uncertainty are inherent features of the data, analyses, models, and calibrated model parameters described in detail in other HPHB supplemental information texts (Table A1). The purpose of this report section is to summarize the characterization of uncertainty of model output (e.g., simulated concentrations) due to model input parameter uncertainty and variability. The USEPA describes three types of uncertainty (USEPA 1992), and each is encountered in the HPHB historical reconstruction analyses: (1) uncertainty pertaining to missing or incomplete information (e.g., lack of VOC-specific concentration data for drinking-water prior to 1982), (2) uncertainty pertaining to a specific model parameter (e.g., contaminant-source characterization data), and (3) uncertainty regarding gaps in scientific theory or model uncertainty (e.g., use of LCM methodology as a surrogate for sequential degradation at supply wells). Numerous methods are described in the literature for conducting uncertainty analysis (Cullen and Frey 1999; Saltelli et al. 2000; Tung and Yen 2005; Hill and Tiedeman 2007). Within the generalized classification of uncertainty analysis, Monte Carlo (MC) simulation is a particularly well-known numerical method (USEPA 1997; Tung and Yen 2005). To evaluate uncertainty associated with modeling analyses of groundwater flow, contaminant fate and transport, and transfer of finished water from Hadnot Point to Holcomb Boulevard, selected probabilistic analyses using MC simulation were conducted. These analyses and evaluations of MC simulation results are described below.

Probabilistic Analyses of Groundwater and Finished-Water Contaminant Concentrations

The use of MC simulation as part of an uncertainty analysis, while widely accepted and used, is often computationally expensive and time consuming. Maslia et al. (2007, 2009b) applied MC simulation to the TT study area to assess uncertainty associated with reconstructed groundwater and finished-water concentrations of PCE and its degradation products originating from one contaminant source. For the HPHB study area, there are five contaminants of concern (PCE, TCE, 1,2-tDCE, VC, and benzene) and multiple contaminant sources that required the application of one regional groundwater model and two fate and transport subdomain models representing the HPIA and HPLF areas. Replicating the approach described in Maslia et al. (2007, 2009b) for conducting a similar uncertainty analysis for the HPHB study area was not computationally feasible. To meet timelines and priorities associated with the ATSDR health studies, a more strategic approach was implemented to assess uncertainty associated with reconstructed groundwater and finished-water concentrations within the HPHB study area. In essence, MC methods were applied to a single contaminant in the study area that exhibited the highest sustained contribution to contamination in finished water. Observations about uncertainty from this selective analysis were then qualitatively extended to the other contaminants and areas of concern.

TCE is the contaminant that is characterized by the longest duration exceeding its respective MCL (Table A14) and the maximum reconstructed and measured concentrations (Table A18). Therefore, TCE was selected as the contaminant used in the MC uncertainty analysis. The uncertainty analysis was conducted by using two approaches: (1) the LCM methodology and (2) Latin hypercube sampling (LHS)[62]. Both approaches offer substantially reduced computational burdens compared to conducting a robust two-stage MC simulation when using the numerical models MODFLOW and MT3DMS (e.g., Maslia et al. [2007, 2009b]). Recall that reconstructed TCE concentrations derived using the LCM methodology are in good agreement with reconstructed TCE concentrations derived by using the aforementioned numerical models and observed data (Figure A25).

Analysis Using Linear Control Model

The LCM system-state equations are deterministic in nature and therefore do not incorporate numerical errors that may originate from modeling or measurement errors from field data collection efforts. To analyze the effect of such errors on the contaminant concentration distributions that are reconstructed, a Kalman filter[63] is coupled with MC simulation within the LCM methodology. Specific details about the development of the uncertainty analysis for the LCM methodology are presented in Guan et al. (2013). Concentrations of TCE in water-supply well HP-651 derived from the LCM methodology uncertainty analysis by using a Kalman filter and MC simulation are shown in Figure A40. In this graph, a band is shown that represents 95 percent of the MC realizations along with the reconstructed TCE concentrations. During the operational period of water-supply well HP-651 (July 1972–January 1985), MC simulation-derived concentrations vary by about ±50 percent about the reconstructed (mean) concentrations. During the same period, observed data exhibit substantially greater variation (Figure A40). For the requirements of the ATSDR health studies—monthly finished-water concentrations—the uncertainty bounds of ±50 percent of monthly mean finished-water concentrations are acceptable, particularly when compared to limited data availability and data variation (Figure A40).

[62] Latin hypercube sampling (LHS) is a form of stratified sampling that is typically used to reduce the number of Monte Carlo simulations (realizations) by a significant factor.

[63] A Kalman filter is a general mathematical approach for integrating noisy data in a way that minimizes the mean of the error squared; the method is used in many branches of science and engineering and allows for efficient estimation of past, present, and future states, even when a precise definition of the modeled system is unknown.

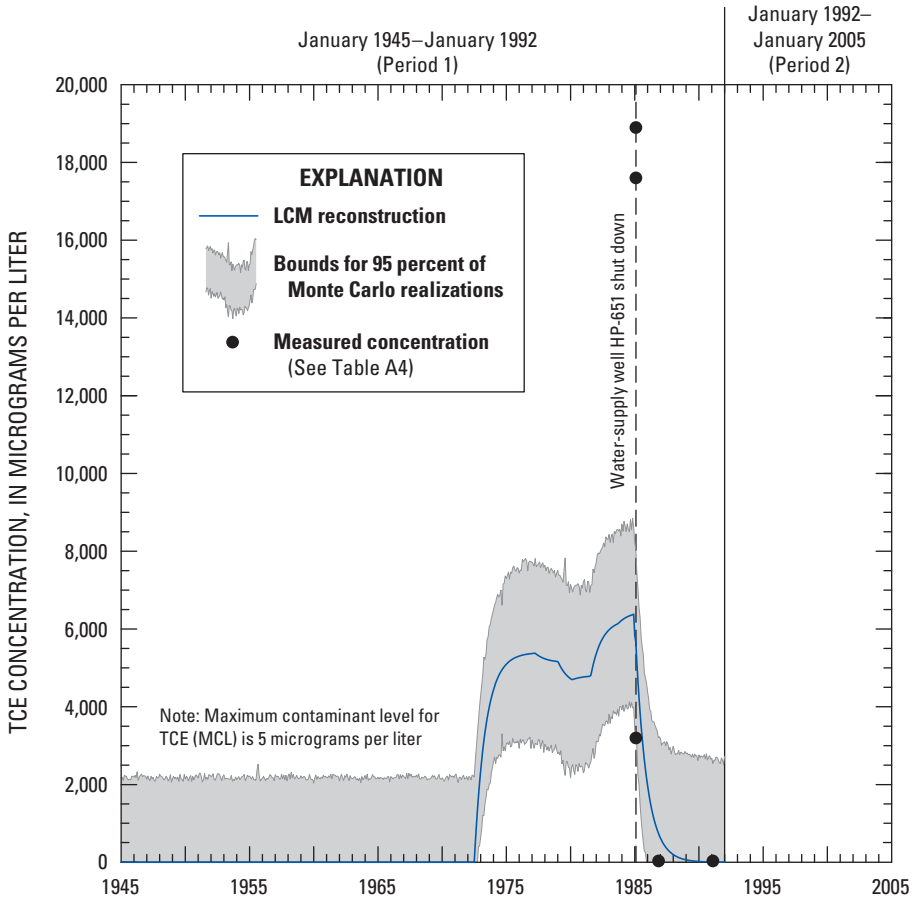


Figure A40. Concentrations of trichloroethylene (TCE) in water-supply well HP-651 derived from uncertainty analysis using Monte Carlo simulation and the linear control model (LCM) methodology, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. (See Figure A14 for well location; Guan et al. 2013 for details on LCM and uncertainty analysis.)

Analysis Using Latin Hypercube Sampling

In order to demonstrate the effect of uncertainty in the pumping schedules of water-supply wells, the LHS methodology is used. LHS is a useful tool for generating a limited number of random samples that are evenly distributed over a multidimensional random field. In this respect, LHS is an ideal approach to overcome the computational expense posed by the MC simulation by reducing the number of simulations required. The LHS technique was first introduced by McKay et al. (1979). Helton and Davis (2003) provide a summary on LHS used for uncertainty analyses of the complex systems. LHS was used to model spatial uncertainty in forest landscape simulations by Xu et al. (2005). Lahkim et al. (1999) applied LHS methodology to reduce the number of simulations required for the uncertainty analysis for the exposure and risk analyses in a polluted aquifer.

For this analysis, MATLAB® (version R2012b, 2012) was used to generate the Latin hypercube samples for the pumping schedules of the wells providing groundwater to HPWTP and HBWTP. The default criterion for LHS is to maximize the minimum distance between points. For this analysis, the number of random variables can be calculated as the product of number of wells and number of months (i.e., 72 wells × 792 months = 57,024 for HPWTP, and 24 wells × 792 months = 19,008 for HBWTP). Replicating the robust approach described in Maslia et al. (2007, 2009b) for conducting uncertainty analyses for the HPHB study area was not computationally feasible even when using the LHS as described herein.

The MATLAB® LHS function that was used generates 10 Latin hypercube samples for the monthly flow produced by all 96 wells included in the analysis. Initially, the values assigned to each well for each month range from 0 to 1. These

normalized samples are then scaled to the actual monthly flows reported by Telci et al. (2013) by multiplying with a range of flows for each well and each month. These flow ranges were determined by finding the difference between the maximum and minimum flows generated for 1,000 MC Markov Chain scenarios that satisfy conservation of mass at the WTP within an error range of ±40 percent. The revised pumping schedules (relative to the calibrated schedules reported in Telci et al. [2013]) are used as an input to the contaminant fate and transport models of the HPIA and HPLF area to reconstruct TCE concentrations delivered to the HPWTP by each well. Reconstructed TCE concentrations at the HPWTP derived from applying the LHS methodology to water-supply well monthly operational schedules are shown in Figure A41. In this figure, the red line indicates the TCE concentration obtained from the calibrated models. The gray lines indicate the TCE concentration variation over time for the 10 random scenarios obtained by LHS methodology. Results shown in Figure A41 indicate that observed data exhibit substantially greater variation than reconstructed concentrations generated using the LHS-MC uncertainty analysis.

Probabilistic Analyses of Finished-Water Transfers from Hadnot Point to Holcomb Boulevard

For the periods of finished-water transfers from Hadnot Point to the Holcomb Boulevard water-distribution system, MC simulation realizations were generated by using the parameter estimation code PEST (Doherty 2003, 2010). MC simulations consisted of 1,000 realizations and assumed a normal distribution for parameter variants. As demonstrated in Maslia et al. (2009b), the Holcomb Boulevard water-distribution system is insensitive to variation in pipe roughness coefficient (C-factor), which is a parameter that affects pressures (and resulting hydraulic heads) in water-distribution system pipelines. Therefore, the parameter that was varied for calibration purposes was nodal demand. Uncertainty of this parameter was assessed by using a probabilistic analysis for simulating water-transfer events. Results for variation in TCE concentrations at five demand locations within Holcomb Boulevard family housing areas are shown in Figure A42.

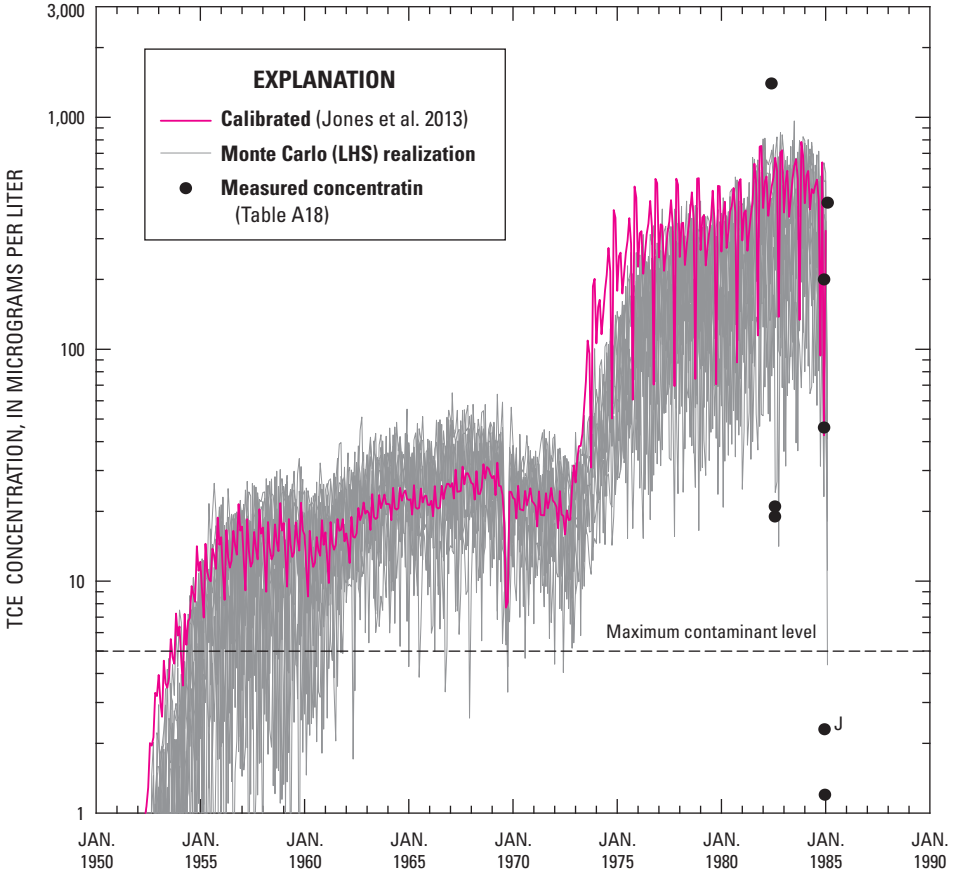


Figure A41. Variations in reconstructed (simulated) finished-water concentrations of trichloroethylene (TCE) derived using Latin hypercube sampling (LHS) methodology on water-supply well monthly operational schedules, Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. [J, estimated]

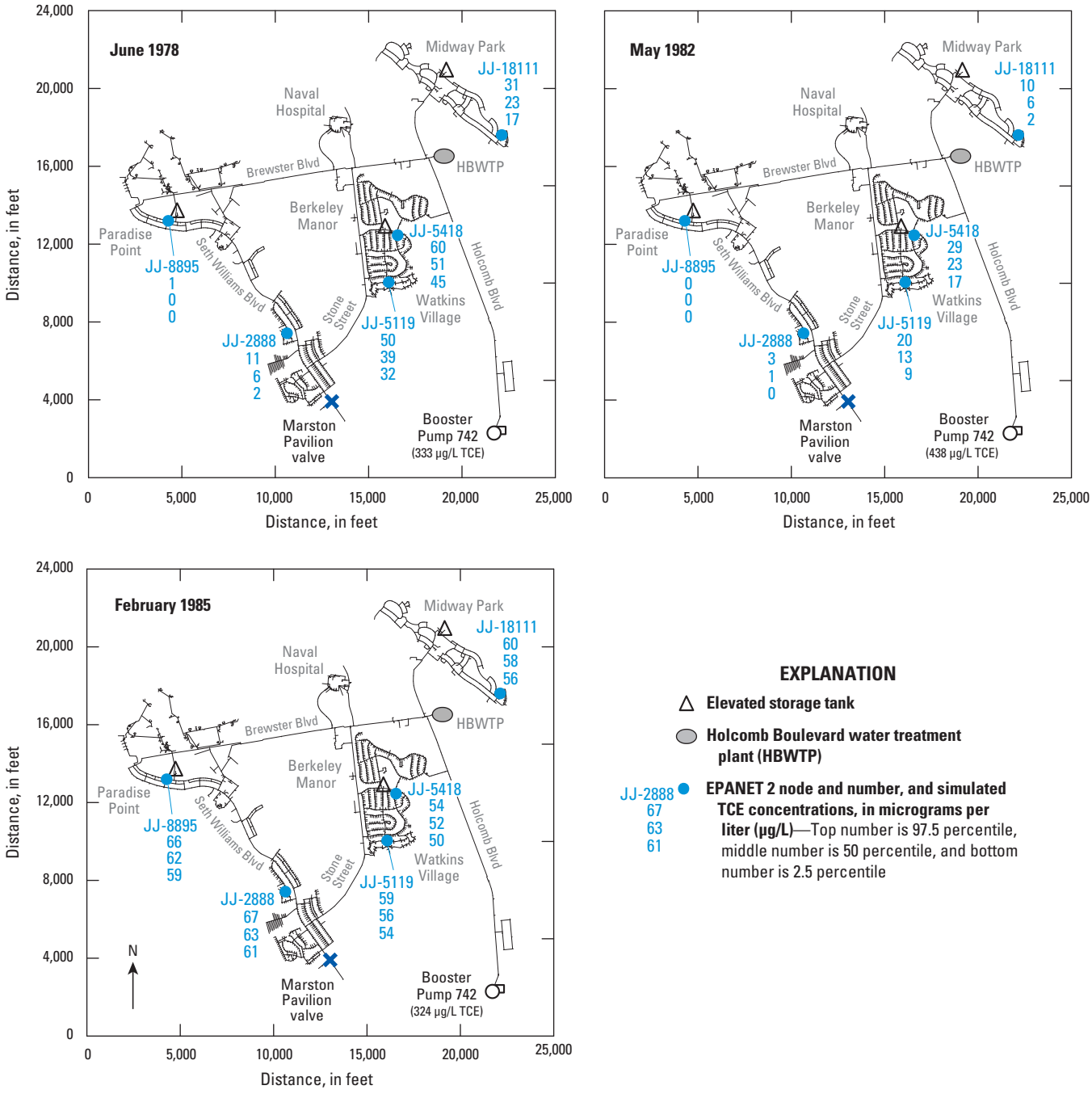


Figure A42. Variations in reconstructed (simulated) concentrations of trichloroethylene (TCE) contamination at selected locations within the Holcomb Boulevard water treatment plant service area resulting from supply of contaminated Hadnot Point finished water, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, June 1978, May 1982, and February 1985.

Results are provided for two Paradise Point locations (a northern and southern location on Seth Williams Boulevard), and one location each for Berkeley Manor, Watkins Village, and Midway Park. For the locations shown, the top number is a maximum ($P_{97.5}$) concentration, the middle number is the median (P_{50}) concentration, and the lower number is the minimum ($P_{2.5}$) concentration that resulted from applying an MC simulation to the water-transfer events shown in Figure A28.

Probabilistic analysis results for reconstructed TCE finished-water concentrations are also listed in Tables A28 and A29. Table A28 provides results that were averaged over an entire housing area (e.g., Watkins Village) whereas Table A29 lists MC simulation results for the specific locations in housing areas shown in Figure A42. MC simulation results listed in Tables A28 and A29 are provided for the 2.5 percentile ($P_{2.5}$), 50 percentile (P_{50}), and 97.5 percentile ($P_{97.5}$) values. Because a normal distribution was assumed, the P_{50} values should be nearly the same as the calibrated monthly mean finished-water concentrations (deterministic values)—results listed in in Tables A28 and A29 confirm this observation.

Results listed in Table A28 can be interpreted as follows. For a Holcomb Boulevard housing area (e.g., Watkins Village), 95 percent of the MC simulated TCE finished-water concentrations will be between the $P_{97.5}$ percentile and the $P_{2.5}$ percentile values. For example, for June 1978 for the Watkins Village housing area, 95 percent of MC simulated TCE finished-water concentrations will be in the range of 32 µg/L

Table A28. Reconstructed (simulated) trichloroethylene (TCE) concentrations in finished water distributed to Holcomb Boulevard family housing areas derived from probabilistic analysis using Monte Carlo simulation, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, June 1978, May 1982, and February 1985.

Housing area	Reconstructed TCE concentration, in micrograms per liter			
	Calibrated[1]	Monte Carlo simulated[2]		
	Mean	$P_{2.5}$	P_{50}	$P_{97.5}$
June 1978				
Paradise Point	3	2	4	8
Midway Park	23	18	23	30
Berkeley Manor	51	44	49	59
Watkins Village	38	32	38	48
May 1982				
Paradise Point	1	0	1	2
Midway Park	6	2	6	9
Berkeley Manor	20	17	20	25
Watkins Village	13	11	14	19
February 1985				
Paradise Point	66	62	65	70
Midway Park	53	52	53	55
Berkeley Manor	54	53	55	57
Watkins Village	56	54	56	59

[1] Calibrated values derived from a single deterministic simulation

[2] Monte Carlo simulated values generated using PEST (Doherty 2003, 2010) consist of 1,000 realizations using normal distribution; $P_{2.5}$, 2.5 percentile; P_{50}, 50 percentile; $P_{97.5}$, 97.5 percentile

Table A29. Reconstructed (simulated) trichloroethylene (TCE) concentrations in finished water at selected locations within Holcomb Boulevard family housing areas derived from probabilistic analysis using Monte Carlo simulation, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, June 1978, May 1982, and February 1985.

Housing area	Selected node number[1]	Reconstructed TCE concentration, in micrograms per liter			
		Calibrated[2]	Monte Carlo simulated[3]		
		Mean	$P_{2.5}$	P_{50}	$P_{97.5}$
June 1978					
Paradise Point	JJ-2888	6	2	6	11
Paradise Point	JJ-8895	0	0	0	1
Midway Park	JJ-18111	23	17	23	31
Berkeley Manor	JJ-5418	49	45	51	60
Watkins Village	JJ-5119	36	32	39	50
May 1982					
Paradise Point	JJ-2888	1	0	1	3
Paradise Point	JJ-8895	0	0	0	0
Midway Park	JJ-18111	6	2	6	10
Berkeley Manor	JJ-5418	24	17	23	29
Watkins Village	JJ-5119	12	9	13	20
February 1985					
Paradise Point	JJ-2888	63	61	63	67
Paradise Point	JJ-8895	61	59	62	66
Midway Park	JJ-18111	57	56	58	60
Berkeley Manor	JJ-5418	52	50	52	54
Watkins Village	JJ-5119	55	54	56	59

[1] See Figure A42; node references EPANET 2 model input file

[2] Calibrated values derived from a single deterministic simulation

[3] Monte Carlo simulated values generated using PEST (Doherty 2003, 2010) consist of 1,000 realizations using normal distribution; $P_{2.5}$, 2.5 percentile; P_{50}, 50 percentile; $P_{97.5}$, 97.5 percentile

to 48 µg/L. For February 1985 for the Paradise Point housing area, 95 percent of MC simulated TCE finished-water concentrations will be in the range of 62 µg/L to 70 µg/L. The probabilistic results listed in Table A28 indicate small variations (factors of 2 or less) in finished-water concentrations for TCE and that the probabilistically determined monthly mean concentrations (P_{50} values) are nearly identical to the calibrated monthly mean concentrations (deterministically determined).

Probabilistic concentration distributions at selected model nodes and housing areas (Figure A41 and Table A29) indicate a range of a factor of about 2 to 3 for a 95-percentile range (97.5 percentile–2.5 percentile) for most locations (e.g., Midway Park for June 1978, Paradise Point for May 1982, and Watkins Village for February 1985). For example, referring to Table A29, for Midway Park for June 1978, the 97.5-percentile ($P_{97.5}$) TCE concentration value is 31 µg/L, and the 2.5-percentile ($P_{2.5}$) TCE concentration value is 17 µg/L, which is a range of about a factor of 2. For the 8-day period of January 28–February 4, 1985, when the HBWTP was shut down and all finished water was supplied by the HPWTP (represented by February 1985 in Figure A42 and Table A29), TCE concentrations at the selected Holcomb Boulevard housing locations derived from the MC simulations vary from 50 µg/L (Berkeley Manor, node JJ-5418) to 67 µg/L (Paradise Point, node JJ-2888). For the 8-day period of January 28–February 4, 1985, represented by February 1985 results listed in Tables A28 and A29, variations in concentrations are relatively small. This may be indicative that finished-water within the Holcomb Boulevard water-distribution system during the period January 28–February 4, 1985 was uniformly mixed with contaminated Hadnot Point finished water. MC simulation results for each month of water transfer for the period June 1972–February 1985 (34 EPANET 2 simulations) are provided in Sautner et al. (2013b).

Discussion

A study of the complexity reported herein, coupled with the use and application of numerical and computational models can benefit from external expert scientific input. Therefore, a brief discussion is provided on scientific input and expert review that was part of the HPHB study effort. Also, five topical areas presented in this Summary and Findings report are worthy of additional discussion so that the reader is fully aware of limitations of information, data, and estimated finished-water concentrations that are part of the historical reconstruction process applied to the HPHB study area. The five areas are related to: (1) information sources and data mining, (2) source characterization, (3) historical reconstruction results, (4) linear control model methodology, and (5) exposure estimates.

Expert Panel Review

Because the application of simulation tools and models requires knowledge and expertise from a variety of scientific and engineering disciplines and the application and development of specific model databases, ATSDR sought independent expert scientific input and review of the project. An expert panel was convened during the early stages of the HPHB study to provide technical advice and guidance on methods, approaches, and interpretations to the historical reconstruction process. During April 29–30, 2009, ATSDR convened an external expert panel to review the approach and methods used in conducting the historical reconstruction analysis and to provide input and recommendations on preliminary data analyses, interpretations, and modeling results (Maslia 2009)[64]. The panel was composed of 13 experts with professional backgrounds from government, academia, and the private sector. Areas of expertise included geohydrologic data analysis, statistical analysis, numerical model development and calibration, groundwater-flow and contaminant fate and transport analysis, hydraulics of water-distribution systems, epidemiology, and public health. Panel members made recommendations in the following six general areas: (1) modeling, (2) calibration, (3) epidemiologic study needs, (4) interconnection between Hadnot Point and Holcomb Boulevard, (5) additional data needs, and (6) time line of the project[65]. Specific recommendations based on the aforementioned six overarching areas and ATSDR's responses to the recommendations are provided in Maslia (2009).

[64] A similar expert review panel was convened for the TT study area historical reconstruction analyses during March 28–29, 2005 (Maslia 2005).

[65] Prior to the end of the expert panel meeting on April 30, 2009, each of the 13 panelists individually provided their final overall comments and recommendations to ATSDR. The verbatim transcript of the meeting contains the comments and recommendations expressed by each panelist (Maslia 2009, Volume II of the transcript on the CD-ROM).

Information Sources and Data Mining

As a result of the historical reconstruction process, many of the environmental data collected by USMCB Camp Lejeune and its contractors that are relevant to the HPHB study area are now compiled in publicly available reports. For example, data relevant to groundwater contaminants at 18 CERCLA (i.e., IRP) sites at USMCB Camp Lejeune are now tabulated and presented in the Chapter C report (Faye et al. 2010); data relevant to groundwater contamination from 64 RCRA (AST/UST) sites are tabulated and presented in the Chapter D report (Faye et al. 2012). However, information discovery and data mining are not exact processes that can be relied upon to identify a specific piece of information or data point. Although every attempt has been made to cull information and data from disparate and numerous sources such as web portals, consulting reports, and data files for relevant, model-specific information and data (Appendix A2), the processes described herein cannot be used to state unequivocally that every piece of information or every data point has been obtained, viewed, categorized, or interpreted—best practices for model calibration do not require this.

Source Characterization

Identification and knowledge of sources for contaminants of concern to this study (e.g., PCE, TCE, and benzene) are requisites for model input data and reconstruction of water-supply well concentrations and finished-water concentrations at the WTPs. For the HPHB study area and specifically within the HPIA, numerous AST/UST and IRP sites were identified containing potential contaminant source locations (Table A7). Specific data relevant to contaminant source operations and chronologies of operations (e.g., dates and times when contaminants were used, spilled, or deposited) were generally not available, nor were the temporal variations in concentrations of contaminant sources available. Thus, for the HPHB study area contaminant fate and transport subdomain models (Figures A12–A14), determining these types of source identification and characterization data became part of the calibration process. Some of the areas identified as potential sources in Table A7 were included in the calibrated fate and transport models to achieve a "best fit" calibration. Reconstructed (simulated) water-supply well and WTP finished-water concentrations represent contaminant contributions from confirmed and potential sources.

Historical Reconstruction Results

Results of the historical reconstruction process—(1) concentrations at water-supply wells (Appendix A3), (2) finished-water concentrations at the HPWTP (Appendix A7), and (3) finished water distributed to Holcomb Boulevard housing areas (Appendix A8)— represent the last day of the month listed in the aforementioned appendixes in terms of model output. For example, for January 1968, the simulated TCE concentration at water-supply well HP-602 of 463 µg/L (Appendix A3) should be interpreted as occurring (in the model) on January 31, 1968; likewise, results listed for November 1984 for a simulated PCE concentration of 31 µg/L at the HPWTP (Appendix A7) should be interpreted as occurring on November 30, 1984. These monthly concentrations represent the most likely estimates of concentration occurring on a typical day during a month and are designated herein as monthly mean concentrations.

Simulated (reconstructed) benzene concentrations in water-supply wells HP-602 and HP-603 (Figure A20, Appendix A3) indicate concentration ranges of approximately 40–200 µg/L and 5–100 µg/L, respectively, during the core period of interest (1968–1985) for the epidemiological studies. Although reconstructed benzene concentrations for well HP-602 are in reasonable agreement with field data, reconstructed benzene concentrations for water-supply well HP-603 are less consistent with field data (Table A5). One or all of several lines of reasoning possibly explain the disparity between reconstructed and sampled benzene concentrations in well HP-603: (1) the release date of hydrocarbon fuels in the vicinity of Building 1613 is unknown and its representation in the numerical model is uncertain, (2) the source concentration and size of the source area during much of the period of simulation are unknown and their representation in a numerical model is consequently highly uncertain, and (3) local hydraulic, fate, and transport characteristics in the vicinity of Building 1613 and water-supply well HP-603 may be different from the average hydraulic, fate, and transport properties defined within the model subdomain (Figure A13 and Table A12). Issues pertaining to source release and concentration were addressed by conducting sensitivity analyses varying model source area location, concentration, release date, and the contribution of benzene-contaminated and TCE-contaminated groundwater to finished-water concentrations at the HPWTP. For benzene, results indicated somewhat improved reconstructed concentrations in well HP-603 (Figure A35 and Table A25) compared to field data (Table A5); however, the corresponding changes in reconstructed benzene concentrations at the HPWTP are minimal (Figure A36). Differences in TCE source-release dates (from calibrated source-release dates) indicate that variations (and uncertainty) due to a lack of documentation and data do not appear to have a substantial effect on historical reconstruction results of interest to the ATSDR epidemiological studies—finished-water concentrations of TCE during the period 1968–1985 (Figure A37).

Linear Control Model Methodology

As part of the historical reconstruction process, a simpler method to determine contaminant concentrations at water-supply wells was developed—the linear control model (LCM) methodology (Chapter A–Supplement 5 [Guan et al. 2012]). Results obtained using the LCM methodology show very good agreement with available field data for water-supply well HP-651 (Figures A25). Although these results appear promising, caution should be used in generalizing the applicability of the LCM methodology and results because sufficient data were available solely for analyses at water-supply well HP-651 (HPLF area); data were insufficient to apply the LCM methodology to other historically contaminated water-supply wells at the HPIA (e.g., HP-602, HP-634). The LCM methodology is a novel method and has not been documented or applied elsewhere in published literature.

Exposure Estimates

The reconstructed finished-water concentrations of contaminants of concern (PCE, TCE, 1,2-tDCE, VC, and benzene) are monthly mean estimates and are not accurate enough to be interpreted on a daily basis. Instead, these contaminant estimates can be used to look for trends in the exposed population by helping to differentiate between those with little or no exposure and other exposure groupings. The health studies do not determine the disease risks to individuals who may have been exposed to these contaminants. Rather, these health studies are conducted to improve scientific knowledge of the possible health effects of these contaminants. This is not a limitation of the water modeling but a reflection of the goal to have these types of estimates for the epidemiological investigations planned by ATSDR.

Summary and Conclusions

The Agency for Toxic Substances and Disease Registry (ATSDR) is conducting epidemiological studies to evaluate the potential for health effects from exposures to volatile organic compounds [tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene] in finished water at U.S. Marine Corps Base Camp Lejeune, North Carolina. To obtain estimates of historical exposures, the ATSDR is using water-modeling techniques and the process of historical reconstruction to quantify concentrations of particular contaminants in finished water and to compute the level and duration of human exposure to contaminated drinking water. Based on information sources, field data, modeling analyses and results, and the historical reconstruction process, the following conclusions are made with respect to groundwater and finished-water contamination for the Hadnot Point–Holcomb Boulevard (HPHB) study area.

For the Hadnot Point Industrial Area (HPIA):

- The maximum reconstructed (simulated) monthly mean TCE concentrations at water-supply wells HP-602, HP-608, and HP-634 were 658 micrograms per liter (µg/L) during January 1959, 50 µg/L during September 1972, and 659 µg/L during October 1968, respectively (Table A14). Measured TCE concentrations at well HP-602 ranged from an estimated 0.7 µg/L to 1,600 µg/L during the period of record, July 1984 to January 1991 (Table A4). Corresponding concentrations at well HP-608 ranged from 9 µg/L to110 µg/L during the period of record, December 1984 to November 1986. In well HP-634 between December 1984 and January 1991, TCE concentrations ranged from less than detection limits to 1,300 µg/L.

- At water-supply wells with measured benzene concentrations exceeding detection limits (HP-602 and HP-608), the maximum reconstructed (simulated) monthly benzene concentration was 236 µg/L at well HP-602 during November 1984 and 11 µg/L at well HP-608 during September 1979 (Table A14, Appendix A3). Measured benzene concentrations at well HP-602 during the period of record, July 1984 to January 1991, ranged from less than 1.0 µg/L to 720 µg/L. Measured benzene concentrations at well HP-608 during the period of record, December 1984 to November 1986, ranged from 1.6 µg/L to an estimated 4.0 µg/L. All measured benzene concentrations in well HP-603 were below detection limits (Table A5).

For the Hadnot Point landfill (HPLF) area:

- The maximum reconstructed (simulated) monthly mean TCE concentration at water-supply well HP-651 was 7,135 µg/L during December 1978 (Table A14). Measured TCE concentrations during the period of record, January 1985 to January 1991, ranged from 13 µg/L to 18,900 µg/L (Table A4).

- The maximum reconstructed (simulated) monthly PCE concentration at water-supply well HP-651 was 353 µg/L during December 1982 (Table A14). Measured PCE concentrations during the period of record, January 1985 through January 1991, ranged from 45 µg/L to 400 µg/L (Table A4).

- The maximum reconstructed (simulated) monthly mean 1,2-tDCE concentration at water-supply well HP-651 was about 4,030 µg/L during December 1984 (Table A14). Measured 1,2-tDCE concentrations during the period of record, January 1985 to November 1986, ranged from 140 µg/L to 8,070 µg/L (Table A4).

- The maximum reconstructed (simulated) monthly mean VC concentration at water-supply well HP-651 was 660 µg/L during November 1984 (Table A14). Measured VC concentrations during the period or record, January 1985 to January 1991, ranged from 70 µg/L to 655 µg/L (Table A4).

For the Hadnot Point water treatment plant (HPWTP) service area:

- The reconstructed duration of exposure to finished water exceeding the current maximum contaminant level (MCL) for TCE was 374 months (August 1953–January 1985) (Table A14). With the onset of pumping at well HP-651 during July 1972, the concentration of TCE in well HP-651 affected the resulting finished-water concentrations of TCE at the HPWTP, which exceeded 750 µg/L during November 1983 (Table A14). Measured TCE concentrations in finished water at the HPWTP during the period May 1982 through February 1985 ranged from 1.2 µg/L to 1,400 µg/L (Faye et al. 2010, Table C11).

- The reconstructed duration of exposure to finished water exceeding the current MCL for PCE was 114 months (August 1974–January 1985) (Table A14), also a consequence of the onset of pumping of well HP-651. The maximum reconstructed finished-water concentration of PCE was about 40 µg/L during November 1983 (Table A14). Measured PCE concentrations at the HPWTP ranged from below detection limits (1–10 µg/L) to 100 µg/L during the period May 1982–February 1985 (Faye et al. 2010, Table C11).

- The reconstructed duration of exposure to finished water exceeding the current MCL for benzene was 63 months (January 1979–November 1984) (Table A14); the maximum reconstructed finished water concentration of benzene was about 12 µg/L during April 1984 (Table A14). Measured benzene concentrations at the HPWTP ranged from below detection limits (10 µg/L) to 38 µg/L during the period December 1984–December 1985. An unexplained value of 2,500 µg/L of benzene was measured on November 11, 1985 (Faye et al. 2010, Table C12).

For the Holcomb Boulevard housing area:

- When this housing area was serviced by the HPWTP (prior to June 1972), the maximum reconstructed (simulated) monthly mean TCE concentration in finished water of interest to the ATSDR health studies (January 1968–December 1985) was 32 µg/L during August 1968 and August 1969 (Appendix A7). The minimum reconstructed (simulated) monthly mean TCE concentration in finished water of interest to the health studies (January 1968–December 1985) was 8 µg/L (September and October 1969). TCE concentrations in finished water first exceeded the MCL during August 1953 (Appendix A7).

- Subsequent to June 1972 when the Holcomb Boulevard water treatment plant (HBWTP) came online to service this housing area, an interconnection analysis indicates that the maximum reconstructed (simulated) TCE concentration in finished water was 66 µg/L during February 1985 for the Paradise Point area (Figure A29).

- Subsequent to June 1972 when the HBWTP came online to service this housing area, the maximum reconstructed (simulated) monthly concentrations for PCE, 1,2-tDCE, and VC in finished water for the Holcomb Boulevard housing area occurred during February 1985 and were 3 µg/L, 33 µg/L, and 6 µg/L, respectively (Table A21). The maximum reconstructed (simulated) monthly concentration for benzene was 3 µg/L, occurring during January, February, April, May, and June 1972 (Table A21).

Based on data, analyses, interpretations, model calibrations, and sensitivity and uncertainty analyses, the historical reconstruction process provides evidence that finished-water concentrations at the HPWTP substantially exceeded the MCL for TCE (5 µg/L) prior to and during the core period (1968–1985) of the ATSDR epidemiological studies (Figure A27, Table A14). It is most likely that TCE first exceeded its current MCL during August 1953, but this exceedance could have been as early as November 1948 if releases of TCE to the subsurface began during or immediately following the onset of construction (1941/1942) of USMCB Camp Lejeune. (Figure A37). Finished-water concentrations exceeded the MCL for PCE (5 µg/L) during the period 1975–1985; 1,2-tDCE and VC also exceeded their respective MCLs (100 µg/L and 2 µg/L, respectively) during the period 1975–1985. Although substantial volumes of fuel were lost due to leakage to the subsurface (range of 0.9 to 1.6 million gallons, Table A16), finished-water concentrations only slightly exceeded the MCL for benzene (5 µg/L) during the period 1980–1985 (Figure A27). Within the Holcomb Boulevard housing area, except for the 8-day period of January 28–February 4, 1985, when the HBWTP was out of service, only TCE routinely exceeded its MCL during intermittent periods of connection with the Hadnot Point water-distribution system (Table A21).

Using the historical reconstruction process, monthly mean concentrations of contaminants of concern in finished water have been estimated. Bounds of variation about the reconstructed monthly mean finished-water concentrations generally have a range of about an order of magnitude or less. These results allow epidemiologists to categorize exposure into several categories rather than relying on crude classification estimates of exposed versus unexposed populations for the epidemiological studies at USMCB Camp Lejeune, North Carolina.

Availability of Input Data Files, Models, and Simulation Results

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

Predevelopment and transient groundwater flow

- Model code: MODFLOW-2005
- Web site: *http://water.usgs.gov/nrp/gwsoftware/modflow.html*

Fate and transport of contaminants dissolved in groundwater as a single specie

- Model code: MT3DMS-5.3
- Web site: *http://hydro.geo.ua.edu/*

Distribution of water and contaminants in a water-distribution system

- Model code: EPANET 2 (Build 2.00.12)
- Web site: *http://www.epa.gov/nrmrl/wswrd/dw/epanet.html*

Objective parameter estimation and uncertainty analysis

- Model code: PEST-12
- Web site: *http://www.pesthomepage.org/*

Specialized model codes and model input data files were developed specifically for the Hadnot Point-Holcomb Boulevard study area analyses by the Multimedia Environmental Simulations Laboratory (MESL) at the School of Civil and Environmental Engineering, Georgia Institute of Technology. These specialized codes and input data files were developed for reconstructing monthly historical water-supply well operations (TechWellOp), estimating light nonaqeuous phase liquid (LNAPL) volume (mass) in groundwater (TechNAPLVol), simulating three-dimensional LNAPL migration (TechFlowMP), reconstructing contaminant concentrations in water-supply wells by using a linear control model methodology (TechControl), and conducting probabilistic analyses of intermittent connections (1972–1985) of the Hadnot Point and Holcomb Boulevard water-distribution systems using a Markov Chain model (TechMarkovChain). These models are described and applied in Telci et al. (2013), Guan et al. (2013), Jang et al. (2013), and Sautner et al. (2013b). Contact information and questions related to these codes are provided on the Internet at the MESL Web site at *http://mesl.ce.gatech.edu*.

Also included on the CD-ROM accompanying this report is a file that contains results for monthly simulated concentrations of PCE, TCE, 1,2-tDCE, VC, and benzene at historically operated water-supply wells (Appendix A3), in finished water at the HPWTP for the period January 1942–June 2008 (Appendix A7), and at Holcomb Boulevard housing areas for the period January 1972–December 1985 (Appendix A8). These files are prepared in Adobe® Portable Document Format (PDF).

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

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References [66]

Agency for Toxic Substances and Disease Registry. Toxicological Profile for Tetrachloroethylene. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service, Agency for Toxic Substances and Disease Registry; 1997a. [cited 2012 December 12]; Available from *http://www.atsdr.cdc.gov/ToxProfiles/tp18.pdf*

Agency for Toxic Substances and Disease Registry. Toxicological Profile for Trichloroethylene. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service, Agency for Toxic Substances and Disease Registry; 1997b. [cited 2012 December 12]; Available from *http://www.atsdr.cdc.gov/ToxProfiles/tp19.pdf*

Agency for Toxic Substances and Disease Registry. Volatile Organic Compounds in Drinking Water and Adverse Pregnancy Outcomes, United States Marine Corps Base, Camp Lejeune. Atlanta, GA: U.S. Department of Health and Human Services; 1998.

AGVIQ-CH2M HILL, Vapor Intrusion Evaluation Report (6 Volumes), Marine Corps Base Camp Lejeune, North Carolina; 2009. Contract No.: N62467-03-D-0260.

AH Environmental Consultants. Long Term Water System Master Plan—Draft Plan, Marine Corps Base, Camp Lejeune. Norfolk, VA: Naval Facilities Engineering Command, Atlantic Division; 2001. Contract No.: N62470-00-D-3300, Delivery Order 0011.

AH Environmental Consultants. Wellhead Protection Plan—2002 Update, Final Report, Marine Corps Base, Camp Lejeune, North Carolina; 2002. Contract No.: N62470-00-D-3300.

AH Environmental Consultants. ATSDR Support—Estimation of VOC Removal, Final Report, Marine Corps Base, Camp Lejeune, North Carolina; 2004a. Contract No.: DACW56-03-R-103, Delivery Order 02.

AH Environmental Consultants. Meter Installation Work Plan, Draft Report, Marine Corps Base, Camp Lejeune, North Carolina; 2004b. Contract No.: DACW56-03-D-1008, Task Order 002.

AH Environmental Consultants. Water Distribution System Modeling Support, Draft Report, Marine Corps Base, Camp Lejeune, North Carolina; 2004c. Contract No.: DACW56-03-R-103, Delivery Order 0001.

AH Environmental Consultants. Raw Water Master Plan, Final Report, Marine Corps Base Camp Lejeune, North Carolina; 2005. Contract No.: N62470-04-D-2284.

Aliev FA, and Larin VB. Optimization of Linear Control Systems: Analytical Methods and Computational Algorithms. Gordon and Breach Science Publishers; 1998.

ASTM. Standard Guide for Conducting a Sensitivity Analysis for a Ground-Water Flow Model Application. ASTM Guide D5611-94 (Reapproved 2002). West Conshohocken, PA: ASTM; 1994.

AWWA Engineering Computer Applications Committee. Calibration Guidelines for Water Distribution System Modeling. Proceedings: AWWA Information Management and Technology Conference (IMTech); 1999 April; New Orleans, LA. New York: American Water Works Association; 1999.

Baker Environmental, Inc. Final Feasibility Study for Operable Unit No.1 (Sites 21, 24, and 78), Marine Corps Base Camp Lejeune, North Carolina; 1994. Contract Task Order 0177, Contract No.: N62470-89-D-4814 (CERCLA Administrative Record file #1256).

Baker Environmental, Inc. Final Basewide Remediation Assessment, Groundwater Study (BRAGS), Marine Corps Base Camp Lejeune, North Carolina; 1998a. Contract Task Order 0140, Contract No.: N62470-89-D-4814 (CERCLA Administrative Record file #02013).

Baker Environmental, Inc. Groundwater Modeling Report, Operable Unit No. 9, Site 73—Amphibious Vehicle Maintenance Facility, Marine Corps Base Camp Lejeune, North Carolina, 1998b. Contract Task Order 0312, Contract No.: N62470-89-D-4814 (CERCLA Administrative Record File #02583).

Bove FJ, Fulcomer MC, Klotz JB, Esmart J, Dufficy EM, and Savrin JE. Public Drinking Water Contamination and Birth Outcomes. American Journal of Epidemiology. 1995;14:850–862.

Bove FJ, and Ruckart PZ. An Assessment of the Feasibility of Conducting Future Epidemiological Studies at USMC Base Camp Lejeune. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2008. [cited 2012 July 31]; Available from *http://www.atsdr.cdc.gov/sites/activities.html*

Bove F, Shim Y, and Zeitz P. Drinking Water Contaminants and Adverse Pregnancy Outcomes: A Review. Environmental Health Perspectives. 2002;110(S):61–74.

Brooks RH, and Corey AT. Hydraulic Properties of Porous Media. Fort Collins, CO: Colorado State University Hydrology Papers 3; 1964 March.

Brooks RH, and Corey AT. Properties of Porous Media Affecting Fluid Flow. Journal of Irrigation Division, American Society of Civil Engineers. 1966; 92(IR2):61–88.

[66] Certain documents have been provided to ATSDR by the Department of the Navy (Headquarters Marine Corps, Eastern Area Counsel Office, and Marine Corps Base Camp Lejeune) under terms of "For Official Use Only" (FOUO) documents. Some of these documents are not releasable by ATSDR under the terms of FOUO.

Catlin Engineers and Scientists. Marine Corps Base Camp Lejeune, UST Management Web Portal File #01185, p. 526–562; 2010.

Cesario L. Modeling, Analysis, and Design of Water Distribution Systems. Denver, CO: American Water Works Association; 1995.

CH2M HILL. Final Site Management Plan, Fiscal Year 2006, Marine Corps Base (MCB) Camp Lejeune, North Carolina. Norfolk, VA: Naval Facilities Engineering Command, Atlantic Division; 2006. Contract No.: N62470-03-D-4186.

CH2M HILL. Final Site Management Plan, Fiscal Year 2007, Marine Corps Base (MCB) Camp Lejeune, North Carolina. Norfolk, VA: Naval Facilities Engineering Command, Atlantic Division; 2007a. Contract No.: N62470-02-D-3052.

CH2M HILL. Final Site Management Plan, Fiscal Year 2008, Marine Corps Base Camp Lejeune, Jacksonville, North Carolina. Norfolk, VA: Naval Facilities Engineering Command, Atlantic Division; 2007b. Contract No.: N62470-02-D-3052.

CH2M HILL. Final Site Management Plan, Fiscal Year 2009, Marine Corps Base Camp Lejeune, Jacksonville, North Carolina. Norfolk, VA: Naval Facilities Engineering Command, Atlantic Division; 2008. Contract No.: N62470-02-D-3052.

CH2M HILL. Final Site Management Plan, Fiscal Year 2010, Marine Corps Base Camp Lejeune, Jacksonville, North Carolina. Norfolk, VA: Naval Facilities Engineering Command, Atlantic Division; 2009. Contract No.: N62470-08-D-1000.

CH2M HILL. Final Site Management Plan, Fiscal Year 2011, Marine Corps Base Camp Lejeune, Jacksonville, North Carolina. Norfolk, VA: Naval Facilities Engineering Command, Atlantic Division; 2010. Contract No.: N62470-08-D-1000.

CH2M HILL and Baker Environmental, Inc. Final Fiscal Year 2005 Site Management Plan, Marine Corps Base Camp Lejeune, North Carolina. Norfolk, VA: Naval Facilities Engineering Command, Atlantic Division; 2005. Contract No.: N62470-02-D-3052.

CH2M HILL, Inc. Evaluation of Cogdel's Creek, Marine Corps Base Camp Lejeune, North Carolina. Charlotte, NC: U.S. Army Corps of Engineers; 1998. Contract No.: DACA01-96-D-0028, Delivery Order 0025.

CH2M HILL, Inc. Hadnot Point Fuel Farm/Building 1101, Remediation Assessment Report, Marine Corps Base, Camp Lejeune, North Carolina; 2001. Contract No.: N62470-95-D6007, Navy CLEAN II Program, March 2, 2001 (UST File #0670).

Clement TP, Gautum TR, Lee KK, Truex MJ, and Davis GB. Modeling of DNAPL-Dissolution, Rate-Limited Sorption and Biodegradation Reactions in Groundwater Systems. Bioremediation Journal. 2004;8(1–2):47–64.

CLHDW CDR, Camp Lejeune Historic Drinking Water Consolidated Document Repository, 1199–10257 (not consecutively numbered), provided on electronic media to ATSDR, For Official Use Only (FOUO) documents. U.S. Marine Corps Base Camp Lejeune, Environmental Management Division; March 2011.

CLW, Camp Lejeune Water Documents, 0001–8761 (not consecutively available), provided on CD-ROM format. In: Maslia ML, Sautner JB, Faye RE, Suárez-Soto RJ, Aral MM, Grayman WM, Jang W, Wang J, Bove FJ, Ruckart PZ, Valenzuela C, Green JW Jr, and Krueger AL. Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—Chapter A: Summary of Findings. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2007.

Cohn P, Klotz J, Bove F, Berkowitz M, and Fagliano J. Drinking Water Contamination and the Incidence of Leukemia and Non-Hodgkin's Lymphoma. Environmental Health Perspectives. 1994;102(6–7):556–561.

Costas K, Knorr RS, and Condon SK. A Case-Control Study of Childhood Leukemia in Woburn, Massachusetts: The Relationship Between Leukemia Incidence and Exposure to Public Drinking Water. The Science of the Total Environment. 2002;300:23–35.

Cullen AC, and Frey HC. Probabilistic Techniques in Exposure Assessment: A Handbook for Dealing with Variability and Uncertainty in Models and Inputs. New York: Plenum Press; 1999.

Daus AD, and Frind EO. An Alternating Direction Galerkin Technique for Simulation of Contaminant Transport in Complex Groundwater Systems. Water Resources Research. 1985;21(5):653–664.

Dewberry and Davis. Permit to Construct Municipal Solid Waste Landfill, Phase I, Marine Corps Base Camp Lejeune, North Carolina. Norfolk, VA: Naval Facilities Engineering Command, Atlantic Division; 1995.

Doherty J. Ground Water Model Calibration Using Pilot Points and Regularization. Ground Water. 2003;41(2):107–177.

Doherty J. PEST: Model Independent Parameter Estimation, User Manual; 2010. [cited 2012 July 24]; Available from *http://www.pesthomepage.org/Downloads.php*

ECG, Inc. Marine Corps Base Camp Lejeune and Marine Corps Air Station, New River, Water Conservation Analysis. Vienna, VA: ECG, Inc.; 1999.

Environmental Science and Engineering, Inc. Characterization Step Report for Hadnot Point Industrial Area, Confirmation Study to Determine Existence and Possible Migration of Chemicals In Situ. Marine Corps Base Camp Lejeune, North Carolina; 1988. Contract No. N62470-83-C-6106 (CERCLA Administrative Record File #258).

Environmental Systems & Technologies. SpillCAD User and Technical Guide, ES&T Software, Ltd. Blacksburg, VA: ES&T; 1993.

Farr AM, Houghtalen RJ, and McWhorter DB. Volume Estimation of Light Nonaqueous Phase Liquids in Porous Media. Ground Water. 1990;28(1):48–56.

Faye RE. 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 F: Simulation of the Fate and Transport of Tetrachloroethylene (PCE). Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2008.

Faye RE. Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina—Chapter B: Geohydrologic Framework of the Brewster Boulevard and Castle Hayne Aquifer Systems and the Tarawa Terrace Aquifer. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2012.

Faye RE, Anderson BA, Suárez-Soto RJ, and Sautner JB. Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina—Chapter C: Occurrence of Selected Contaminants in Groundwater at Installation Restoration Program Sites. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2010.

Faye RE, and Green JW Jr. 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 E: Occurrence of Contaminants in Groundwater. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2007.

Faye RE, Jones LE, and Suárez-Soto RJ. Descriptions and Characterizations of Water-Level Data and Groundwater Flow for the Brewster Boulevard and Castle Hayne Aquifer Systems and the Tarawa Terrace Aquifer—Supplement 3. In: Maslia ML, Suárez-Soto RJ, Sautner JB, Anderson BA, Jones LE, Faye RE, Aral MM, Guan J, Jang W, Telci IT, Grayman WM, Bove FJ, Ruckart PZ, and Moore SM. Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina—Chapter A: Summary and Findings. Agency for Toxic Substances and Disease Registry; 2013.

Faye RE, Suárez-Soto RJ, and Maslia ML. Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina—Chapter D: Occurrence of Selected Contaminants in Groundwater at Above-Ground and Underground Storage Tank Sites. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2012.

Faye RE, and Valenzuela C. 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 C: Simulation of Groundwater Flow. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2007.

Gangadharan AC, Narayanan TV, Raghavan R, and Amoruso G. Leak Prevention in Underground Storage Tanks: A State-of-the-Art Survey. Cincinnati, OH: U.S. Environmental Protection Agency, Hazardous Waste Engineering Research Laboratory, Office of Research and Development; 1987. Report No.: EPA/600/2-87/018.

Geraghty and Miller. Final Report: Phase I LUST Study (Tables), Marine Corps Base Camp Lejeune, North Carolina; 1990. Contract No. N62470-86-C-8746. (UST Management Web Portal File #504).

Geophex, Ltd. Wellhead Management Program, Engineering Study 91-36, Submitted to Officer In Charge of Construction, Marine Corps Base Camp Lejeune, North Carolina; 1991. Contract No.: N62470-90-D-6756 (Camp Lejeune Water Document #1917).

Goldberg SJ, Lebowitz MD, Graver EJ, and Hicks S. An Association of Human Congenital Cardiac Malformations and Drinking Water Contaminants. Journal of the American College of Cardiology. 1990;15:155–164.

Golden Software, Inc. Grapher™ 9, 2D & 3D Graphing for Scientists, Engineers & Business Professionals. Golden, CO: Golden Software, Inc.; 2011a. [cited 2012 March 2]; Available from *http://www.GoldenSoftware.com*

Golden Software, Inc. Surfer® 10, Contouring & 3D Surface Mapping for Scientists & Engineers. Golden, CO: Golden Software, Inc.; 2011b. [cited 2012 March 2]; Available from *http://www.GoldenSoftware.com*

Guan J, Anderson BA, Aral MM, and Maslia ML. Theory, Development, and Application of Linear Control Model Methodology to Reconstruct Historical Contaminant Concentrations at Selected Water-Supply Wells—Supplement 5. In: Maslia ML, Suárez-Soto RJ, Sautner JB, Anderson BA, Jones LE, Faye RE, Aral MM, Guan J, Jang W, Telci IT, Grayman WM, Bove FJ, Ruckart PZ, and Moore SM. Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina—Chapter A: Summary and Findings. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2013.

Guan J, Jang W, Maslia ML, and Aral MM. Historical Reconstruction of Groundwater Contamination at Contaminated Sites and Uncertainty Analysis. In: Palmer RN, ed. Proceedings of the World Environmental & Water Resources Congress, Providence, RI: American Society of Civil Engineers, Environmental and Water Resources Congress 2010 Challenges of Change; 2010, May 16–20 [on CD-ROM].

Guan J, Maslia MM, and Aral MM. A Methodology to Reconstruct Groundwater Contamination History with Limited Field Data. In: Starrett S, ed. Proceedings of the World Environmental & Water Resources Congress, Kansas City, MO: American Society of Civil Engineers, Environmental and Water Resources Congress 2009 Great Rivers; 2009, May 17–21 [on CD-ROM].

Guha N, Loomis D, Grosse Y, et al. Carcinogenicity of Trichloroethylene, Tetrachloroethylene, some other Chlorinated Solvents, and their Metabolites. The Lancet Oncology. 2012;13(12):1192–1193.

Harbaugh AW. MODFLOW-2005, The U.S. Geological Survey modular ground-water model–the Ground-Water Flow Processes. Reston, VA: U.S. Geological Survey Techniques and Methods 6-A16; 2005.

Harbaugh AW, and McDonald MG. User's Documentation of MODFLOW-96, an Update to the U.S. Geological Survey Modular Finite-Difference Ground-Water Flow Model. Reston, VA: U.S. Geological Survey Open-File Report 96-458; 1996.

Harned DA, Lloyd OB Jr, and Treece MW Jr. Assessment of Hydrologic and Hydrogeologic Data at Camp Lejeune Marine Corps Base, North Carolina. Raleigh, NC: U.S. Geological Survey Water-Resources Investigations Report 89-4006; 1989.

Helton JC, and Davis FJ. Latin Hypercube Sampling and the Propagation of Uncertainty in Analyses of Complex Systems. Reliability Engineering & System Safety. 2003;81(1):23–69.

Henry Von Oesen and Associates, Inc. Study of Two Water Plants, Tarawa Terrace–Montford Point, Camp Lejeune, North Carolina; 1979.

Hill MC, and Tiedeman CR. Effective Groundwater Model Calibration. Hoboken: John Wiley & Sons, Inc.; 2007.

Huling SG, and Weaver JW. Dense Nonaqueous Phase Liquids. Washington, D.C.: U.S. Environmental Protection Agency, Office of Research and Development and Office of Solid Waste and Emergency Response; 1991 March. Report No.: EPA/540/4-91-002.

Jang W, and Aral NN. Three-Dimensional Multiphase Flow and Multi-Species Transport Model, TechFlowMP. Report No. MESL-02-05. Multimedia Environmental Simulations Laboratory, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, Georgia; 2005.

Jang W, and Aral MM. Density-Driven Transport of Volatile Organic Compounds and Its Impact on Contaminated Groundwater Plume Evolution. Transport in Porous Media. 2007;67(3):353–374.

Jang W, and Aral MM. Effect of Biotransformation on Multi-Species Plume Evolution and Natural Attenuation. Transport in Porous Media. 2008a;72(2):207–226.

Jang W, and Aral MM. Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—Chapter G: Simulation of Three-Dimensional Multispecies, Multiphase Mass Transport of Tetrachloroethylene (PCE) and Associated Degradation By-Products. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2008b.

Jang W, and Aral MM. Multiphase Flow Fields in In-Situ Air Sparging and Its Effect on Remediation. Transport in Porous Media. 2009;76(1):99–119.

Jang W, Anderson BA, Suárez-Soto RJ, Aral MM, and Maslia ML. Source Characterization and Simulation of the Migration of Light Nonaqueous Phase Liquids (LNAPLs) in the Vicinity of the Hadnot Point Industrial Area—Supplement 7. In: Maslia ML, Suárez-Soto RJ, Sautner JB, Anderson BA, Jones LE, Faye RE, Aral MM, Guan J, Jang W, Telci IT, Grayman WM, Bove FJ, Ruckart PZ, and Moore SM. Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina—Chapter A: Summary and Findings. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2013.

Jones LE, Suárez-Soto RJ, Anderson BA, and Maslia ML. Characterization and Simulation of Fate and Transport of Selected Volatile Organic Compounds in the Vicinities of the Hadnot Point Industrial Area and Landfill—Supplement 6. In: Maslia ML, Suárez-Soto RJ, Sautner JB, Anderson BA, Jones LE, Faye RE, Aral MM, Guan J, Jang W, Telci IT, Grayman WM, Bove FJ, Ruckart PZ, and Moore SM. Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina—Chapter A: Summary and Findings. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2013.

JTC Environmental Consultants, Inc. Laboratory Analyses on Naval Samples, JTC Report #85-513; 1985. Contract No.: N62470-84-B-6932.

Kopecky KJ, Davis S, Hamilton TE, Saporito MS, and Onstad LE. Estimation of Thyroid Radiation Doses for the Hanford Thyroid Disease Study: Results and Implications for Statistical Power of the Epidemiological Analyses. Health Physics. 2004;87(1):15–32.

Kueper BH, Wealthall GP, Smith JWN, Leharne SA, and Lerner DN. An Illustrated Handbook of DNAPL Transport and Fate in the Subsurface. Bristol, United Kingdom: Environment Agency R&D Publication 133; 2003 June.

Lahkim MB, Garcia LA, and Nuckols JR. Stochastic Modeling of Exposure and Risk in a Contaminated Heterogeneous Aquifer. 2: Application of Latin Hypercube Sampling. Environmental Engineering Science. 1999;16(5):329–343.

Lawrence SJ. 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 D: Properties of Degradation Pathways of Common Organic Compounds in Groundwater. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2007.

Mackay DM, and Cherry JA. Groundwater Contamination: Pump-and-Treat Remediation. Environmental Science and Technology. 1989;23(6):630–636.

Malcolm Pirnie, Inc. Corrosion Control Study, Hadnot Point & MCAS New River Water Systems, Marine Corps Base Camp Lejeune; 1999. Contract No.: N62470-92-D-7256.

Malcolm Pirnie, Inc. Range Final Environmental Vulnerability Assessment, Marine Corps Base Camp Lejeune. Washington, DC: Marine Corps Headquarters; 2009.

Marine Corps Base Camp Lejeune. ATSDR-DON Data Mining & Discovery Technical Work Group Meeting, 21–22 July 2010. Camp Lejeune, NC; 2010.

Maslia ML, editor. Expert Peer Review Panel Evaluating ATSDR's Water-Modeling Activities in Support of the Current Study of Childhood Birth Defects and Cancer at U.S. Marine Corps Base Camp Lejeune, North Carolina: Atlanta, March 28–29, 2005; *Prepared by* Eastern Research Group, Inc., Atlanta, GA; *Prepared for* Agency for Toxic Substances and Disease Registry (ATSDR), Atlanta, GA, 31 p., 4 app.

Maslia ML, editor. Expert Panel Assessing Methods and Analyses for Historical Reconstruction of Groundwater Resources and Distribution of Drinking Water at Hadnot Point, Holcomb Boulevard, and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina, April 29–30, 2009; *Prepared by* Eastern Research Group, Inc., Atlanta, GA; *Prepared for* Agency for Toxic Substances and Disease Registry (ATSDR), Atlanta, GA, 149 p.

Maslia ML, Sautner JB, and Aral MM. Analysis of the 1998 Water-Distribution System Serving the Dover Township Area, New Jersey: Field-Data Collection Activities and Water-Distribution System Modeling. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2000.

Maslia ML, Sautner JB, Aral MM, Gillig RE, Reyes JJ, and Williams RC. Historical Reconstruction of the Water-Distribution System Serving the Dover Township Area, New Jersey: January 1962–December 1996. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2001 October.

Maslia ML, Reyes RJ, Gillig RE, Sautner JB, Fagliano JB, and Aral MM. Public Health Partnerships Addressing Childhood Cancer Investigations: Case Study of Toms River, Dover Township, New Jersey, USA. International Journal of Hygiene and Environmental Health. 2005;2008:45–54.

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

Maslia ML, Aral MM, Faye RE, Suárez-Soto RJ, Sautner JB, Wang J, Jang W, Bove FJ, and Ruckart PZ. Reconstructing Historical Exposures to Volatile Organic Compound-Contaminated Drinking Water at a U.S. Military Base. Water Quality, Exposure and Health. 2009a;1(1):49–68.

Maslia ML, Suárez-Soto RJ, Wang J, Aral MM, Faye RE, Sautner JB, Valenzuela C, and Grayman WM. 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 I: Parameter Sensitivity, Uncertainty, and Variability Associated with Model Simulations of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2009b.

Maslia ML, Aral MM, Faye RE, Grayman WM, Suarez-Soto, RJ, Sautner JB, Anderson BA, Bove FJ, Ruckart PZ, and Moore SM. Comment on Article, Complexities in Hindcasting Models—When Should We Say Enough is Enough," by T. Prabhakar Clement. Ground Water. 2012;50(1):10–16.

Maslia ML, Suárez-Soto RJ, Sautner JB, Anderson BA, Jones LE, Faye RE, Aral MM, Guan J, Jang W, Telci IT, Grayman WM, Bove FJ, Ruckart PZ, and Moore, SM. Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina—Chapter A: Summary and Findings. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2013.

Massachusetts Department of Public Health (MDPH), Centers for Disease Control and Prevention (CDC), and Massachusetts Health Research Institute. Final Report of the Woburn Environmental and Birth Study. Boston, MA: Massachusetts Department of Public Health; 1996.

Masters GM. Introduction to Environmental Engineering and Science. 2nded: Prentice Hall; 1998.

MATLAB®, version R2012b (computer software), The MathWorks Inc., Natick, MA: 2012. [cited 2013 Janaury 23]; Available from *http://www.mathworks.com*

McKay MD, Beckman RJ, and Conover WJ. A Compariosn of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code. Technometrics. 1979;21(2):239–245.

McLaren/Hart-ChemRisk. Oak Ridge Dose Reconstruction Project Summary Report. Alameda, CA: McLaren/Hart-ChemRisk; 2000.

McSwain KB. Groundwater Level and Specific Conductance Monitoring at Marine Corps Base, Camp Lejeune, Onslow County, North Carolina, 2007–2008. Reston, VA: U.S. Geological Survey Open-File Report 2010-1103; 2010.

National Toxicology Program. Report on Carcinogens, Twelfth. Research Triangle Park, NC: U.S. Department of Health and Human Services, Public Health Service; 2011.

Naval Facilities Engineering Command. Atlantic Division, Survey of Potable Water Treatment Plants and Swimming Pools Water Treatment at Marine Corps Base, Camp Lejeune; 1986 (Camp Lejeune Water Document CLW #4938).

Naval Facilities Engineering Command. Master Plan, Camp Lejeune Complex, North Carolina. Norfolk, VA: Naval Facilities Engineering Command, Atlantic Division, Report 23511; 1988?; (contains ~1983 information).

NCDC, National Climatic Data Center. Precipitation and Evaporation Data for the Hoffman/Maysville Station, NC. Ashville, NC: National Climatic Data Center; 2008. [cited 2012 March 6]; Available from *http://www.ncdc.noaa.gov/oa/ncdc.html*

Newell CJ, Acree SD, Ross RR, and Huling SG. Light Nonaqueous Phase Liquids. EPA Ground Water Issue. Ada, OK: U.S. Environmental Protection Agency, R.S. Kerr Environmental Research Laboratory; 1995. Report No. EPA/540/S-95/500.

NJDHSS, New Jersey Department of Health and Senior Services. Case-Control Study of Childhood Cancers in Dover Township (Ocean County), New Jersey. Trenton, NJ: New Jersey Department of Health and Senior Services; 2003.

North Carolina Department of Environment and Natural Resources. Central Coastal Plan Capacity Use Investigation Report. Raleigh, NC: North Carolina Department of Environment and Natural Resources, Division of Water Resources; 1998.

O'Brien and Gere Engineers, Inc. Final Report, Contaminated Ground Water Study, Marine Corps Base Camp Lejeune, North Carolina, Hadnot Point Area; 1988. Contract No.: N62470-86-C-8740 (CERCLA Administrative Record File #417).

O'Brien and Gere Engineers, Inc. Preliminary Engineering Report, Product Recovery System Design, Hadnot Point Fuel Farm, Marine Corps Base Camp Lejeune, North Carolina; 1990. Contract No.: N62470-88-D-5825 (CERCLA Administrative Record File #382).

Pankow JF, and Cherry JA. Dense Chlorinated Solvents and Other DNAPLs in Groundwater: History, Behavior, and Remediation. Waterloo Press; 1996.

Pardalos PM, and Yatsenk V. Optimization and Control of Bilinear Systems: Theory, Algorithms, and Applications. Springer Science+Business Media; 2008.

Peavy HS, Rowe DR, and Tchobanoglous G. Environmental Engineering. MacGraw-Hill, Inc.; 1985.

Pontius FW, editor. Drinking Water Regulations and Health. Wiley-Interscience, John Wiley & Sons, Inc.; 2003.

Reif JS, Burch JB, Nuckols JR, Metzger L, Ellington D, and Anger KW. Neurobehavioral Effects of Exposure to Trichloroethylene Through a Municipal Water Supply. Environmental Research. 2003;93:248–258.

Rhea Engineers and Consultants, Inc. Technical Memorandum. IR O&M Summary for July 2011, Rhea Project No. 520, July 7, 2011a. Contract No. N40085-09-D-3237.

Rhea Engineers and Consultants, Inc. Technical Memorandum. IR O&M Summary for July 2011, Rhea Project No. 520, August 8, 2011b. Contract No. N40085-09-D-3237.

Richard Catlin and Associates, Inc. Leaking Underground Storage Tank Site Assessment Work Plan. Building 1601 Marine Corps Base Camp Lejeune, North Carolina; 1996. Contract No. N62470-93-D-4020. (UST Management Web Portal File #172).

Ricker JA. A Practical Method to Evaluate Ground Water Contaminant Plume Stability. Ground Water Monitoring & Remediation. 2008;28(4):85–94.

Rodenbeck SE, and Maslia ML. Groundwater Modeling and GIS to Determine Exposure to TCE at Tucson. Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management. 1998;2(2):53–61.

Rodenbeck SE, Sanderson LM, and Rene A. Maternal Exposure to Trichloroethylene in Drinking Water and Birth-Weight Outcomes. Archives of Environmental Health. 2000;55:188–194.

Ross SM. Introduction to Probability Models. Academic Press; 1997.

Rossman LA. EPANET 2 Users Manual. Cincinnati: U.S. Environmental Protection Agency, National Risk Management Research Laboratory; 2000 September. Report No.: EPA/600-R-00/057.

Rothman KJ, Greenland S, and Lash TL. Modern Epidemiology, 3rd edition. Lippincott Williams; 2008.

Sahmel J, Devlin D, Paustenbach D, Hollins D, and Gaffney S. The Role of Exposure Reconstruction in Occupational Human Health Risk Assessment: Current Methods and a Recommended Framework. Critical Reviews in Toxicology. 2010;40(9):799–843.

Saltelli A, Chan K, and Scott EM, editors. Sensitivity Analysis. Chichester, England: John Wiley & Sons, Ltd.; 2000.

Sautner JB, Maslia ML, Valenzuela C, Grayman WM, Aral MM, and Green JW Jr. Field Testing of Water-Distribution Systems at the U.S. Marine Corps Base Camp Lejeune, North Carolina, in Support of an Epidemiologic Study. Proceedings: World Environmental and Water Resources Congress; 2005 May 15–19, Anchorage, AK.

Sautner JB, Maslia ML, and Grayman WM. Storage Tank Mixing Models: Comparison of Tracer Data with Model Simulation. Proceedings: World Environmental and Water Resources Congress; 2007 May 15–19, Tampa, FL.

Sautner JB, Anderson BA, Suárez-Soto RJ, and Maslia ML. Descriptions and Characterizations of Data Pertinent to Water-Supply Well Capacities, Histories, and Operations—Supplement 1. In: Maslia ML, Suárez-Soto RJ, Sautner JB, Anderson BA, Jones LE, Faye RE, Aral MM, Guan J, Jang W, Telci IT, Grayman WM, Bove FJ, Ruckart PZ, and Moore SM. Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina—Chapter A: Summary and Findings. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2013a.

Sautner JB, Grayman WM, Telci IT, Maslia ML, and Aral MM. Field Tests, Data Analyses, and Simulation of the Distribution of Drinking Water with Emphasis on Intermittent Transfers of Drinking Water Between the Hadnot Point and Holcomb Boulevard Water-Distribution Systems—Supplement 8. In: Maslia ML, Suárez-Soto RJ, Sautner JB, Anderson BA, Jones LE, Faye RE, Aral MM, Guan J, Jang W, Telci IT, Grayman WM, Bove FJ, Ruckart PZ, and Moore SM. Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina—Chapter A: Summary and Findings. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2013b.

Schnoor JL. Environmental Modeling. New York: John Wiley & Sons, Inc.; 1996.

Schwille F. Dense Chlorinated Solvents in Porous and Fractured Media. Translated by Pankow, JF. Boca Raton: Lewis Publishers (CRC Press); 1988.

Singer PC. Trihalomethanes and Other By-Products Formed by Chlorination of Drinking Water. In: Uman MF, editor. Keeping Pace with Science and Engineering. Washington, DC: National Academy Press; 1993.

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Soil Survey Geographic (SSURGO) Database for Onslow County, North Carolina; 2009. [cited 2010 November 4]; Available from *http://soildatamart.nrcs.usda.gov*

Sonnenfeld N, Hertz-Picciotto I, and Kaye WE. Tetrachloroethylene in Drinking Water and Birth Outcomes at the U.S. Marine Corps Base at Camp Lejeune, North Carolina. American Journal of Epidemiology. 2001;154(10):902–908.

Sovereign Consulting Inc. Final Annual Groundwater Monitoring Report 2006–2007 (Building 900). Marine Corps Base Camp Lejeune, North Carolina. 2007. Contract Number: N62470-04-D-0205 (UST Management Web Portal File #900AMRFINAL2007).

Suárez-Soto RJ, Jones LE, and Maslia ML. Simulation of Three-Dimensional Groundwater Flow—Supplement 4. In: Maslia ML, Suárez-Soto RJ, Sautner JB, Anderson BA, Jones LE, Faye RE, Aral MM, Guan J, Jang W, Telci IT, Grayman WM, Bove FJ, Ruckart PZ, and Moore SM. Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina—Chapter A: Summary and Findings. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2013.

Telci IT, Sautner JB, Suárez-Soto RJ, Anderson BA, Maslia ML, and Aral MM. Development and Application of a Methodology to Characterize Present-Day and Historical Water-Supply Well Operations—Supplement 2. In: Maslia ML, Suárez-Soto RJ, Sautner JB, Anderson BA, Jones LE, Faye RE, Aral MM, Guan J, Jang W, Telci IT, Grayman WM, Bove FJ, Ruckart PZ, and Moore SM. Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina—Chapter A: Summary and Findings. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2013.

Tung Y-K and Yen B-C. Hydrosystems Engineering Uncertainty Analysis. McGraw-Hill; 2005.

U.S. Army Engineer Research and Development Center. Department of Defense Groundwater Modeling System (GMS), version 8. Vicksburg, MS: U.S. Army Corps of Engineers, Engineer Research and Development Center; 2008. [cited 2012 March 2]; Available from *http://chl.erdc.usace.army.mil/gms*

U.S. Department of Agriculture, Soil Conservation Service. Soil Survey of Onslow County, North Carolina; 1982.

U.S. Department of the Navy (DON) and Agency for Toxic Substances and Disease Registry (ATSDR). Camp Lejeune Data Mining Technical Workgroup Closeout Report. Atlanta, GA. 2012. [cited 2012 December 12]; Available from *http://www.atsdr.cdc.gov/sites/lejeune/index.html*

U.S. Environmental Protection Agency. Control of Trihalomethanes in Drinking Water. Final Rule. Federal Register 44:68624; 1979.

U.S. Environmental Protection Agency. Underground Motor Fuel Storage Tanks: A National Survey. Washington, DC: United States Environmental Protection Agency; 1986. Report No.: EPA-560/5-86-013.

U.S. Environmental Protection Agency. Causes of Release from UST Systems. Washington DC: United States Environmental Protection Agency; 1987. Report No.: EPA 510-R-92-702.

U.S. Environmental Protection Agency. Guidelines for Exposure Assessment. Washington, DC: U.S. Environmental Protection Agency, Risk Assessment Forum; 1992 March. Report No.: EPA 600-Z-92-001.

U.S. Environmental Protection Agency. Contaminant Specific Fact Sheets, Volatile Organic Chemicals—Technical Version; 1995. Report No.: EPA 811-F-95-004-T. [cited 2006 January 11]; Available from *http://www.epa.gov/safewater/dwh/t-voc.html*

U.S. Environmental Protection Agency. Guiding Principles for Monte Carlo Analysis. Washington, DC: United States Environmental Protection Agency; 1997 March. Report No.: EPA 630-R-97-001.

U.S. Environmental Protection Agency. Toxicological Review of Vinyl Chloride (CAS No. 75-01-4) in Support of Summary Information on the Integrated Risk Information System (IRIS); 2000. Report No.: EPA/635R-00/004. [cited 2012 April 9]; Available from *http://www.epa.gov/iris/toxreviews/1001tr.pdf*

U.S. Environmental Protection Agency. National Primary Drinking Water Standards; 2003. Report No.: EPA 816-F-03-016. [cited 2007 January 25]; Available from *http://www.epa.gov/water/*

U.S. Environmental Protection Agency. How to Evaluate Alternative Cleanup Technologies for Underground Storage Tank Sites—A Guide for Corrective Action Plan Reviewers. Washington, D.C.: U.S. Environmental Protection Agency; 2004. Report No.: EPA 510-B-95-007. [cited 2013 February 8]; Available from *http://www.epa.gov/swerust1/pubs/tums.htm*

U.S. Environmental Protection Agency. Guidelines for Carcinogen Risk Assessment; 2005. Report No.: EPA/630/P-03/001F. [cited 2012 February 16]; Available from *http://www.epa.gov/cancerguidelines*

U.S. Environmental Protection Agency. National Primary Drinking Water Regulations; 2009. Report No.: EPA 816-F-09-004. [cited 2012 July 28]; Available from *http://www.epa.gov/drink/contaminants/index.cfm*

U.S. Environmental Protection Agency. Toxicological Review of Trichloroethylene (CAS No. 79-01-6) in Support of Summary Information on the Integrated Risk Information System (IRIS); 2011. Report No.: EPA/635/R-09/011F. [cited 2012 February 17]; Available from *http://www.epa.gov/iris/toxreviews/0199tr/0199tr.pdf*

U.S. Environmental Protection Agency. Toxicological Review of Tetrachloroethylene (Perchloroethylene) (CASRN 127-18-4) in Support of Summary Information on the Integrated Risk Information System (IRIS); 2012. Report No.: EPA/635/R-08/011A. [cited 2012 February 16]; Available from *http://www.epa.gov/iris/toxreviews/0106tr.pdf*

UST Management Web Portal File, (file number and title vary and not consecutively available), provided to ATSDR in digital format by the Department of the Navy (Headquarters Marine Corps and Marine Corps Base Camp Lejeune) under terms of "For Official Use Only" (FOUO) documents, accessed 2010–2012.

Water and Air Research, Inc. Initial Assessment Study of Marine Corps Base Camp Lejeune, North Carolina, UIC-M67001; 1983. (CERCLA Administrative Record File #124).

Watson AD. Onslow County, A Brief History. North Carolina Division of Archives and History; 1995.

Weaver JW, Charbeneau RJ, Tauxe JD, and Provost JB. The Hydrocarbon Spill Screening Model (HSSM), Volume 1, Users Guide (Version 1.1, revised October 1996). Athens, GA: U.S. Environmental Protection Agency, Office of Research and Development; 1996.

Xu CG, He HS, Hu YM, Chang Y, Li XZ, and Bu RC. Latin Hypercube Sampling and Geostatistical Modeling of Spatial Uncertainty in a Spatially Explicit Forest Landscape Model Simulation. Ecological Modelling. 2005;185(2–4):255–269.

Zheng C. MT3DMS v5.3 Supplemental User's Guide. Technical Report to the U.S. Army Engineer Research and Development Center. Tuscaloosa, AL: Department of Geological Sciences, University of Alabama; 2010. [cited 2013 February 25]; Available from *http://hydro.geo.ua.edu/mt3d/mt3dms_v5_supplemental.pdf*

Zheng C, and Bennett GD. Applied Contaminant Transport Modeling, Second Edition. Wiley-Interscience; 2002.

Zheng C, and Wang PP. MT3DMS: A Modular Three-Dimensional Multi-Species Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems: Documentation and User's Guide. Vicksburg, MS: U.S. Army Engineer Research and Development Center; 1999. Report No.: SERDP-99.

Appendix A1. Summaries of Hadnot Point–Holcomb Boulevard chapter reports and supplemental information, U.S. Marine Corps Base Camp Lejeune, North Carolina

Summaries of Hadnot Point–Holcomb Boulevard (HPHB) chapter reports (A, B, C, and D) and supplemental information sections of Chapter A (Supplements 1–8) are described below. Electronic versions of each chapter report and each Chapter A supplement are on the computer disc, read-only memory (CD-ROM) media provided in the back pocket of the Chapter A report. The chapter reports and supplements will be made available on the ATSDR Camp Lejeune Web site at *http://www.atsdr.cdc.gov/sites/lejeune/index.html*.

Chapter A: Summary and Findings (Maslia et al. 2013—this report) provides both a summary of technical findings and detailed analyses of historical reconstruction of groundwater flow, contaminant fate and transport, and distribution of finished water within the Hadnot Point and Holcomb Boulevard water treatment plant (HPWTP and HBWTP, respectively) service areas. Contaminants of concern to the ATSDR health studies described in this report are tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene. Among the topics covered in this chapter are (1) the purpose of the HPHB study area historical reconstruction analysis, (2) review of contaminants of concern (volatile organic compounds [VOCs])for ATSDR health studies, (3) base-housing information and water-supply data (4) methods for reconstructing historical concentrations in finished water, which include data mining and contaminant-source identification and characterization, (5) application of numerical models and computational tools, (6) historical reconstruction analyses and results for the Hadnot Point Industrial Area (HPIA) and Hadnot Point landfill (HPLF) area, (7) reconstructed concentrations in finished water at the HPWTP, (8) analyses of intermittent transfers of contaminated finished water from the HPWTP to the Holcomb Boulevard family housing areas during years 1972–1985, and (9) selected bounding estimates of historical reconstruction results using sensitivity and uncertainty analyses. Historical reconstruction results summarized in Chapter A provide considerable evidence that concentrations of several contaminants of interest in finished water delivered by the HPWTP substantially exceeded current maximum contaminant levels (MCLs) during all or much of the epidemiological study period of 1968–1985. Included in this chapter report is a comprehensive table listing disparate information sources used to extract pertinent information and data that were needed to develop model input databases used to conduct historical reconstruction analyses. In this report, a CD-ROM is included that contains all chapter reports (A–D), Chapter A supplements (1–8), selected calibrated model input files, and reconstructed (simulated) concentrations at selected water-supply wells and in finished-water at the HPWTP and within the Holcomb Boulevard water-distribution system.

Chapter A–Supplement 1: Descriptions and Characterizations of Data Pertinent to Water-Supply Well Capacities, Histories, and Operations (Sautner et al. 2013a) provides specific documentation for 96 water-supply wells in terms of capacities, histories, and operations that operated during the period 1942–June 2008 and provided groundwater to the HPWTP and HBWTP. Hundreds of documents and reports were reviewed, and numerous discussions with former and current water treatment plant (WTP) operators took place. Notable information was recorded and analyzed for each specific water-supply well to determine the chronological record of a well's operation (well history) starting from the time the well was placed into service and ending with the time the well was abandoned. A listing of the documented historical well operations has been created for each water-supply well and is used to better understand how the Hadnot Point and Holcomb Boulevard water-distribution systems were historically operated. This information and data are used to assist with the reconstruction of historical monthly operations for each water-supply well when little or no information is available. Tabulated well histories from the 96 water-supply wells described in this Supplement 1 report were used to reconstruct historical monthly operations for water-supply wells. Information contained in Chapter A–Supplement 1 was necessary to conduct groundwater-flow and contaminant fate and transport modeling as part of the historical reconstruction process.

Chapter A–Supplement 2: Development and Application of a Methodology to Characterize Present-Day and Historical Water-Supply Well Operations (Telci et al. 2013) describes a methodology that is developed to estimate the historical monthly volume of groundwater pumped from water-supply wells in the HPHB study area. The available data on operational patterns of water-supply wells consist of the capacities of the wells, the operational state of the wells on a daily basis, and the volume of water delivered to the WTPs on daily and monthly bases. The overall operational timeframe of the Hadnot Point and Holcomb Boulevard water-distribution systems is divided into two periods: "present-day" (1998–2008) and "Reconstruction" (1942–1997). In Supplement 2, the present-day period is defined as the time during which daily water-supply well operational data are available. The reconstruction period is defined as the time when water-supply well operational data are limited or unavailable. The methodology is an efficient and effective way of integrating available data for present-day conditions (1998–2008) with the prediction process for the historical years (1942–1998). Results demonstrate that historical estimates of water-supply well operations using this methodology are reasonable, and

therefore, can be readily applied to groundwater-flow and contaminant fate and transport model simulations for the HPHB study area.

Chapter A–Supplement 3: Descriptions and Characterizations of Water-Level Data and Groundwater Flow for the Brewster Boulevard and Castle Hayne Aquifer Systems and the Tarawa Terrace Aquifer (Faye et al. 2013) provides summaries of the results of analyses of groundwater-level data and describes corresponding elements of groundwater flow such as vertical hydraulic gradients useful for groundwater-flow model calibration. Field data and theoretical concepts indicate that potentiometric surfaces within the study area are shown to resemble to a large degree a subdued replica of surface topography. Consequently, precipitation that infiltrates to the water table flows laterally from highland to lowland areas and eventually discharges to streams such as Northeast and Wallace Creeks and New River. Vertically downward hydraulic gradients occur in highland areas, resulting in the transfer of groundwater from shallow relatively unconfined aquifers to underlying confined or semi-confined aquifers. Conversely, in the vicinity of large streams such as Wallace and Frenchs Creeks, diffuse upward leakage occurs from underlying confined or semi-confined aquifers. Point water-level data indicating water-table altitudes, water-table altitudes estimated using a regression equation, and estimates of stream levels determined from a digital elevation model (DEM) and topographic maps were used to estimate a predevelopment water-table surface in the study area. Approximate flow lines along hydraulic gradients are shown on a predevelopment potentiometric surface map and extend from highland areas where potentiometric levels are greatest toward streams such as Northeast and Wallace Creeks. The distribution of potentiometric levels and corresponding groundwater-flow directions conform closely to related descriptions of the conceptual model.

Chapter A–Supplement 4: Simulation of Three-Dimensional Groundwater Flow (Suárez-Soto et al. 2013**)** provides detailed analyses of groundwater flow based on data and model simulations for the HPHB study area. Predevelopment (steady state) and transient three-dimensional groundwater-flow models were developed using MODFLOW-2005 (Harbaugh 2005). Multiple groundwater-flow models were necessary to describe both predevelopment and transient conditions, which focused on the HPIA and HPLF subdomain areas. The predevelopment model is characterized by a uniform finite-difference grid consisting of 300-ft × 300-ft cells. Transient models—one for the HPIA and one for the HPLF subdomain areas—were characterized by variably spaced finite-difference grids consisting of cells ranging in size from 300 ft × 300 ft to 50 ft × 50 ft—the 50-ft × 50-ft cells being necessary to meet fate and transport numerical modeling requirements. The variably spaced grid models were used to simulate local transient conditions and contaminant fate and transport in the HPIA and HPLF subdomain areas (Jones et al. 2013). All models consist of seven layers representing the Brewster Boulevard and Castle Hayne aquifer systems and Tarawa Terrace aquifer described by Faye (2012). The predevelopment calibration represents long-term average conditions, and transient simulations represent conditions occurring as a consequence of water-supply well operations. The 798 monthly stress periods were used to represent transient conditions during the period January 1942–June 2008. Model cells coincident with water-supply wells were assigned reconstructed pumpage values based on the methodology described in Telci et al. (2013).

Chapter A–Supplement 5: Theory, Development, and Application of Linear Control Model Methodology to Reconstruct Historical Contaminant Concentrations at Selected Water-Supply Wells (Guan et al. 2013) describes the development of an alternate modeling approach using a linear state-space representation of a contaminated aquifer system, designated in this Supplement 5 report as a linear control model (LCM). The LCM is used to reconstruct historical concentrations at water-supply wells. The LCM approach is substantially less resource-intensive and requires less effort in terms of model parameter identification and calibration than traditional (numerical) groundwater-flow and contaminant fate and transport modeling approaches. The mathematical development for the LCM approach is described in detail and then verified by using synthesized data from the numerical groundwater model developed for the Tarawa Terrace study area (Faye and Green 2007; Faye and Valenzuela 2007). The LCM (TechControl) is then applied to the HPLF to reconstruct the history of chlorinated solvent contamination at water-supply well HP-651; the well was shut down in early 1985 when chlorinated solvents were detected in the well. The LCM approach utilizes the historical operating schedule of water-supply well HP-651 in conjunction with post-shutdown (1985–2004) measured contaminant concentrations in groundwater to reconstruct the history of contaminants in the water-supply well prior to 1985.

Chapter A–Supplement 6: Source Characterization and Simulation of Fate and Transport of Selected Volatile Organic Compounds in the Vicinities of the Hadnot Point Industrial Area and Landfill (Jones et al. 2013) describes reconstruction (simulation) of historical concentrations of tetrachloroethylene (PCE), trichloroethylene (TCE), and benzene in finished water in the vicinities of the HPIA and the HPLF area. A contaminant fate and transport model was used to simulate contaminant migration from source locations through the groundwater system and to estimate monthly mean contaminant concentrations in water withdrawn from production wells in the vicinity of the HPIA and the HPLF area. The monthly mean contaminant concentrations were subsequently input to a mixing model to quantify monthly mean concentrations of the contaminants in finished water that supplied the housing areas and other facilities served by the HPWTP. Review of available records indicates that the earliest production wells began operation in the early 1940s, and contaminants leaked into the subsurface as early as the late 1940s. Concentrations of the contaminants were simulated using monthly intervals for the entire period of production-well operation from January 1942 through June 2008, the date of the most recently available

data. The applied and calibrated fate and transport models, described in Supplement 6, were based on the groundwater-flow models that are described in Suárez-Soto et al. (2013).

Chapter A–Supplement 7: Source Characterization and Simulation of the Migration of Light Nonaqueous Phase Liquids (LNAPLs) in the Vicinity of the Hadnot Point Industrial Area (Jang et al. 2013) describes (1) the migration potential and distribution of LNAPLs for several hypothetical scenarios, (2) the estimation of LNAPL volume based on field measurements of LNAPL thicknesses in the HPIA, and (3) the transport of dissolved contaminants within the HPIA. The analysis was carried out by using complex modeling of multiphase flow through pore spaces. The analysis of LNAPL flow delineated the migration and expansion of free-phase LNAPL plumes and the spatial variation in LNAPL saturation in the modeling domain with time. Based on available field data of LNAPL thickness from observation wells, the mass distribution and volume of LNAPLs in the subsurface at the HPIA were estimated using the TechNAPLVol model code. The computed LNAPL volume ranged from approximately 0.9 to 1.6 million gallons. The mass distribution (or saturation profile) of LNAPLs in the subsurface was used as the contaminant-source input for a fate and transport analysis of dissolved LNAPL components in groundwater at the HPIA. The TechFlowMP multiphase flow and multispecies contaminant transport model was used to simulate the dissolution and subsequent fate and transport of dissolved-phase benzene and xylenes in the HPIA.

Chapter A–Supplement 8: Field Tests, Data Analyses, and Simulation of the Distribution of Drinking Water with Emphasis on Intermittent Transfers of Drinking Water Between the Hadnot Point and Holcomb Boulevard Water-Distribution Systems (Sautner et al. 2013b) provides detailed information on the design of field tests conducted during 2004 to ascertain water-distribution system properties for Hadnot Point and Holcomb Boulevard. By using information and data gathered during the field tests, along with data provided by Camp Lejeune water utility staff, an extended period simulation model for water-distribution system hydraulics and water-quality dynamics was developed and calibrated using EPANET 2 (Rossman 2000). The calibrated EPANET 2 model of the Holcomb Boulevard water-distribution system was used in conjunction with Markov Chain analysis to estimate the concentrations of VOCs during the period 1972–1985. During this time, contaminated Hadnot Point finished water was intermittently provided to the Holcomb Boulevard housing areas. Within the Holcomb Boulevard housing area, except for the 8-day period of January 28–February 4, 1985, when the HBWTP was out of service, only TCE routinely exceeded its MCL during intermittent periods of connection with the Hadnot Point water-distribution system.

Chapter B: Geohydrologic Framework of the Brewster Boulevard and Castle Hayne Aquifer Systems and the Tarawa Terrace Aquifer (Faye 2012) provides detailed analyses and interpretations of well, borehole, and geophysical data used to develop the geohydrologic framework of the Brewster Boulevard and Castle Hayne aquifer systems and the Tarawa Terrace aquifer. The geometry and lithology of seven aquifers and related confining units are described in a series of sections, maps, and tables. Hydraulic characteristics, including hydraulic conductivity, transmissivity, storativity, and leakance parameters, are tabulated for several geohydrologic units. Where data density is sufficient, maps showing spatial distributions of hydraulic conductivity are included.

Chapter C: Occurrence of Selected Contaminants in Groundwater at Installation Restoration Program Sites (Faye et al. 2010) provides detailed accounting of the known occurrences of contaminants of concern (e.g., PCE and TCE) and their related degradation products in groundwater at selected Installation Restoration Program (IRP) sites within the HPWTP and HBWTB service areas at U.S. Marine Corp Base (USMCB) Camp Lejeune. These sites were identified by the Department of the Navy under the auspices of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Concentrations of these constituents in water-supply wells and in finished water of the HPWTP and HBWTP also are described. Collectively, these data provide most of the base of information necessary to construct the fate and transport models used to reconstruct (simulate) historical concentrations of contaminants within the water-distribution systems serviced by the HPWTP and HBWTP. Additionally, this report provides a detailed summary of historical information useful to ongoing and future exposure and health studies at USMCB Camp Lejeune, including a chronology of residential housing areas served by the HPWTP and HBWTP, annual operational capacities of the WTPs, locations and construction details of water-supply wells and water-quality monitor wells, and a summary and discussion of relevant environmental investigations at 18 IRP sites within the study area where contaminated groundwater occurred or was thought to have occurred.

Chapter D: Occurrence of Selected Contaminants in Groundwater at Above-Ground and Underground Storage Tank Sites (Faye et al. 2012) provides summaries of results of investigations at 64 designated Resource Conservation and Recovery Act (RCRA) study areas and emphasizes the occurrence and distribution of benzene, toluene, ethylbenzene, and xylenes (BTEX) components within groundwater of the areas served by the HPWTP and HBWTP. The volume of BTEX mass removed from the subsurface during remediation at selected locations within the service areas also is summarized. Results of analyses of samples collected in monitor wells at several CERCLA investigation study areas co-located with RCRA areas are also included herein. Concentrations of chlorinated alkenes such as PCE and TCE are also described where plumes of BTEX and chlorinated alkenes are mixed at several locations.

Appendix A2. Information sources used to extract model-related data for historical reconstruction analyses, U.S. Marine Corps Base Camp Lejeune, North Carolina

Appendix A2. Information sources used to extract model-specific data for historical reconstruction analyses, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[Refer to end of Appendix A2 for a list of abbreviations and acronyms]

Information source	Original media	Supplier or location of information source	Approximate quantity or size	Description	Date obtained (date of information)
ATSDR information requests and selected authored reports					
ATSDR information request, July 11, 2003	CD–ROM	Camp Lejeune	CD–ROMs with numerous files	Final Basewide Remediation Assessment Groundwater Study (Baker 1998a); GIS data for Camp Lejeune; historical water-supply well data from wellhead management program study (Geophex Ltd. 1991); wellhead protection plan update (AH Environmental Consultants 2002); historical water treatment plant booster pump information (Henry Von Oesen and Associates, Inc. 1979)	Aug. 2003 (varies)
ATSDR information request, 2004	CD–ROM, DVD	Camp Lejeune	About 25 gigabytes	Natural color digital orthophotography; data layers maintained in the integrated geographic information repository (IGIR) master database, Feb. 2004; TIFF files	Nov. 2004 (Feb. 2004)
ATSDR information request, 2005	Paper	Camp Lejeune	12 pages	Documentation for startup of Holcomb Boulevard water treatment plant; acquisition data form, April 1973; plant account record card, July 1990; Newspaper (Globe) article, August 1972; Command chronology, July–Dec 1972	Sept. 2005 (June–Dec. 1972)
ATSDR information request, Dec. 1, 2005	CD–ROM	Camp Lejeune	3 CD–ROMs	VOC impacted drinking water document database (CLW database); TCE/PCE sample result summary spreadsheet; JTC historical laboratory analytical results (subset of CLW database, about 34 files)	Dec. 2005 (1980–1986)
ATSDR information request, 2006	CD–ROM, DVD	Camp Lejeune	1 CD–ROM, 1 DVD	Natural color digital orthophotography of entire base, Feb. 2004, MrSID image format; color infrared color digital orthophotography of entire base, Mar. 1996, MrSID image format	Sept. 2006 (Nov. 2004; Mar. 1996)
ATSDR information request, May 2009	CD–ROM, DVD, paper	Camp Lejeune	CD–ROM, DVD, paper	186 documents (PDFs) from the Camp Lejeune Historic Drinking Water Consolidated Document Repository (f/k/a BAH files); 31 sets of contract drawings from Public Works vault; Raw Water Master Plan (AH Environmental Consultants 2005); Draft (2009) USGS groundwater- level report, (published as McSwain 2010); Permit to Construct Municipal Solid Waste Landfill (Dewberry and Davis 1995); Evaluation of Cogdell's Creek (CH2M HILL, Inc. 1998); Corrosion Control Study, Hadnot Point and Marine Corps Air Station (MCAS) New River (Malcolm Pirnie 1999)	July 2009 (varies)
ATSDR information request, Nov. 2009	CD–ROM	Camp Lejeune	1 CD–ROM (about 160 megabytes)	Site Management Plans for 2007, 2008, 2009, and 2010 (CH2M HILL 2007a,b, 2008, 2009)	Dec. 2009 (Apr. 2007–Aug. 2009)
ATSDR information request, Apr. 2011	CD–ROM	USEPA, Region IV	57 files, 19 megabytes	JTC Laboratory analyses on Naval samples	Sept. 2011 (Feb. 1985–Apr. 1986)

Appendix A2. Information sources used to extract model-specific data for historical reconstruction analyses, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[Refer to end of Appendix A2 for a list of abbreviations and acronyms]

Information source	Original media	Supplier or location of information source	Approximate quantity or size	Description	Date obtained (date of information)
ATSDR information requests and selected authored reports—Continued					
Hadnot Point–Holcomb Boulevard reports	Paper; electronic (PDF)	ATSDR *http://www.atsdr.cdc.gov/sites/lejeune/watermodeling.html*	Three reports (Chapters B, C, and D), about 40 megabytes	Analyses and interpretations of data to develop geohydrologic framework of the Brewster Boulevard and Castle Hayne aqufier systems and the Tarawa Terrace aquifer; analyses of selected contaminants within the HPWTP and HBWTP service areas and vicinities at Camp Lejeune; among contaminants of interest in this report series, PCE, TCE, 1,2-tDCE, benzene, and vinyl chloride	Oct. 2010, Jan. 2012, Dec. 2012 (1940s–2008)
Public Health Assessment for ABC One-Hour Cleaners	Paper	ATSDR records room and LAN	1 folder in records room	Administrative records for 1990 public health assessment; 1996 site review and update also available	Aug. 1990; Sept. 1996 (Aug. 1990; Sept. 1996)
Public Health Assessment for Camp Lejeune	Paper	ATSDR records room and LAN	52 folders in records room and numerous electronic files	Administrative records for 1997 public health assessment	Aug. 1997 (Aug. 1997)
Tarawa Terrace reports	Paper; electronic (PDF)	ATSDR *http://www.atsdr.cdc.gov/sites/lejeune/watermodeling.html*	Executive summary report and 9 report volumes (Chapters A–I); about 100 megabytes	Analyses of the Tarawa Terrace drinking-water system at Camp Lejeune that was contaminated with PCE and its degradation by-products from the nearby, off-base, ABC One-Hour Cleaners	2007–2009 (1950s–1994)
Databases and information portals					
ABC One-Hour Cleaners site reports	Paper; electronic (PDF)	USEPA Web site: *http://www.epa.gov/*	About 25 electronic files (PDF), 125 megabytes	Reports primarily related to CERCLA activities at ABC One-Hour Cleaners site; files vary in size from a few pages to several hundred pages	2003–2007 (1986–2007)
Camp Lejeune Historic Drinking Water Consolidated Document Repository (CLHDW CDR)	Electronic (PDF)	Camp Lejeune	514 pages (index only); about 8,000–10,000 documents	The index (f/k/a BAH index) is a list of documents compiled from a base-wide search of buildings and documents; a single index entry may reference several boxes to tens of boxes of documents and information records	Apr. 2009 (varies)
Camp Lejeune Historic Drinking Water Consolidated Document Repository (CLHDW CDR)	Electronic (PDF)	Camp Lejeune	7,403 files, 158 gigabytes	Documents, handwritten notes, reports, lab analyses, water-supply data, compiled from a base-wide search of buildings and documents; a single file may reference several one-page documents or several hundred pages of information and records	Mar. 2011 (varies)
Camp Lejeune water document (CLW files)	CD–ROM	Camp Lejeune	About 574 megabytes; about 1,100 files	Documents, handwritten notes, reports, lab analyses primarily related to water supply, distribution, and water-quality issues; files vary in size from a few pages to several hundred pages	Dec. 2005 (varies)
CERCLA administrative record for ABC One-Hour Cleaners	Paper and electronic (PDF)	USEPA Web site: *http://www.epa.gov/*	About 100 files listed on CERCLA administrative record index	Documents, handwritten notes, and reports primarily related to CERCLA activities at ABC One-Hour Cleaners site; files vary in size from a few pages to several hundred pages	2003–2007 (1986–1994)

Appendix A2. Information sources used to extract model-specific data for historical reconstruction analyses, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[Refer to end of Appendix A2 for a list of abbreviations and acronyms]

Information source	Original media	Supplier or location of information source	Approximate quantity or size	Description	Date obtained (date of information)
Databases and information portals—Continued					
CERCLA administrative record for Camp Lejeune	Hard drive (provided by Camp Lejeune)	Baker Engineers, Inc., Web portal; *http://www.bakerenv.com/camplejeune_irp*	About 15 gigabytes; about 3,700 files	Documents, handwritten notes, and reports primarily related to installation restoration program sites at Camp Lejeune; files vary in size from a few pages to several hundred pages	Jan. 2006 (varies)
Environmental Management Division (EMD) document index	Electronic (MS Excel; PDF)	Camp Lejeune	Hundreds to thousands of reports and documents	Reports and documents related to base IRP, wastewater, drinking water, surface water, groundwater, indoor air quality, vapor intrusion, solid waste, landfill activities, environmental conservation, compliance, wellhead management, etc.	2003–2010 (varies)
Terrabase—IRP sites	CD–ROM (MS Access)	Catlin/Camp Lejeune	About 1.3 million records of analytical data	Analytical data associated with base IRP provided to Catlin by Camp Lejeune; IRP data derived from other source documents	Apr. 2010 (1984–2010)
Terrabase—UST sites	CD–ROM (MS Access)	Catlin/Camp Lejeune	About 700,000 records of analytical data	Time frame of data is 1984 to 2005. Database developed from database provided to Catlin by Camp Lejeune during November 2005; contains analytical data for UST sites	Mar. 2010 (1984–2005)
UST files	Electronic (Web portal)	Camp Lejeune; Catlin Engineers and Scientists *http://lejeune.Webmainframe.com* (proprietary)	1,535 files	Information, site data, meeting minutes, monitoring data, etc., related to all UST sites and activities at Camp Lejeune; files vary in size from a few pages to exceeding 1,000 pages	Mar. 2010 (1986–2009)
Drinking-water system information and data					
AH Environmental reports on drinking-water systems	Paper	Camp Lejeune	6 reports, about 250 pages	Cataloging and information gathering of drinking-water systems at Camp Lejeune; all reports by AH Environmental Consultants: (1) Long Term Water System Master Plan (Dec. 2001), (2) Wellhead Protection Plan—2002 Update (Aug. 2002), (3) Water Distribution System Modeling Support (Aug. 2004), (4) ATSDR Support—Estimation of VOC Removal (Dec. 2004), (5) Meter Installation Work Plan (Dec. 2004), and Raw Water Master Plan (March 2005)	Aug. 2003–Dec. 2005 (2001–2005)
Golf course watering information	Paper	Camp Lejeune	5 electronic files	Scanned images (PDFs and TIFFs) of golf course sprinkler locations and information	Sept. 2010 (Mar. 1969; Aug. 1991; June 1993)
Pump rating curves	Paper	Camp Lejeune	4 pages	Pump rating curves for finished water pumps at Hadnot Point and Holcomb Boulevard water treatment plants	Mar. 2004 (~1985?)

Appendix A2. Information sources used to extract model-specific data for historical reconstruction analyses, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[Refer to end of Appendix A2 for a list of abbreviations and acronyms]

Information source	Original media	Supplier or location of information source	Approximate quantity or size	Description	Date obtained (date of information)
Drinking-water system information and data—Continued					
Survey of selected water-distribution system locations	Electronic (MS Excel)	U.S. Geological Survey, North Carolina Water Science Center	27 fire hydrants and 7 water-storage tanks	Horizontal and vertical survey data for selected hydrants and water-storage tanks	May–July 2004 (May–July 2004)
Survey of selected water-distribution system locations	Electronic (MS Excel)	Parker and Associates (subcontractor to Eastern Research Group, Inc.)	56 fire hydrants, 21 monuments, and 6 water-storage tanks	Horizontal and vertical survey data for selected hydrants and water-storage tanks	Oct. 2004 (Oct. 2004)
Water treatment plant flow data	CD–ROM	Camp Lejeune	About 100 megabytes	2-minute SCADA data for various times during 2004–2005	2004–2007 (Mar. 2004–Sept. 2005)
Water treatment plant flow data	Electronic (MS Excel); paper	Camp Lejeune	About 15 megabytes	Daily and monthly flows from water treatment plants; 1995–1999 in paper format; 2000–2005 in electronic format	2004–2009 (1999–2005)
Water utility maps	CD–ROM; paper	Camp Lejeune	About 100–150 files, 500 megabytes	Historical (1956–1987) water utility maps, scanned in as TIFFs, showing water-distribution systems aboard Camp Lejeune	July 2006 (1956–1987)
Water utility and housing maps	CD–ROM	Camp Lejeune	About 500 files, 525 megabytes	Historical (1940s and 1950s) water utility and housing maps, scanned in as TIFFs, 50-ft and 500-ft scales	Oct. 2003 (1940s–1950s)
Water plant log books	Paper	Camp Lejeune	About 2,100 pages	CLW files 6610.pdf–8761.pdf; handwritten entries in water utility log books containing information on mechanical repairs, water-supply operations, water-quality issues, and customer contacts and complaints	Dec. 2005 (varies)
Water-supply wells capacity data	Paper	Camp Lejeune	About 110 wells	Historical and present-day notes, information and data on operations and capacity histories of Tarawa Terrace, Holcomb Boulevard, and Hadnot Point water-supply wells	Aug. 2003–Aug. 2010 (1940s–2010)
Water-supply well operational data	CD–ROM	Camp Lejeune	10,000 scanned pages	Ten years of daily records, 1999–2008, indicating water-supply well on-off cycling operations—handwritten entries	2009 (1999–2008)
Housing records and information					
Housing maps	Paper	Camp Lejeune	About 10 maps (sheets)	Paper maps that show housing units, addition of housing units, and estimated number of housing units	Date unknown (1940s–1990s)
Housing records	Paper	Camp Lejeune	About 90,000 records	Camp Lejeune housing records used for identifying enlisted and officer personal housing locations; obtained for small for gestational age study (ATSDR 1998)	About 1994 (1950s–1995)

Appendix A2. Information sources used to extract model-specific data for historical reconstruction analyses, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[Refer to end of Appendix A2 for a list of abbreviations and acronyms]

Information source	Original media	Supplier or location of information source	Approximate quantity or size	Description	Date obtained (date of information)
Map information and data					
Airborne laser digital imagery; spatial data, Onslow County, NC	DVD	Spectrum Mapping Corporation, North Carolina	44 DVDs (about 170 gigabytes)	Digital orthophotographs of Onslow County, North Carolina	Nov. 2004 (Feb. 2003?)
AutoCAD files	CD–ROM	Camp Lejeune	About 100 megabytes; 70 files	Quadrangle maps of Camp Lejeune containing features such as topography, utility lines, wastewater and water-distribution systems, housing locations, etc.	Oct. 2003 (1996)
Camp Lejeune survey control data	Paper	Camp Lejeune	1 report (85 pages)	Report on geodetic survey to upgrade and update horizontal control aboard U.S. Marine Corps Base Camp Lejeune	2005 (Sept. 1984)
Digital elevation model (DEM) data	DVD	U.S. Geological Survey, North Carolina Water Science Center	1.9 gigabytes	LIDAR-derived DEM data for Camp Lejeune area, 20-ft and 5-ft grids; obtained from the NC Flood Mapping Program	Jan. 2004; Aug. 2010 (May 31, 2002)
Digital topographic contour data	CD–ROM	U.S. Geological Survey, North Carolina Water Science Center	650 megabytes	2-ft contours created from the 20-ft LIDAR-derived DEM, available from the NC Flood Mapping Program; projection is NC State Plane, NAD 83, units feet	Feb. 2004 (May 31, 2002)
Geographic information system files	CD–ROM; DVD	Camp Lejeune	Several dozen CD–ROMs and DVDs	Installation geospatial information and historical satellite imagery files	Aug. 2003–July 2009 (1938–June 2009)
Soil Survey Geographic (SSURGO) database for Onslow County, North Carolina	Electronic	Natural Resources Conservation Service, United States Department of Agriculture *http://soildatamart.nrcs.usda.gov*	1.6 megabytes	Georeferenced digital map data and tabular data of soils and attribute data for Onslow County, NC, provided in ESRI Arcview shapefile format	Nov. 2010 (Sept. 2003–June 2009)
North Carolina documents and reports					
Central Coastal Plain Capacity Use Investigation Report	Electronic (PDF)	NCDENR, Division of Water Resources	1 report (24 pages)	Report describing the central coastal plain capacity use area under the 1967 Water Use Act (NCDENR 1998)	Nov. 2003 (Nov. 1998)
Detailed soil maps for Onslow County, NC	CD–ROM	North Carolina Center for Geographic Information and Analysis	52 megabytes	Detailed digital soils maps for Onslow County, North Carolina	Apr. 2005 (2003–2004)
North Carolina water-supply plan	Electronic (PDF)	North Carolina Department of Environment and Natural Resources (NCDENR)	1 report and 20 appendixes (about 150 pages)	Compilation of more than 500 water-supply plans developed by local government water systems to assess water-supply needs over the next 20 years; report dated January 2001 and based on local water-supply plans developed during 1998 and 1999	Nov. 2003 (1998–1999)

Appendix A2. Information sources used to extract model-specific data for historical reconstruction analyses, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[Refer to end of Appendix A2 for a list of abbreviations and acronyms]

Information source	Original media	Supplier or location of information source	Approximate quantity or size	Description	Date obtained (date of information)
North Carolina documents and reports—Continued					
State of North Carolina Records	CD–ROM, DVD, paper	NCDENR and historical archives in Raleigh and Wilmington[1]	5 CD–ROMs, 1 DVD, (historical files unknown)	Historical and present-day water-supply information; water-supply well construction information; site information for Hadnot Point fuel farm (IR site 22) and Hadnot Point Industrial Area (IR site 78)	Mar. 2004; June 2010; Aug. 2010 (1980–2007)
State of North Carolina vital statistics data files	Paper	NCDENR	1 report (116 pages)	Documentation of North Carolina vital statistic data files available for public use	Unknown (Oct. 1993)
Miscellaneous information, data, and reports					
Community group Web sites	Electronic	*http://www.watersurvivors.com* *http://www.tftptf.com/*	N/A	Former marine's and citizen's Web sites containing miscellaneous information and numerous Camp Lejeune documents (current and historical). Historical obtained from the U.S. Marine Corps through FOIA requests	N/A (N/A)
National Climatic Data Center (NCDC)	Electronic	NCDC, Asheville, NC *http://www.ncdc.noaa.gov/oa/ncdc.html*	6 files, about 6 megabytes	Precipitation and evaporation data for the Hoffman/Maysville station, NC	Dec. 2008 (Dec. 1945–Dec. 2008)
National Geophysical Data Center (NGDC)	Electronic	NGDC, Boulder, CO *http://www.ngdc.noaa.gov*	4 files, about 600 kilobytes	Bathymetry survey data for New River area of Camp Lejeune, NC; 5 surveys: H04697 (1927), H05277 (1933), H05301 (1933), H05302 (1933), and H09882 (1980)	Dec. 2008 (1927, 1933, 1980)
Onslow County, NC Soil Survey	Paper	U.S. Department of Agriculture, Soil Conservation Service	1 report (152 pages)	Information that can be used for land-planning programs in Onslow County; report contains predictions of soil behavior for selected land uses	May 2003 (1982)
Specific DON and USMC reports	CD–ROM; electronic (PDF); paper	Camp Lejeune	10–15 volumes	Base Master Plans for 1972 (CERCLA Administrative Record File #0368) and 1988 (NAVFAC 1988?); Water Conservation Study (ECG Inc. 1999); Site Management Plans 2005–2011 (CH2M HILL and Baker Environmental, Inc. 2005; CH2M HILL 2006, 2007a, 2007b, 2008, 2009, 2010); Range Environmental Vulnerability Assessment report (Malcolm Pirnie 2009); Vapor Intrusion report (AGVIQ–CH2M HILL 2009)	2005–2010 (1984–2009)
Technical Memoranda	Electronic (PDF)	Camp Lejeune	Several electronic files	SWMU 350, IR site 88, Area of Potential Concern reports 9, 10, and 11	May 2010 (Mar.–May 2010)
U.S. Geological Survey open files and reports	Paper	USGS, North Carolina Water Science Center, Raleigh	Several hundred to thousand pages; published reports	Files on well construction, well locations, and water use at Camp Lejeune; published reports on Camp Lejeune	Mar. 2004 (1940s–1987)
Vapor intrusion activities	Electronic (PDF); paper	USEPA; NAVFAC (Camp Lejeune)	Several reports including one 6-volume report	Reports describing vapor intrusion activities at ABC One-Hour Cleaners, Tarawa Terrace Elementary School, and Camp Lejeune (Mainside)	2007–2009 (2007–2009)

[1] In searching the historical archives in Raleigh, North Carolina, information contained in files folders dated 1969–1989 were missing.

Appendix A2. Information sources used to extract model-specific data for historical reconstruction analyses, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[Refer to end of Appendix A4 for a list of abbreviations and acronyms]

List of abbreviations and acronyms:

1,2-tDCE, *trans*-1,2-dichloroethylene
ATSDR, Agency for Toxic Substances and Disease Registry
BAH, Booze Allen Hamilton
Catlin, Richard Catlin and Associates, Inc. or Catlin Engineers and Scientists (see Rerference Section)
CD–ROM, computer disc, read-only memory
CERCLA, Comprehensive Environmental Response, Compensation, and Liability Act of 1980
CLW, Camp Lejeune water document
DEM, digital elevation model
DON, Department of the Navy
DVD, digital video disc
ESRI, Environmental Systems Research Institute
f/k/a, formerly known as
FOIA, Freedom of Information Act
ft, foot
GIS, geographic information system
HBWTP, Holcomb Boulevard water treatment plant
HPWTP, Hadnot Point water treatment plant
IGIR, integrated geographic information repository
IRP, Installation Restoration Program
JTC, JTC Environmental Consultants, Inc. (see Reference Section)
LAN, local area network
LIDAR, line detection and ranging
MS, Microsoft, Excel, and Access are either registered trademarks or trademarks of Microsoft Corporation in the United States and/or other countries
N/A, not available
NAD 83, North American Datum of 1983
NAVFAC, Naval Facilities Engineering Command
NC, North Carolina
NCDC, National Climatic Data Center
NCDENR, North Carolina Department of Environment and Natural Resources
NGDC, National Geophysical Data Center
PCE, tetrachloroethylene
PDF, portable document file format
PHA, public health assessment
SCADA, supervisory control and data acquisition
SWMU, solid waste management unit
TCE, trichloroethylene
TIFF, tagged image file format
USEPA, U.S. Environmental Protection Agency
USGS, U.S. Geological Survey
USMC, U.S. Marine Corps
UST, underground storage tank
VOC, volatile organic compound

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
1–6	Jan. 1942–June 1942	—	—	—	—	—	—	—	—	—	—	—	—
7–114	July 1942–June 1951	—	—	0	0	0	—	—	—	—	0	0	0
115	July 1951	—	—	0	1	0	—	—	—	—	0	0	0
116	Aug. 1951	—	—	0	2	0	—	—	—	—	0	0	0
117	Sept. 1951	—	—	0	4	0	—	—	—	—	0	0	0
118	Oct. 1951	—	—	0	5	0	—	—	—	—	0	0	0
119	Nov. 1951	—	—	0	9	0	—	—	—	—	0	0	0
120	Dec. 1951	—	—	0	12	0	—	—	—	—	0	0	0
121	Jan. 1952	—	—	0	18	0	—	—	—	—	0	0	0
122	Feb. 1952	—	—	0	23	0	—	—	—	—	0	0	0
123	Mar. 1952	—	—	0	27	0	—	—	—	—	0	0	0
124	Apr. 1952	—	—	0	34	0	—	—	—	—	0	0	0
125	May 1952	—	—	0	42	0	—	—	—	—	0	0	0
126	June 1952	—	—	0	49	0	—	—	—	—	0	0	0
127	July 1952	—	—	0	58	0	—	—	—	—	0	0	0
128	Aug. 1952	—	—	0	71	0	—	—	—	—	0	0	0
129	Sept. 1952	—	—	0	81	0	—	—	—	—	0	0	0
130	Oct. 1952	—	—	0	92	0	—	—	—	—	0	0	0
131	Nov. 1952	—	—	0	106	0	—	—	—	—	0	0	0
132	Dec. 1952	—	—	0	120	0	—	—	—	—	0	0	0
133	Jan. 1953	—	—	0	136	0	—	—	—	—	0	0	0
134	Feb. 1953	—	—	0	148	0	—	—	—	—	0	0	0
135	Mar. 1953	—	—	0	157	0	—	—	—	—	0	0	0
136	Apr. 1953	—	—	0	170	0	—	—	—	—	0	0	0
137	May 1953	—	—	0	181	0	—	—	—	—	0	0	0
138	June 1953	—	—	0	191	0	—	—	—	—	0	0	0
139	July 1953	—	—	0	201	0	—	—	—	—	0	0	0
140	Aug. 1953	—	—	0	218	0	—	—	—	—	0	0	0
141	Sept. 1953	—	—	0	229	0	—	—	—	—	0	0	0
142	Oct. 1953	—	—	0	238	0	—	—	—	—	0	0	0
143	Nov. 1953	—	—	0	252	0	—	—	—	—	0	0	0
144	Dec. 1953	—	—	0	264	0	—	—	—	—	0	0	0
145	Jan. 1954	—	—	0	275	0	—	—	—	—	0	0	0
146	Feb. 1954	—	—	0	283	0	—	—	—	—	0	0	0
147	Mar. 1954	—	—	0	287	0	—	—	—	—	0	0	0
148	Apr. 1954	—	—	0	296	0	—	—	—	—	0	0	0
149	May 1954	—	—	0	303	0	—	—	—	—	0	0	0
150	June 1954	—	—	0	311	0	—	—	—	—	0	0	0

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2- dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Handot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
151	July 1954	—	—	0	320	0	—	—	—	—	0	0	0
152	Aug. 1954	—	—	0	334	0	—	—	—	—	0	0	0
153	Sept. 1954	—	—	0	346	—	—	—	—	—	0	0	—
154	Oct. 1954	—	—	0	356	—	—	—	—	—	0	0	—
155	Nov. 1954	—	—	0	375	—	—	—	—	—	0	0	—
156	Dec. 1954	—	—	0	388	—	—	—	—	—	0	0	—
157	Jan. 1955	—	—	0	403	—	—	—	—	—	0	0	—
158	Feb. 1955	—	—	0	413	—	—	—	—	—	0	—	—
159	Mar. 1955	—	—	0	419	—	—	—	—	—	0	—	—
160	Apr. 1955	—	—	0	433	—	—	—	—	—	0	—	—
161	May 1955	—	—	0	443	—	—	—	—	—	1	—	—
162	June 1955	—	—	0	453	—	—	—	—	—	1	—	—
163	July 1955	—	—	0	464	0	—	—	—	—	1	0	0
164	Aug. 1955	—	—	0	484	0	—	—	—	—	1	0	0
165	Sept. 1955	—	—	0	514	0	—	—	—	—	1	0	0
166	Oct. 1955	—	—	0	524	0	—	—	—	—	1	0	0
167	Nov. 1955	—	—	0	532	1	—	—	—	—	1	0	0
168	Dec. 1955	—	—	0	537	1	—	—	—	—	1	0	0
169	Jan. 1956	—	—	0	543	1	—	—	—	—	1	0	0
170	Feb. 1956	—	—	0	547	1	—	—	—	—	1	0	0
171	Mar. 1956	—	—	1	547	1	—	—	—	—	1	0	0
172	Apr. 1956	—	—	1	548	1	—	—	—	—	1	0	0
173	May 1956	—	—	1	552	1	—	—	—	—	1	0	0
174	June 1956	—	—	1	554	1	—	—	—	—	1	0	0
175	July 1956	—	—	1	557	2	—	—	—	—	2	—	0
176	Aug. 1956	—	—	1	565	2	—	—	—	—	2	—	0
177	Sept. 1956	—	—	1	571	2	—	—	—	—	2	—	1
178	Oct. 1956	—	—	1	576	2	—	—	—	—	2	—	1
179	Nov. 1956	—	—	1	584	2	—	—	—	—	2	—	1
180	Dec. 1956	—	—	1	588	3	—	—	—	—	2	—	1
181	Jan. 1957	—	—	1	596	3	—	—	—	—	2	—	1
182	Feb. 1957	—	—	1	598	3	—	—	—	—	2	—	1
183	Mar. 1957	—	—	1	598	4	—	—	—	—	2	—	1
184	Apr. 1957	—	—	1	602	4	—	—	—	—	3	—	1
185	May 1957	—	—	1	605	4	—	—	—	—	3	0	1
186	June 1957	—	—	1	608	5	—	—	—	—	3	0	1
187	July 1957	—	—	1	609	5	—	—	—	—	3	0	1
188	Aug. 1957	—	—	2	613	5	—	—	—	—	3	0	1
189	Sept. 1957	—	—	2	619	6	—	—	—	—	3	0	1
190	Oct. 1957	—	—	2	619	6	—	—	—	—	3	0	1
191	Nov. 1957	—	—	2	627	7	—	—	—	—	4	0	1
192	Dec. 1957	—	—	2	631	7	—	—	—	—	4	0	1

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2- dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Handot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
193	Jan. 1958	—	—	2	637	7	—	—	—	—	4	0	1
194	Feb. 1958	—	—	2	639	8	—	—	—	—	4	0	1
195	Mar. 1958	—	—	2	638	8	—	—	—	—	4	0	2
196	Apr. 1958	—	—	2	640	9	—	—	—	—	5	0	2
197	May 1958	—	—	2	642	10	—	—	—	—	5	0	2
198	June 1958	—	—	2	643	10	—	—	—	—	5	0	2
199	July 1958	—	—	3	644	11	—	—	—	—	5	0	2
200	Aug. 1958	—	—	3	646	11	—	—	—	—	5	0	2
201	Sept. 1958	—	—	3	650	12	—	—	—	—	6	0	2
202	Oct. 1958	—	—	3	651	13	—	—	—	—	6	0	2
203	Nov. 1958	—	—	3	656	14	—	—	—	—	6	0	2
204	Dec. 1958	—	—	3	657	14	—	—	—	—	6	0	2
205	Jan. 1959	—	—	3	658	15	—	—	—	—	7	0	2
206	Feb. 1959	—	—	3	658	15	—	—	—	—	7	0	2
207	Mar. 1959	—	—	3	655	16	—	—	—	—	7	0	2
208	Apr. 1959	—	—	3	654	17	—	—	—	—	7	0	2
209	May 1959	—	—	4	653	18	—	—	—	—	8	0	2
210	June 1959	—	—	4	650	18	—	—	—	—	8	0	2
211	July 1959	—	—	4	649	19	—	—	—	—	8	0	2
212	Aug. 1959	—	—	4	650	20	—	—	—	—	8	0	2
213	Sept. 1959	—	—	4	651	21	—	—	—	—	9	0	2
214	Oct. 1959	—	—	4	648	22	—	—	—	—	9	0	2
215	Nov. 1959	—	—	4	652	23	—	—	—	—	9	0	2
216	Dec. 1959	—	—	4	652	24	—	—	—	—	10	0	2
217	Jan. 1960	—	—	4	654	25	0	—	—	—	10	0	3
218	Feb. 1960	—	—	4	652	26	0	—	—	—	10	0	3
219	Mar. 1960	—	—	5	647	27	0	—	—	—	10	0	3
220	Apr. 1960	—	—	5	645	27	0	—	—	—	11	0	3
221	May 1960	—	—	5	643	28	1	—	—	—	11	0	3
222	June 1960	—	—	5	639	29	2	—	—	—	11	0	3
223	July 1960	—	—	5	640	30	3	—	—	—	11	0	3
224	Aug. 1960	—	—	5	638	31	6	—	—	—	12	0	3
225	Sept. 1960	—	—	5	637	32	9	—	—	—	12	0	3
226	Oct. 1960	—	—	5	632	33	14	—	—	—	12	0	3
227	Nov. 1960	—	—	5	632	33	19	—	—	—	13	0	3
228	Dec. 1960	—	—	5	630	34	25	—	—	—	13	0	3

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2- dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Handot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
229	Jan. 1961	—	—	5	629	34	32	—	—	—	14	0	3
230	Feb. 1961	—	—	5	626	35	41	—	—	—	14	0	3
231	Mar. 1961	—	—	5	621	35	51	—	—	—	14	0	3
232	Apr. 1961	—	—	5	621	36	63	—	—	—	15	0	3
233	May 1961	—	—	6	621	37	74	—	—	—	15	0	3
234	June 1961	—	—	6	622	38	88	—	—	—	15	0	3
235	July 1961	—	—	6	620	39	102	—	—	—	16	0	3
236	Aug. 1961	—	—	6	620	40	120	—	—	—	16	0	3
237	Sept. 1961	—	—	6	620	40	133	—	—	—	16	0	3
238	Oct. 1961	—	—	6	615	41	149	—	—	—	17	0	3
239	Nov. 1961	—	—	6	614	41	161	—	—	—	17	0	3
240	Dec. 1961	—	—	6	610	41	175	—	—	—	17	0	3
241	Jan. 1962	—	—	6	607	41	188	—	—	—	18	0	3
242	Feb. 1962	—	—	6	602	41	209	—	—	—	18	0	3
243	Mar. 1962	—	—	6	594	41	226	—	—	—	18	0	3
244	Apr. 1962	—	—	6	590	41	245	—	—	—	19	0	3
245	May 1962	—	—	6	588	41	258	—	—	—	19	0	3
246	June 1962	—	—	6	587	42	279	—	—	—	19	0	4
247	July 1962	—	—	7	585	43	300	—	—	—	20	0	4
248	Aug. 1962	—	—	7	584	44	325	—	—	—	20	0	4
249	Sept. 1962	—	—	7	583	45	339	—	—	—	20	0	4
250	Oct. 1962	—	—	7	577	45	357	—	—	—	21	0	4
251	Nov. 1962	—	—	7	574	45	370	—	—	—	21	0	4
252	Dec. 1962	—	—	7	571	45	382	—	—	—	22	0	4
253	Jan. 1963	—	—	7	569	45	395	—	—	—	22	0	4
254	Feb. 1963	—	—	7	566	45	412	—	—	—	22	0	4
255	Mar. 1963	—	—	7	559	45	424	—	—	—	22	0	4
256	Apr. 1963	—	—	7	553	45	438	—	—	—	23	0	4
257	May 1963	—	—	7	550	45	448	—	—	—	23	0	4
258	June 1963	—	—	7	545	45	457	—	—	—	24	0	4
259	July 1963	—	—	7	540	45	466	—	—	—	24	0	4
260	Aug. 1963	—	—	8	538	45	483	—	—	—	25	0	4
261	Sept. 1963	—	—	8	536	45	492	—	—	—	25	0	4
262	Oct. 1963	—	—	8	532	45	504	—	—	—	25	0	4
263	Nov. 1963	—	—	8	531	45	511	—	—	—	26	0	4
264	Dec. 1963	—	—	8	529	45	517	—	—	—	26	0	4

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[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
265	Jan. 1964	—	—	8	529	45	524	—	—	—	27	0	4
266	Feb. 1964	—	—	8	527	45	534	—	—	—	27	0	4
267	Mar. 1964	—	—	8	522	45	539	—	—	—	27	0	4
268	Apr. 1964	—	—	8	518	45	547	—	—	—	28	0	4
269	May 1964	—	—	8	516	45	552	—	—	—	28	0	4
270	June 1964	—	—	8	512	45	556	—	—	—	28	0	4
271	July 1964	—	—	8	510	46	563	—	—	—	29	0	4
272	Aug. 1964	—	—	8	508	46	573	—	—	—	29	0	4
273	Sept. 1964	—	—	8	507	46	580	—	—	—	30	0	5
274	Oct. 1964	—	—	8	505	47	589	—	—	—	30	0	5
275	Nov. 1964	—	—	9	503	47	589	—	—	—	31	0	5
276	Dec. 1964	—	—	9	501	46	591	—	—	—	31	0	5
277	Jan. 1965	—	—	9	499	46	588	—	—	—	31	0	5
278	Feb. 1965	—	—	9	497	46	592	—	—	—	32	0	5
279	Mar. 1965	—	—	9	492	46	594	—	—	—	32	0	5
280	Apr. 1965	—	—	9	487	45	595	—	—	—	32	0	5
281	May 1965	—	—	9	484	45	594	—	—	—	33	0	5
282	June 1965	—	—	9	483	46	597	—	—	—	33	0	5
283	July 1965	—	—	9	481	46	600	—	—	—	33	0	5
284	Aug. 1965	—	—	9	478	46	604	—	—	—	34	0	5
285	Sept. 1965	—	—	9	475	46	601	—	—	—	34	1	5
286	Oct. 1965	—	—	9	470	45	600	—	—	—	35	1	5
287	Nov. 1965	—	—	9	468	45	594	—	—	—	35	1	5
288	Dec. 1965	—	—	9	465	44	588	—	—	—	36	1	5
289	Jan. 1966	—	—	9	464	43	586	—	—	—	36	1	5
290	Feb. 1966	—	—	9	462	43	589	—	—	—	36	1	5
291	Mar. 1966	—	—	9	458	43	590	—	—	—	36	2	5
292	Apr. 1966	—	—	9	455	42	591	—	—	—	37	2	5
293	May 1966	—	—	9	454	43	591	—	—	—	37	2	5
294	June 1966	—	—	9	452	42	593	—	—	—	38	2	5
295	July 1966	—	—	9	452	43	598	—	—	—	38	3	5
296	Aug. 1966	—	—	9	453	43	610	—	—	—	39	3	5
297	Sept. 1966	—	—	10	454	44	613	—	—	—	39	3	5
298	Oct. 1966	—	—	10	450	44	615	—	—	—	39	4	5
299	Nov. 1966	—	—	10	450	43	612	—	—	—	40	4	5
300	Dec. 1966	—	—	10	451	43	613	—	—	—	41	4	5

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2- dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Handot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
301	Jan. 1967	—	—	10	452	43	613	—	—	—	42	4	5
302	Feb. 1967	—	—	10	453	43	619	—	—	—	42	4	5
303	Mar. 1967	—	—	10	449	43	619	—	—	—	42	4	5
304	Apr. 1967	—	—	10	449	42	623	—	—	—	43	5	5
305	May 1967	—	—	10	448	42	622	—	—	—	43	5	5
306	June 1967	—	—	10	447	42	623	—	—	—	43	5	5
307	July 1967	—	—	10	448	43	630	—	—	—	44	5	5
308	Aug. 1967	—	—	11	452	43	642	—	—	—	45	5	5
309	Sept. 1967	—	—	11	454	43	646	—	—	—	45	5	6
310	Oct. 1967	—	—	11	453	43	651	—	—	—	46	5	6
311	Nov. 1967	—	—	11	457	44	652	—	—	—	47	6	6
312	Dec. 1967	—	—	11	461	44	657	—	—	—	47	6	6
313	Jan. 1968	—	—	11	463	44	656	—	—	—	48	6	6
314	Feb. 1968	—	—	11	463	44	657	—	—	—	48	6	6
315	Mar. 1968	—	—	11	459	44	654	—	—	—	48	6	6
316	Apr. 1968	—	—	11	459	44	654	—	—	—	49	6	6
317	May 1968	—	—	11	458	44	648	—	—	—	49	6	6
318	June 1968	—	—	11	456	44	646	—	—	—	49	7	6
319	July 1968	—	—	11	457	44	649	—	—	—	50	7	6
320	Aug. 1968	—	—	11	459	44	655	—	—	—	51	7	6
321	Sept. 1968	—	—	11	460	45	655	—	—	—	51	7	6
322	Oct. 1968	—	—	11	460	45	659	—	—	—	51	7	6
323	Nov. 1968	—	—	12	465	45	658	—	—	—	52	8	6
324	Dec. 1968	—	—	12	467	45	658	—	—	—	53	8	6
325	Jan. 1969	—	—	12	469	45	653	—	—	—	53	8	6
326	Feb. 1969	—	—	12	469	45	654	—	—	—	53	8	6
327	Mar. 1969	—	—	12	466	45	651	—	—	—	53	8	6
328	Apr. 1969	—	—	12	466	46	652	—	—	—	54	8	6
329	May 1969	—	—	12	466	46	647	—	—	—	55	9	6
330	June 1969	—	—	12	466	46	648	—	—	—	55	8	6
331	July 1969	—	—	12	467	47	647	—	—	—	56	8	6
332	Aug. 1969	—	—	12	467	47	636	—	—	—	56	10	6
333	Sept. 1969	—	—	12	466	48	609	—	—	—	56	11	6
334	Oct. 1969	—	—	12	459	48	582	—	—	—	55	12	6
335	Nov. 1969	—	—	12	452	48	581	—	—	—	57	13	6
336	Dec. 1969	—	—	12	452	48	576	—	—	—	58	14	6

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2- dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Handot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
337	Jan. 1970	—	—	12	453	48	566	—	—	—	59	15	6
338	Feb. 1970	—	—	12	454	48	563	—	—	—	59	16	6
339	Mar. 1970	—	—	12	452	48	556	—	—	—	59	17	6
340	Apr. 1970	—	—	12	451	47	550	—	—	—	60	18	6
341	May 1970	—	—	12	452	47	540	—	—	—	61	18	6
342	June 1970	—	—	11	451	47	533	—	—	—	61	19	6
343	July 1970	—	—	11	453	47	529	—	—	—	62	20	6
344	Aug. 1970	—	—	12	457	48	529	—	—	—	63	20	6
345	Sept. 1970	—	—	11	459	49	524	—	—	—	64	21	6
346	Oct. 1970	—	—	11	459	48	519	—	—	—	64	22	6
347	Nov. 1970	—	—	11	461	48	509	—	—	—	65	23	6
348	Dec. 1970	—	—	11	463	48	502	—	—	—	66	24	6
349	Jan. 1971	—	—	11	466	48	493	—	—	—	67	25	6
350	Feb. 1971	—	—	11	468	48	490	—	—	—	67	26	6
351	Mar. 1971	—	—	11	467	48	485	—	—	—	67	26	6
352	Apr. 1971	—	—	11	466	48	481	—	—	—	68	27	6
353	May 1971	—	—	11	468	48	474	—	—	—	69	28	6
354	June 1971	—	—	11	470	48	470	—	—	—	70	29	6
355	July 1971	—	—	11	472	48	468	—	—	—	70	29	7
356	Aug. 1971	—	—	11	474	49	468	—	—	—	71	30	7
357	Sept. 1971	—	—	11	477	49	464	—	—	—	72	31	7
358	Oct. 1971	—	—	11	482	50	466	—	—	—	73	31	7
359	Nov. 1971	—	—	11	484	50	461	—	—	—	74	32	7
360	Dec. 1971	—	—	11	488	50	454	—	—	—	75	33	7
361	Jan. 1972	—	—	11	491	50	447	—	—	—	76	34	7
362	Feb. 1972	—	—	11	493	50	446	—	—	—	76	35	7
363	Mar. 1972	—	—	11	492	50	441	—	—	—	77	36	7
364	Apr. 1972	—	—	11	489	50	437	—	—	—	78	37	7
365	May 1972	—	—	10	490	50	430	—	—	—	79	38	7
366	June 1972	—	—	10	490	50	426	—	—	—	79	38	7
367	July 1972	0	1	10	490	50	422	—	69	8	80	39	7
368	Aug. 1972	0	9	10	490	50	420	—	634	16	81	40	7
369	Sept. 1972	0	27	10	490	50	415	—	1102	25	82	41	7
370	Oct. 1972	0	31	10	487	50	410	—	1491	33	82	42	7
371	Nov. 1972	1	94	10	487	50	404	—	1815	41	83	42	7
372	Dec. 1972	2	215	10	487	50	398	—	2083	49	84	43	7

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2- dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Handot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
373	Jan. 1973	2	283	10	487	50	392	—	2,306	57	85	44	7
374	Feb. 1973	3	391	10	486	49	389	—	2,492	64	85	45	7
375	Mar. 1973	5	538	9	483	49	383	—	2,646	72	85	46	7
376	Apr. 1973	6	636	9	479	49	381	—	2,773	80	87	46	7
377	May 1973	8	771	9	477	49	374	—	2,880	87	87	48	7
378	June 1973	10	954	9	477	49	372	—	2,968	95	88	48	7
379	July 1973	13	1,187	9	474	49	367	—	3,041	102	88	49	7
380	Aug. 1973	18	1,530	9	472	49	366	—	3,102	110	89	50	8
381	Sept. 1973	22	1,761	9	471	49	362	—	3,152	117	90	51	8
382	Oct. 1973	22	1,738	9	467	48	358	—	3,194	124	91	52	8
383	Nov. 1973	31	2,209	9	465	47	348	—	3,229	131	92	52	7
384	Dec. 1973	39	2,637	9	465	47	344	—	3,258	139	92	52	8
385	Jan. 1974	43	2,776	8	465	47	339	—	3,282	146	93	52	8
386	Feb. 1974	48	2,998	8	463	46	337	—	3,302	152	93	53	8
387	Mar. 1974	54	3,234	8	461	46	332	—	3,318	159	93	53	8
388	Apr. 1974	57	3,344	8	456	46	330	—	3,332	166	95	54	8
389	May 1974	62	3,501	8	457	46	326	—	3,344	173	95	53	8
390	June 1974	68	3,711	8	455	47	324	—	3,353	179	96	54	8
391	July 1974	75	3,947	8	453	47	321	—	3,361	186	97	55	8
392	Aug. 1974	84	4,255	8	453	47	322	—	3,368	192	98	55	8
393	Sept. 1974	91	4,406	8	452	47	318	—	3,373	199	98	55	8
394	Oct. 1974	90	4,256	8	449	47	315	—	3,377	205	99	57	8
395	Nov. 1974	103	4,749	8	446	46	308	—	3,381	211	100	57	8
396	Dec. 1974	114	5,039	8	444	46	304	—	3,384	217	101	58	8
397	Jan. 1975	119	5,061	8	444	46	300	—	3,387	223	102	58	8
398	Feb. 1975	126	5,205	7	443	45	298	—	3,389	229	102	59	8
399	Mar. 1975	133	5,338	7	438	45	293	—	3,391	235	102	60	8
400	Apr. 1975	136	5,372	7	434	45	292	—	3,392	241	103	60	8
402	May 1975	141	5,425	7	433	45	288	—	3,394	247	104	60	8
402	June 1975	147	5,550	7	431	45	286	—	3,395	253	104	61	8
403	July 1975	154	5,677	7	431	45	285	—	3,395	258	105	60	9
404	Aug. 1975	163	5,840	7	429	45	285	—	3,396	264	106	61	9
405	Sept. 1975	168	5,899	7	432	46	285	—	3,397	270	107	60	9
406	Oct. 1975	165	5,647	7	430	46	283	—	3,397	275	108	62	9
407	Nov. 1975	178	6,061	7	428	46	278	—	3,398	280	109	62	9
408	Dec. 1975	188	6,208	7	427	46	274	—	3,398	286	110	63	9

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2- dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Handot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
409	Jan. 1976	193	6,211	7	425	45	271	—	3,398	291	111	64	9
410	Feb. 1976	199	6,297	7	423	44	269	—	3,398	296	111	65	9
411	Mar. 1976	206	6,390	7	418	44	267	—	3,399	301	111	66	9
412	Apr. 1976	209	6,374	7	415	43	265	—	3,399	306	113	67	9
413	May 1976	213	6,411	6	415	43	263	—	3,399	311	113	67	9
414	June 1976	220	6,490	6	416	43	263	—	3,399	316	113	67	9
415	July 1976	226	6,574	6	415	43	263	—	3,399	321	114	67	9
416	Aug. 1976	234	6,700	6	417	43	265	—	3,399	326	116	68	9
417	Sept. 1976	239	6,724	6	419	44	265	—	3,399	331	117	68	9
418	Oct. 1976	234	6,484	6	418	44	266	—	3,399	335	117	69	9
419	Nov. 1976	247	6,792	6	419	44	263	—	3,400	340	119	70	9
420	Dec. 1976	256	6,915	6	421	43	262	—	3,400	345	120	70	9
421	Jan. 1977	258	6,860	6	422	43	259	—	3,400	349	121	71	9
422	Feb. 1977	262	6,906	6	420	43	260	—	3,400	354	121	72	9
423	Mar. 1977	267	6,933	6	418	43	258	—	3,400	358	121	72	9
424	Apr. 1977	267	6,881	6	417	42	258	—	3,399	363	122	73	9
425	May 1977	270	6,885	6	418	42	257	—	3,367	368	123	73	9
426	June 1977	274	6,917	6	417	42	257	—	3,341	372	124	74	9
427	July 1977	278	6,957	6	416	42	256	—	3,320	377	124	74	9
428	Aug. 1977	283	7,032	6	417	42	258	—	3,302	382	126	75	9
429	Sept. 1977	286	7,027	6	418	42	258	—	3,287	386	126	76	9
430	Oct. 1977	279	6,771	6	419	42	260	—	3,274	390	127	76	9
431	Nov. 1977	291	7,042	6	421	42	259	—	3,264	395	129	76	9
432	Dec. 1977	297	7,107	6	423	42	258	—	3,255	399	129	77	9
433	Jan. 1978	297	7,039	6	427	—	259	—	3,248	404	131	78	—
434	Feb. 1978	300	7,055	6	427	—	261	—	3,242	408	131	80	—
435	Mar. 1978	303	7,062	6	425	—	261	—	3,238	412	131	81	—
436	Apr. 1978	302	6,998	6	427	—	264	—	3,233	416	133	81	—
437	May 1978	303	6,982	6	428	—	264	—	3,230	420	134	82	—
438	June 1978	306	6,998	6	427	—	263	—	3,227	424	135	83	—
439	July 1978	310	7,039	6	427	—	264	—	3,225	428	136	84	—
440	Aug. 1978	314	7,095	6	430	—	268	—	3,223	432	137	85	—
441	Sept. 1978	316	7,086	6	431	—	268	—	3,222	436	138	86	—
442	Oct. 1978	308	6,849	6	431	—	270	—	3,220	440	138	87	—
443	Nov. 1978	318	7,072	6	434	—	269	—	3,219	443	140	88	—
444	Dec. 1978	323	7,135	—	438	—	269	—	3,218	447	143	90	—

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2- dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Handot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
445	Jan. 1979	322	7,062	—	444	—	—	—	3,218	449	145	91	—
446	Feb. 1979	324	7,068	—	448	—	—	—	3,173	451	146	93	—
447	Mar. 1979	325	7,066	—	449	—	—	—	3,118	452	148	95	—
448	Apr. 1979	324	6,995	—	—	—	—	—	3,073	453	—	97	—
449	May 1979	324	6,968	—	—	—	—	—	3,035	454	—	98	—
450	June 1979	324	6,958	—	—	—	—	—	3,004	455	—	99	—
451	July 1979	326	6,969	—	—	—	212	—	2,978	456	—	100	—
452	Aug. 1979	329	7,015	—	—	—	219	—	2,956	457	—	—	—
453	Sept. 1979	330	6,989	—	—	30	224	—	2,938	459	—	100	11
454	Oct. 1979	322	6,756	—	—	29	230	—	2,923	460	—	101	10
455	Nov. 1979	329	6,934	—	357	29	229	—	2,911	461	141	102	10
456	Dec. 1979	332	6,977	—	359	29	230	—	2,901	462	145	102	10
457	Jan. 1980	331	6,915	—	363	29	231	—	2,892	463	148	103	10
458	Feb. 1980	333	6,943	—	365	28	237	—	2,885	464	150	104	10
459	Mar. 1980	335	6,964	—	366	29	243	—	2,898	466	151	104	10
460	Apr. 1980	334	6,912	—	369	28	249	—	2,921	467	154	106	10
461	May 1980	333	6,879	—	374	29	252	—	2,940	469	156	105	10
462	June 1980	334	6,888	—	376	29	255	—	2,956	471	158	106	10
463	July 1980	336	6,911	—	378	29	260	—	2,969	472	160	107	10
464	Aug. 1980	337	6,926	—	379	29	264	—	2,980	474	161	108	10
465	Sept. 1980	337	6,912	—	381	29	266	—	2,989	475	163	108	10
466	Oct. 1980	328	6,652	—	382	29	271	—	2,997	477	165	109	10
467	Nov. 1980	336	6,870	—	384	29	272	—	3,003	478	167	110	10
468	Dec. 1980	340	6,926	—	387	29	274	—	3,008	480	168	110	10
469	Jan. 1981	339	6,882	—	390	29	277	—	3,013	481	170	111	10
470	Feb. 1981	339	6,880	—	391	29	281	—	3,016	483	171	112	10
471	Mar. 1981	340	6,888	—	390	29	284	—	3,019	484	173	113	10
472	Apr. 1981	339	6,844	—	390	28	289	—	3,022	486	174	114	9
473	May 1981	339	6,844	—	393	28	294	—	3,024	487	175	114	9
474	June 1981	340	6,849	—	394	29	298	—	3,025	488	176	114	9
475	July 1981	342	6,879	—	397	29	305	—	3,027	490	178	114	10
476	Aug. 1981	344	6,930	—	403	30	314	—	3,058	495	180	113	10
477	Sept. 1981	345	6,928	—	405	30	318	—	3,206	499	182	115	10
478	Oct. 1981	337	6,730	—	—	30	327	—	3,329	504	—	116	10
479	Nov. 1981	345	6,921	—	393	30	326	—	3,431	508	182	117	10
480	Dec. 1981	348	6,984	—	394	29	327	—	3,516	513	184	117	10

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[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
481	Jan. 1982	349	6,975	—	400	29	336	—	3,587	517	185	117	10
482	Feb. 1982	350	6,996	—	405	30	346	—	3,646	521	187	118	10
483	Mar. 1982	351	7,008	—	405	30	350	—	3,694	526	189	118	10
484	Apr. 1982	350	6,970	—	406	30	356	—	3,735	530	190	119	10
485	May 1982	350	6,958	—	408	30	358	—	3,769	534	191	120	10
486	June 1982	350	6,964	—	409	30	362	—	3,796	538	193	120	10
487	July 1982	351	6,975	—	410	30	364	—	3,820	542	194	120	10
488	Aug. 1982	353	7,011	—	411	30	370	—	3,839	546	196	121	10
489	Sept. 1982	353	7,017	—	414	30	376	—	3,855	550	197	121	10
490	Oct. 1982	347	6,852	—	415	31	382	—	3,868	555	199	121	10
491	Nov. 1982	352	6,976	—	419	31	384	—	3,877	559	199	121	10
492	Dec. 1982	353	7,012	—	424	31	387	—	3,884	564	201	121	10
493	Jan. 1983	352	6,975	—	427	31	387	—	3,891	568	203	121	10
494	Feb. 1983	352	6,971	—	432	32	391	—	3,896	573	205	120	10
495	Mar. 1983	352	6,972	—	435	33	396	—	3,900	577	208	120	10
496	Apr. 1983	350	6,920	—	434	33	400	—	3,904	581	208	121	10
497	May 1983	350	6,903	—	435	33	399	—	3,907	585	210	121	10
498	June 1983	350	6,923	—	435	33	399	—	3,909	590	212	122	10
499	July 1983	352	6,958	—	434	34	400	—	3,911	594	213	122	10
500	Aug. 1983	353	6,985	—	435	34	402	—	3,913	598	214	123	10
501	Sept. 1983	353	6,976	—	438	34	399	—	3,915	602	215	123	10
502	Oct. 1983	346	6,809	—	441	34	403	—	3,927	606	216	123	10
503	Nov. 1983	352	6,963	—	447	35	—	—	3,945	611	217	123	10
504	Dec. 1983	353	7,004	—	454	35	—	—	3,961	615	219	123	10
505	Jan. 1984	353	6,988	—	464	—	—	—	3,973	620	220	125	—
506	Feb. 1984	353	6,992	—	472	35	370	—	3,984	624	222	124	10
507	Mar. 1984	353	6,998	—	477	35	383	—	3,993	628	226	124	10
508	Apr. 1984	352	6,969	—	481	35	403	—	4,000	632	225	124	10
509	May 1984	352	6,975	—	490	36	420	—	4,006	637	227	124	10
510	June 1984	352	6,975	—	494	37	433	—	4,011	641	230	124	10
511	July 1984	352	6,978	—	496	38	444	1	4,015	645	231	124	10
512	Aug. 1984	352	6,983	—	495	38	456	1	4,019	649	232	124	10
513	Sept. 1984	351	6,966	—	499	40	469	1	4,022	653	233	123	10
514	Oct. 1984	342	6,721	—	495	40	480	1	4,024	656	235	124	10
515	Nov. 1984	348	6,895	—	493	41	478	1	4,027	660	236	123	10
516	Dec. 1984	337	6,583	—	—	—	—	—	4,037	653	—	125	—

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2- dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Handot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
517	Jan. 1985	343	6,772	—	—	—	—	—	3,400	652	—	128	—
518	Feb. 1985	—	—	—	—	—	—	—	—	—	—	129	—
519	Mar. 1985	—	—	—	—	—	—	—	—	—	—	130	—
520	Apr. 1985	—	—	—	—	—	—	—	—	—	—	131	—
521	May 1985	—	—	—	—	—	—	—	—	—	—	132	—
522	June 1985	—	—	—	—	—	—	—	—	—	—	133	—
523	July 1985	—	—	—	—	—	—	—	—	—	—	133	—
524	Aug. 1985	—	—	—	—	—	—	—	—	—	—	133	—
525	Sept. 1985	—	—	—	—	—	—	—	—	—	—	133	—
526	Oct. 1985	—	—	—	—	—	—	—	—	—	—	133	—
527	Nov. 1985	—	—	—	—	—	—	—	—	—	—	133	—
528	Dec. 1985	—	—	—	—	—	—	—	—	—	—	134	—
529	Jan. 1986	—	—	—	—	—	—	—	—	—	—	135	—
530	Feb. 1986	—	—	—	—	—	—	—	—	—	—	136	—
531	Mar. 1986	—	—	—	—	—	—	—	—	—	—	136	—
532	Apr. 1986	—	—	—	—	—	—	—	—	—	—	137	—
533	May 1986	—	—	—	—	—	—	—	—	—	—	138	—
534	June 1986	—	—	—	—	—	—	—	—	—	—	138	—
535	July 1986	—	—	—	—	—	—	—	—	—	—	137	—
536	Aug. 1986	—	—	—	—	—	—	—	—	—	—	137	—
537	Sept. 1986	—	—	—	—	—	—	—	—	—	—	138	—
538	Oct. 1986	—	—	—	—	—	—	—	—	—	—	139	—
539	Nov. 1986	—	—	—	—	—	—	—	—	—	—	139	—
540	Dec. 1986	—	—	—	—	—	—	—	—	—	—	140	—
541	Jan. 1987	—	—	—	—	—	—	—	—	—	—	139	—
542	Feb. 1987	—	—	—	—	—	—	—	—	—	—	141	—
543	Mar. 1987	—	—	—	—	—	—	—	—	—	—	141	—
544	Apr. 1987	—	—	—	—	—	—	—	—	—	—	142	—
545	May 1987	—	—	—	—	—	—	—	—	—	—	142	—
546	June 1987	—	—	—	—	—	—	—	—	—	—	142	—
547	July 1987	—	—	—	—	—	—	—	—	—	—	142	—
548	Aug. 1987	—	—	—	—	—	—	—	—	—	—	143	—
549	Sept. 1987	—	—	—	—	—	—	—	—	—	—	143	—
550	Oct. 1987	—	—	—	—	—	—	—	—	—	—	145	—
551	Nov. 1987	—	—	—	—	—	—	—	—	—	—	145	—
552	Dec. 1987	—	—	—	—	—	—	—	—	—	—	146	—

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2- dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Handot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
553	Jan. 1988	—	—	—	—	—	—	—	—	—	—	146	—
554	Feb. 1988	—	—	—	—	—	—	—	—	—	—	147	—
555	Mar. 1988	—	—	—	—	—	—	—	—	—	—	147	—
556	Apr. 1988	—	—	—	—	—	—	—	—	—	—	148	—
557	May 1988	—	—	—	—	—	—	—	—	—	—	148	—
558	June 1988	—	—	—	—	—	—	—	—	—	—	148	—
559	July 1988	—	—	—	—	—	—	—	—	—	—	148	—
560	Aug. 1988	—	—	—	—	—	—	—	—	—	—	148	—
561	Sept. 1988	—	—	—	—	—	—	—	—	—	—	149	—
562	Oct. 1988	—	—	—	—	—	—	—	—	—	—	150	—
563	Nov. 1988	—	—	—	—	—	—	—	—	—	—	150	—
564	Dec. 1988	—	—	—	—	—	—	—	—	—	—	151	—
565	Jan. 1989	—	—	—	—	—	—	—	—	—	—	151	—
566	Feb. 1989	—	—	—	—	—	—	—	—	—	—	151	—
567	Mar. 1989	—	—	—	—	—	—	—	—	—	—	152	—
568	Apr. 1989	—	—	—	—	—	—	—	—	—	—	151	—
569	May 1989	—	—	—	—	—	—	—	—	—	—	152	—
570	June 1989	—	—	—	—	—	—	—	—	—	—	152	—
571	July 1989	—	—	—	—	—	—	—	—	—	—	152	—
572	Aug. 1989	—	—	—	—	—	—	—	—	—	—	151	—
573	Sept. 1989	—	—	—	—	—	—	—	—	—	—	151	—
574	Oct. 1989	—	—	—	—	—	—	—	—	—	—	152	—
575	Nov. 1989	—	—	—	—	—	—	—	—	—	—	153	—
576	Dec. 1989	—	—	—	—	—	—	—	—	—	—	153	—
577	Jan. 1990	—	—	—	—	—	—	—	—	—	—	154	—
578	Feb. 1990	—	—	—	—	—	—	—	—	—	—	155	—
579	Mar. 1990	—	—	—	—	—	—	—	—	—	—	155	—
580	Apr. 1990	—	—	—	—	—	—	—	—	—	—	156	—
581	May 1990	—	—	—	—	—	—	—	—	—	—	156	—
582	June 1990	—	—	—	—	—	—	—	—	—	—	157	—
583	July 1990	—	—	—	—	—	—	—	—	—	—	157	—
584	Aug. 1990	—	—	—	—	—	—	—	—	—	—	157	—
585	Sept. 1990	—	—	—	—	—	—	—	—	—	—	158	—
586	Oct. 1990	—	—	—	—	—	—	—	—	—	—	159	—
587	Nov. 1990	—	—	—	—	—	—	—	—	—	—	159	—
588	Dec. 1990	—	—	—	—	—	—	—	—	—	—	160	—

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2- dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Handot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
589	Jan. 1991	—	—	—	—	—	—	—	—	—	—	159	—
590	Feb. 1991	—	—	—	—	—	—	—	—	—	—	160	—
591	Mar. 1991	—	—	—	—	—	—	—	—	—	—	160	—
592	Apr. 1991	—	—	—	—	—	—	—	—	—	—	160	—
593	May 1991	—	—	—	—	—	—	—	—	—	—	161	—
594	June 1991	—	—	—	—	—	—	—	—	—	—	160	—
595	July 1991	—	—	—	—	—	—	—	—	—	—	159	—
596	Aug. 1991	—	—	—	—	—	—	—	—	—	—	160	—
597	Sept. 1991	—	—	—	—	—	—	—	—	—	—	160	—
598	Oct. 1991	—	—	—	—	—	—	—	—	—	—	161	—
599	Nov. 1991	—	—	—	—	—	—	—	—	—	—	162	—
600	Dec. 1991	—	—	—	—	—	—	—	—	—	—	162	—
601	Jan. 1992	—	—	—	—	—	—	—	—	—	—	162	—
602	Feb. 1992	—	—	—	—	—	—	—	—	—	—	164	—
603	Mar. 1992	—	—	—	—	—	—	—	—	—	—	164	—
604	Apr. 1992	—	—	—	—	—	—	—	—	—	—	165	—
605	May 1992	—	—	—	—	—	—	—	—	—	—	164	—
606	June 1992	—	—	—	—	—	—	—	—	—	—	165	—
607	July 1992	—	—	—	—	—	—	—	—	—	—	165	—
608	Aug. 1992	—	—	—	—	—	—	—	—	—	—	164	—
609	Sept. 1992	—	—	—	—	—	—	—	—	—	—	165	—
610	Oct. 1992	—	—	—	—	—	—	—	—	—	—	166	—
611	Nov. 1992	—	—	—	—	—	—	—	—	—	—	166	—
612	Dec. 1992	—	—	—	—	—	—	—	—	—	—	167	—
613	Jan. 1993	—	—	—	—	—	—	—	—	—	—	167	—
614	Feb. 1993	—	—	—	—	—	—	—	—	—	—	168	—
615	Mar. 1993	—	—	—	—	—	—	—	—	—	—	168	—
616	Apr. 1993	—	—	—	—	—	—	—	—	—	—	169	—
617	May 1993	—	—	—	—	—	—	—	—	—	—	169	—
618	June 1993	—	—	—	—	—	—	—	—	—	—	170	—
619	July 1993	—	—	—	—	—	—	—	—	—	—	170	—
620	Aug. 1993	—	—	—	—	—	—	—	—	—	—	171	—
621	Sept. 1993	—	—	—	—	—	—	—	—	—	—	170	—
622	Oct. 1993	—	—	—	—	—	—	—	—	—	—	170	—
623	Nov. 1993	—	—	—	—	—	—	—	—	—	—	171	—
624	Dec. 1993	—	—	—	—	—	—	—	—	—	—	172	—

Appendix A3. Reconstructed (simulated) mean concentrations in groundwater at selected water-supply wells for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2- dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene, Handot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[—, no pumping]

Stress period	Month and year	Concentration, in micrograms per liter											
		[1]PCE	[1]TCE						[2]1,2-tDCE	[2]VC	Benzene		
		HP-651	HP-651	HP-601	HP-602	HP-608	HP-634	HP-660	HP-651	HP-651	[3]HP-602	[3]HP-603	[1]HP-608
625	Jan. 1994	—	—	—	—	—	—	—	—	—	—	172	—
626	Feb. 1994	—	—	—	—	—	—	—	—	—	—	172	—
627	Mar. 1994	—	—	—	—	—	—	—	—	—	—	172	—
628	Apr. 1994	—	—	—	—	—	—	—	—	—	—	173	—
629	May 1994	—	—	—	—	—	—	—	—	—	—	173	—
630	June 1994	—	—	—	—	—	—	—	—	—	—	174	—
631	July 1994	—	—	—	—	—	—	—	—	—	—	173	—
632	Aug. 1994	—	—	—	—	—	—	—	—	—	—	174	—
633	Sept. 1994	—	—	—	—	—	—	—	—	—	—	174	—
634	Oct. 1994	—	—	—	—	—	—	—	—	—	—	174	—
635	Nov. 1994	—	—	—	—	—	—	—	—	—	—	174	—
636	Dec. 1994	—	—	—	—	—	—	—	—	—	—	174	—
637	Jan. 1995	—	—	—	—	—	—	—	—	—	—	174	—
638	Feb. 1995	—	—	—	—	—	—	—	—	—	—	175	—
639	Mar. 1995	—	—	—	—	—	—	—	—	—	—	175	—
640	Apr. 1995	—	—	—	—	—	—	—	—	—	—	176	—
641	May 1995	—	—	—	—	—	—	—	—	—	—	176	—
642	June 1995	—	—	—	—	—	—	—	—	—	—	175	—
643	July 1995	—	—	—	—	—	—	—	—	—	—	176	—
644	Aug. 1995	—	—	—	—	—	—	—	—	—	—	176	—
645	Sept. 1995	—	—	—	—	—	—	—	—	—	—	177	—
646	Oct. 1995	—	—	—	—	—	—	—	—	—	—	177	—
647	Nov. 1995	—	—	—	—	—	—	—	—	—	—	177	—
648	Dec. 1995	—	—	—	—	—	—	—	—	—	—	178	—
649	Jan. 1996	—	—	—	—	—	—	—	—	—	—	177	—
650	Feb. 1996	—	—	—	—	—	—	—	—	—	—	178	—
651	Mar. 1996	—	—	—	—	—	—	—	—	—	—	178	—
652	Apr. 1996	—	—	—	—	—	—	—	—	—	—	179	—
653	May 1996	—	—	—	—	—	—	—	—	—	—	179	—
654–798	June 1996–June 2008	—	—	—	—	—	—	—	—	—	—	—	—

[1] Results obtained using MT3DMS model (Jones et al. 2013)

[2] Results obtained using linear control model, TechControl (Guan et al. 2013)

[3] Results obtained using LNAPL model, TechFlowMP (Jang et al. 2013)

Appendix A4. Maps showing reconstructed (simulated) water levels and distribution of trichloroethylene (TCE) within the Hadnot Point Industrial Area fate and transport model subdomain, model layers 1, 3, and 5, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1951, January 1968, November 1984, and June 2008

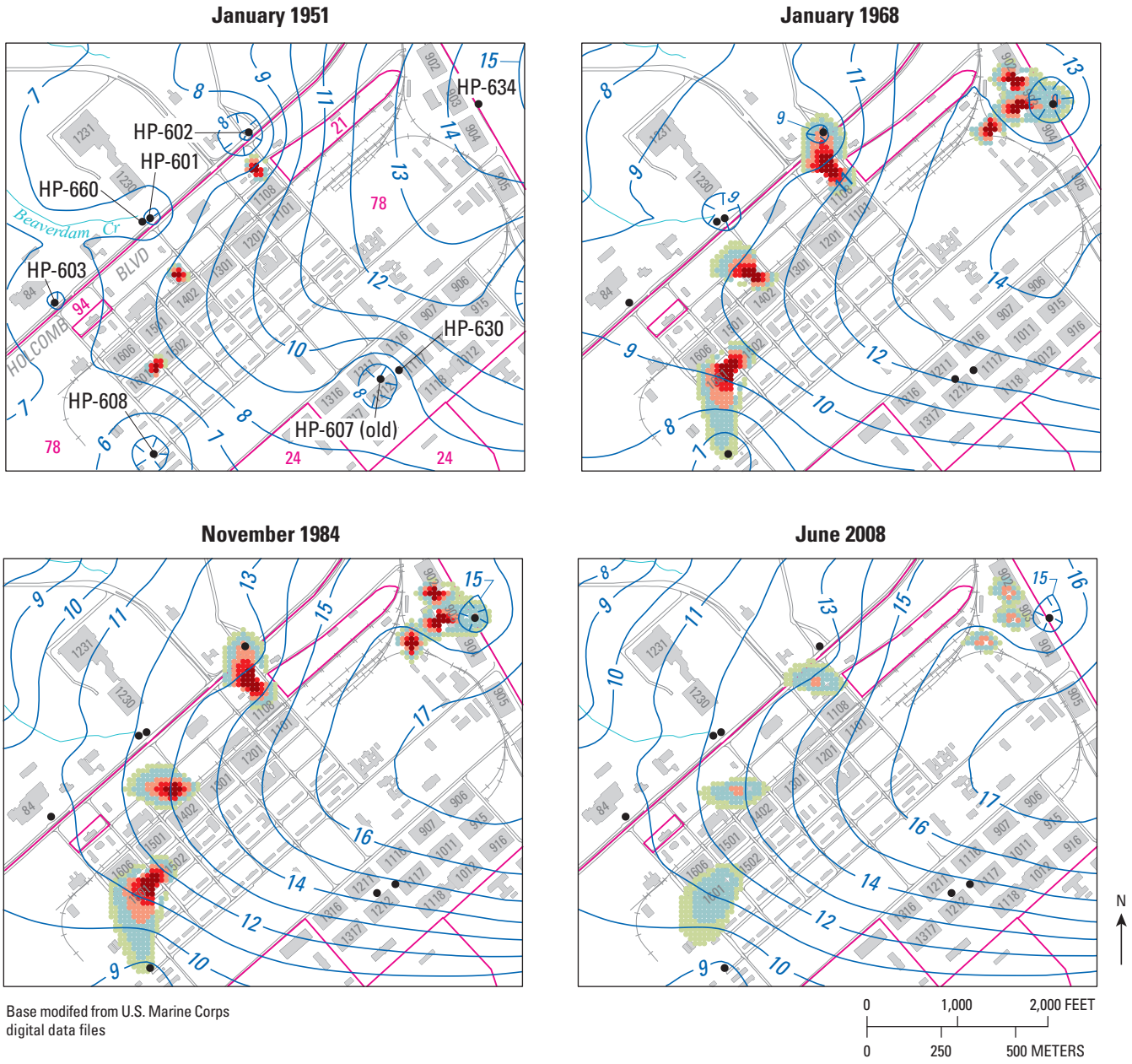


Figure A4.1. Reconstructed (simulated) water levels and distribution of trichloroethylene (TCE) within the Hadnot Point Industrial Area fate and transport model subdomain, model layer 1, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1951, January 1968, November 1984, and June 2008.

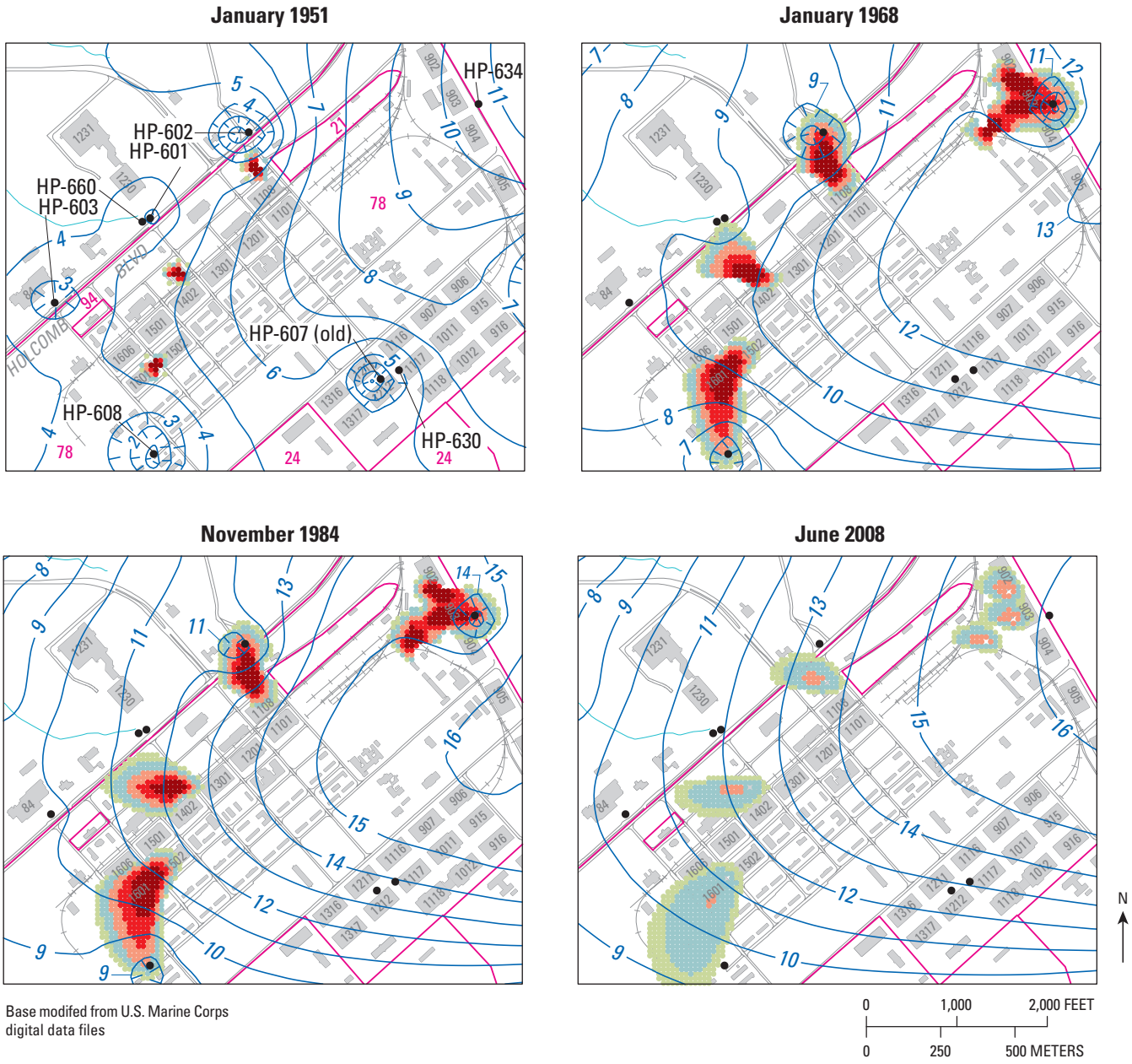


Figure A4.2. Reconstructed (simulated) water levels and distribution of trichloroethylene (TCE) within the Hadnot Point Industrial Area fate and transport model subdomain, model layer 3, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1951, January 1968, November 1984, and June 2008.

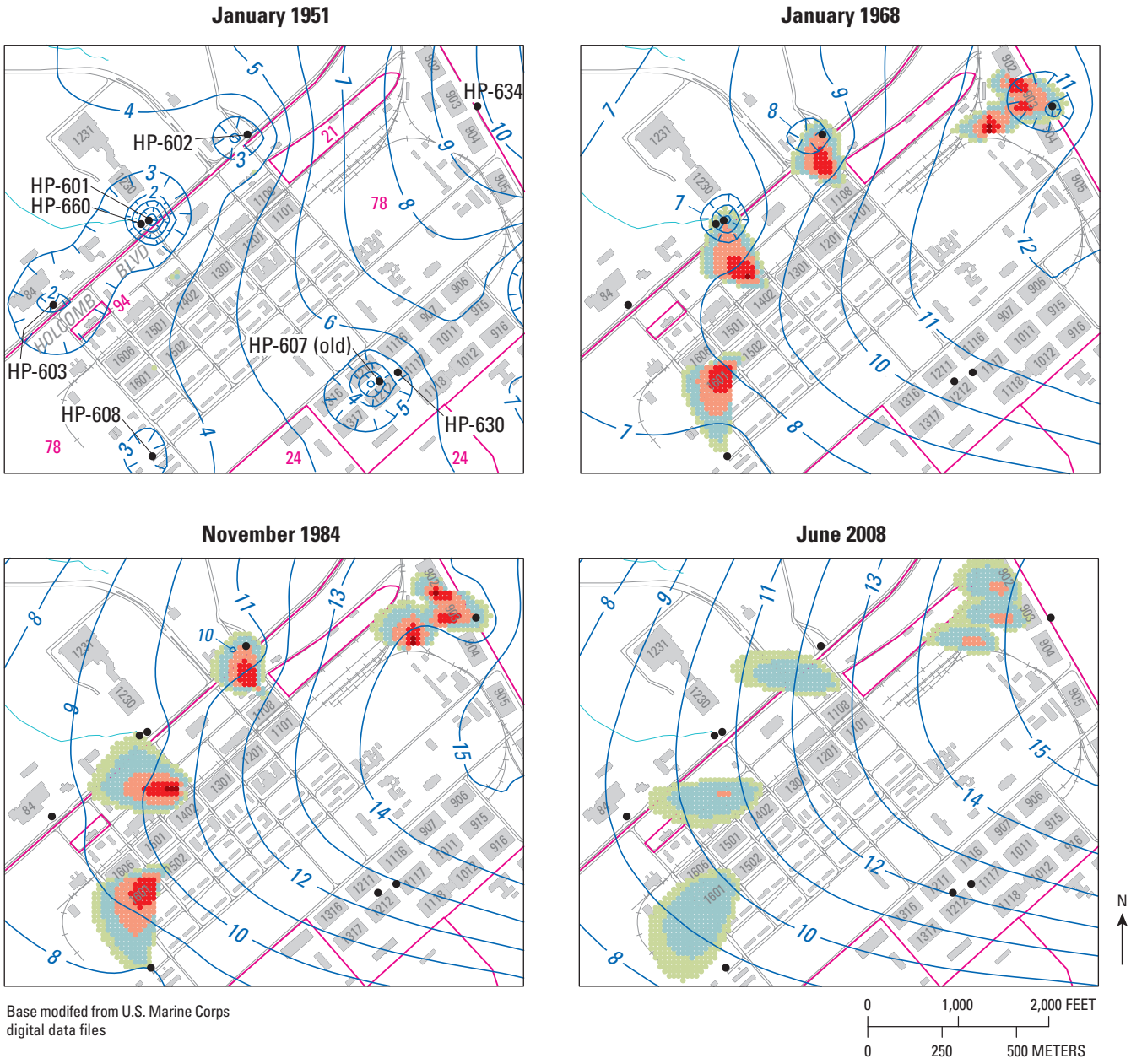
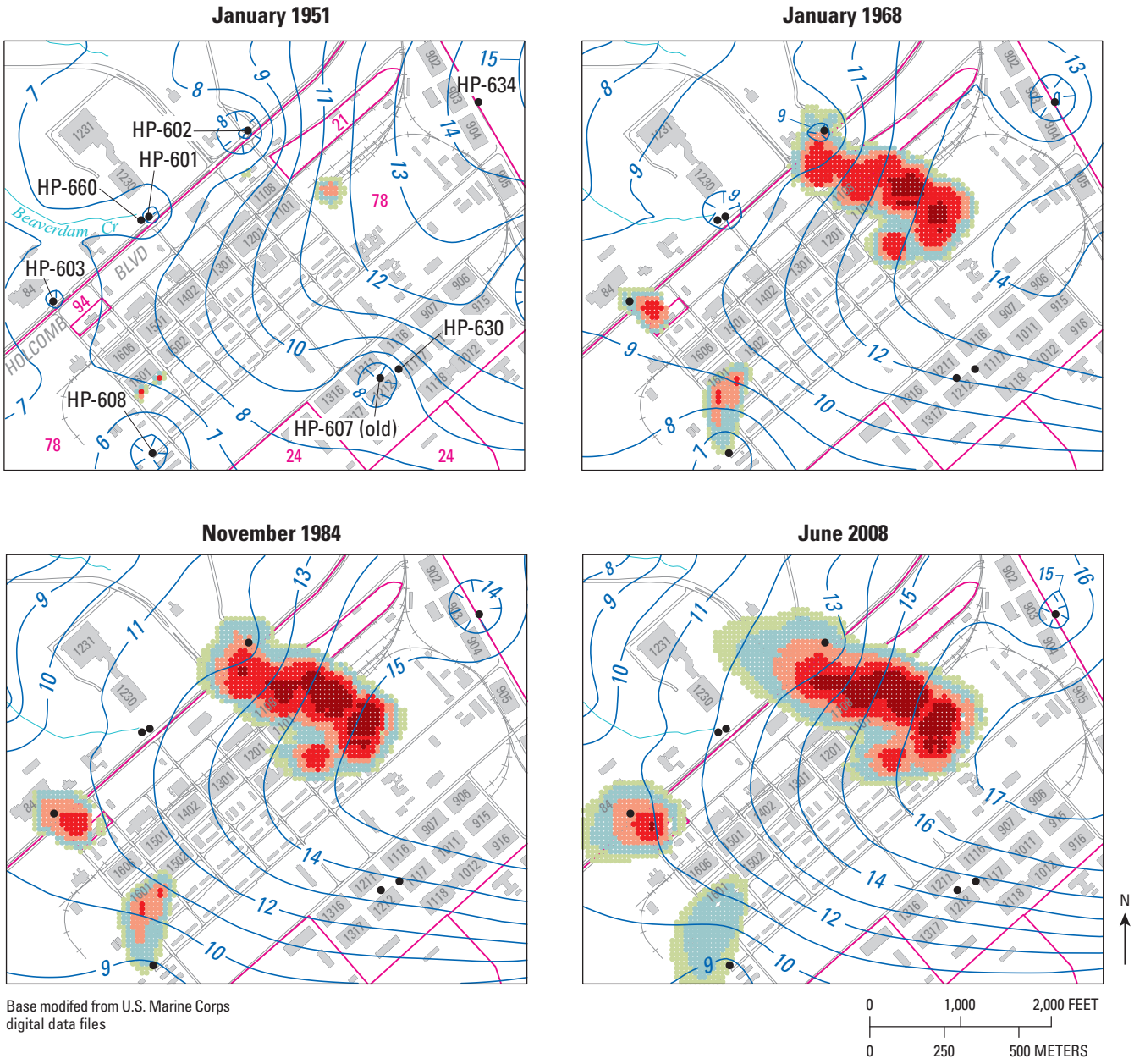


Figure A4.3. Reconstructed (simulated) water levels and distribution of trichloroethylene (TCE) within the Hadnot Point Industrial Area fate and transport model subdomain, model layer 5, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1951, January 1968, November 1984, and June 2008.

Appendix A5. Maps showing reconstructed (simulated) water levels and distribution of benzene within the Hadnot Point Industrial Area fate and transport model subdomain, model layers 1, 3, and 5, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1951, January 1968, November 1984, and June 2008



EXPLANATION

8 — **Simulated potentiometric contour**—Shows simulated potentiometric surface. Hachures indicate depression. Contour interval 1 foot. Datum is National Geodetic Vertical Datum of 1929

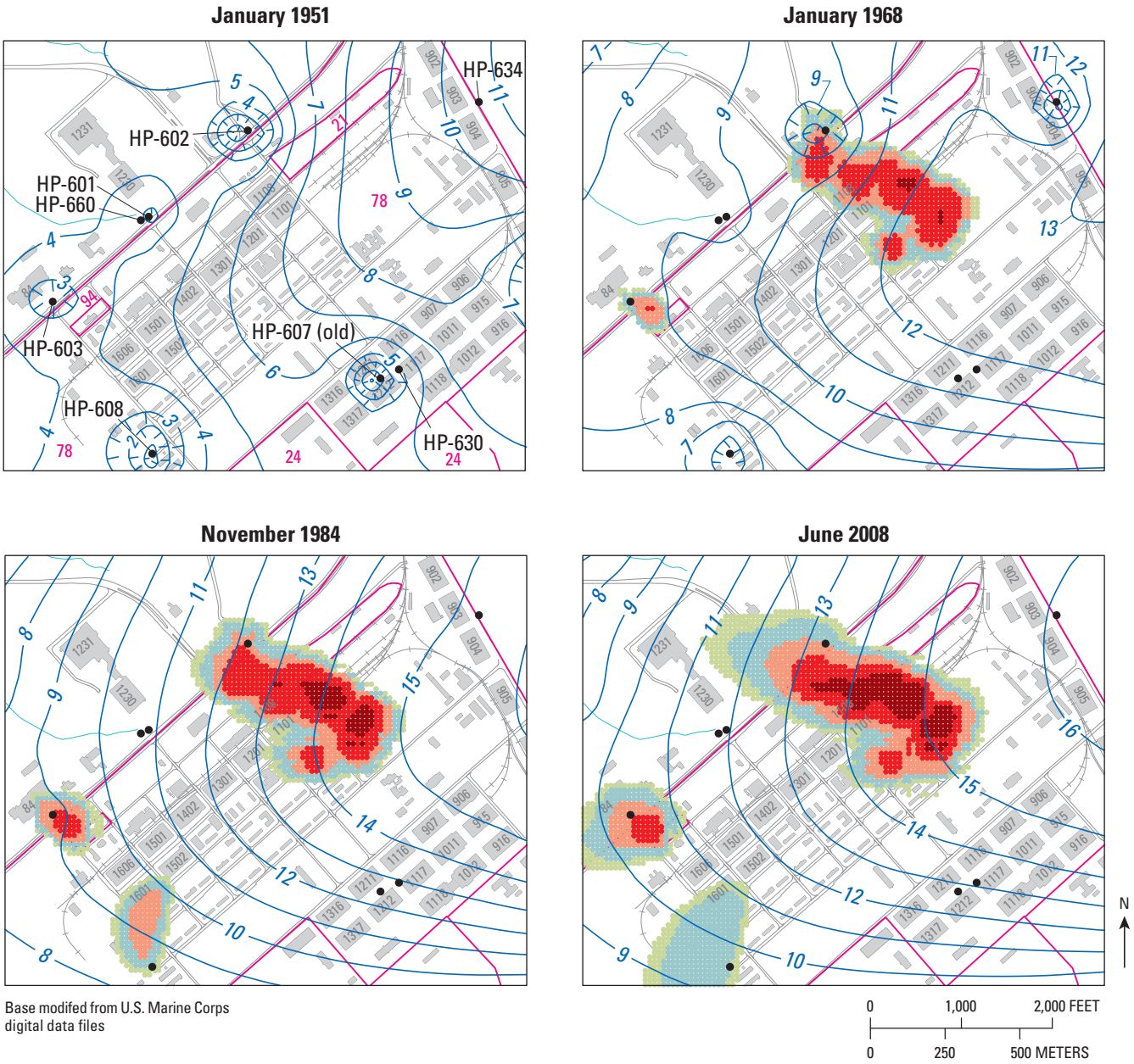
78 — **Installation Restoration Program site boundary and number**

HP-634 — **Water-supply well and number**

Benzene concentration, in micrograms per liter

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

Figure A5.1. Reconstructed (simulated) water levels and distribution of benzene within the Hadnot Point Industrial Area fate and transport model subdomain, model layer 1, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1951, January 1968, November 1984, and June 2008.



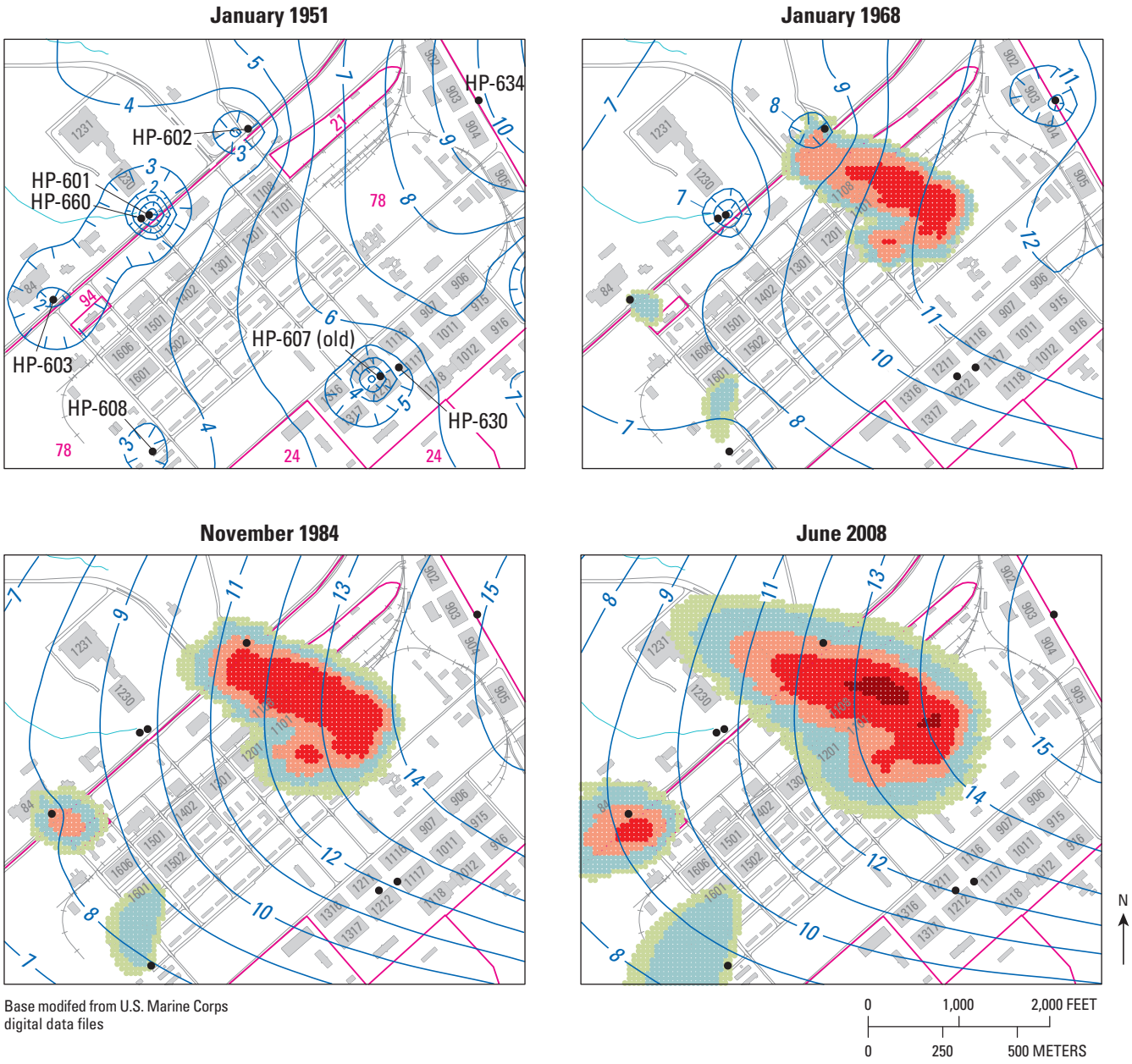
EXPLANATION

- 8 — **Simulated potentiometric contour**—Shows simulated potentiometric surface. Hachures indicate depression. Contour interval 1 foot. Datum is National Geodetic Vertical Datum of 1929
- 78 — **Installation Restoration Program site boundary and number**
- HP-634 — **Water-supply well and number**

Benzene concentration, in micrograms per liter

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

Figure A5.2. Reconstructed (simulated) water levels and distribution of benzene within the Hadnot Point Industrial Area fate and transport model subdomain, model layer 3, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1951, January 1968, November 1984, and June 2008.



EXPLANATION

8 — **Simulated potentiometric contour**—Shows simulated potentiometric surface. Hachures indicate depression. Contour interval 1 foot. Datum is National Geodetic Vertical Datum of 1929

78 — **Installation Restoration Program site boundary and number**

HP-634 — **Water-supply well and number**

Benzene concentration, in micrograms per liter

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

Figure A5.3. Reconstructed (simulated) water levels and distribution of benzene within the Hadnot Point Industrial Area fate and transport model subdomain, model layer 5, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1951, January 1968, November 1984, and June 2008.

Appendix A6. Maps showing reconstructed (simulated) water levels and distribution of trichloroethylene (TCE) and tetrachloroethylene (PCE) within the Hadnot Point landfill area fate and transport model subdomain, model layers 1, 3, and 5, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1968, June 1978, November 1984, and June 2008

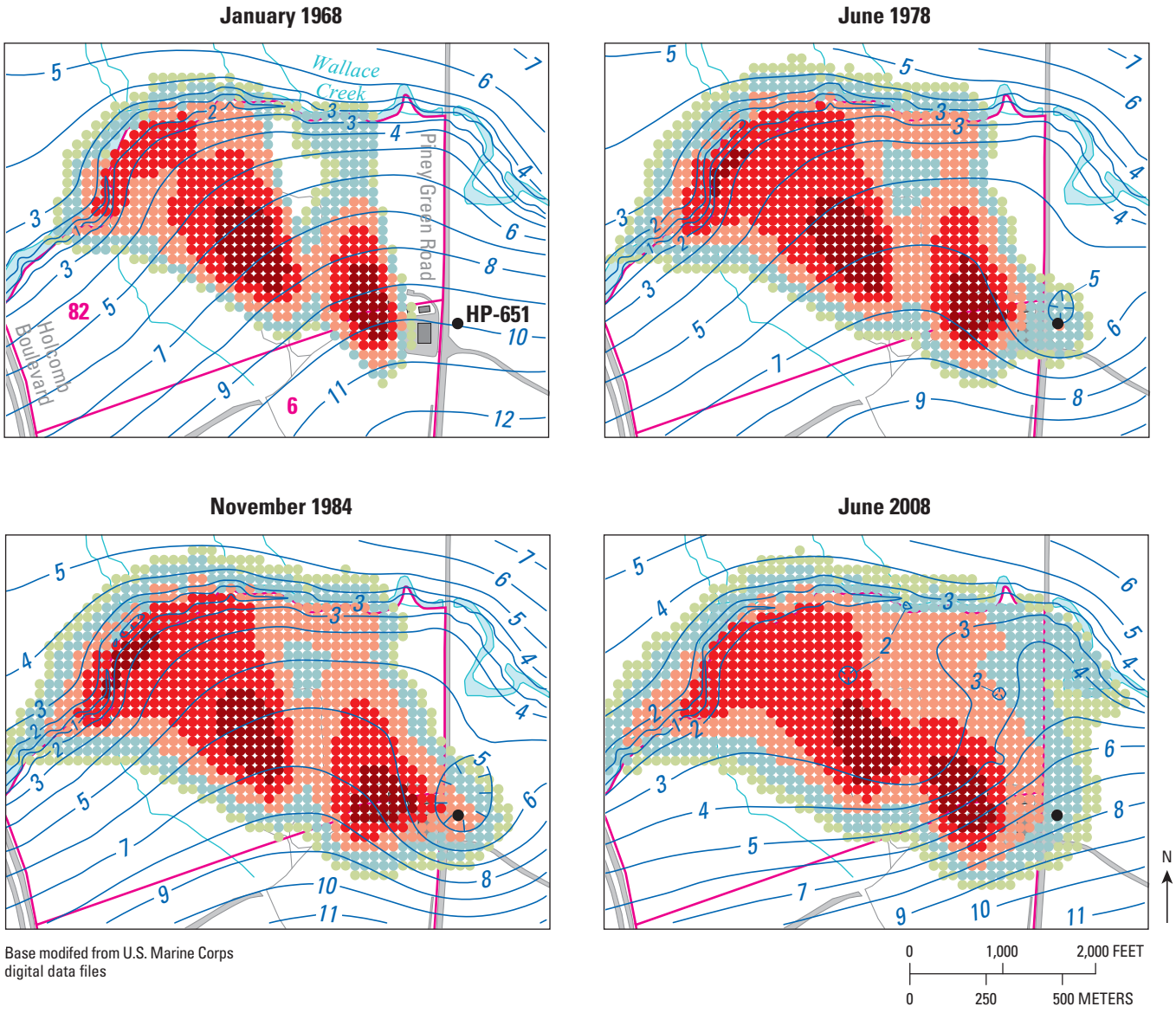


Figure A6.1. Reconstructed (simulated) water levels and distribution of trichloroethylene (TCE) within the Hadnot Point landfill area fate and transport model subdomain, model layer 1, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1968, June 1978, November 1984, and June 2008.

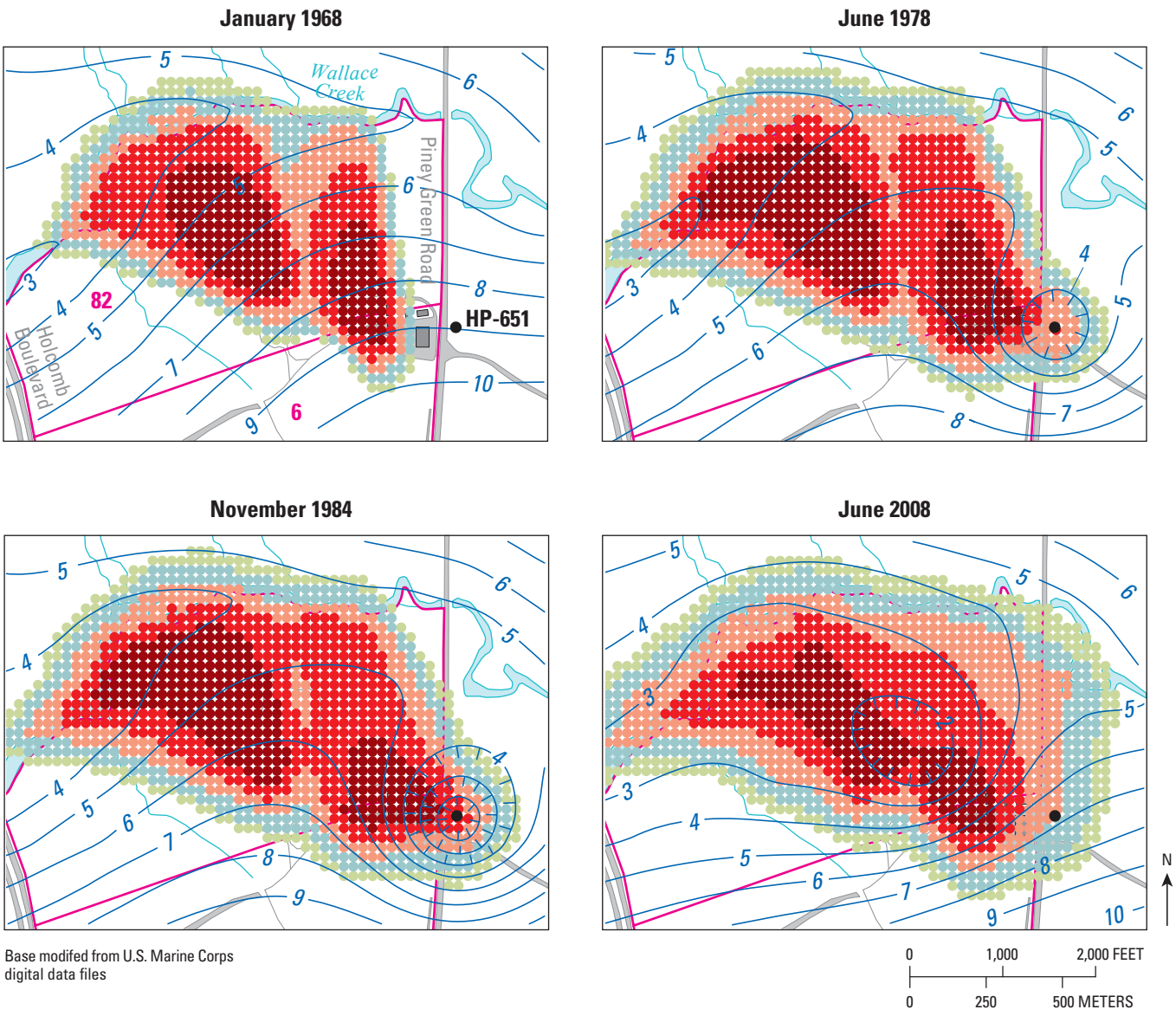


Figure A6.2. Reconstructed (simulated) water levels and distribution of trichloroethylene (TCE) within the Hadnot Point landfill area fate and transport model subdomain, model layer 3, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1968, June 1978, November 1984, and June 2008.

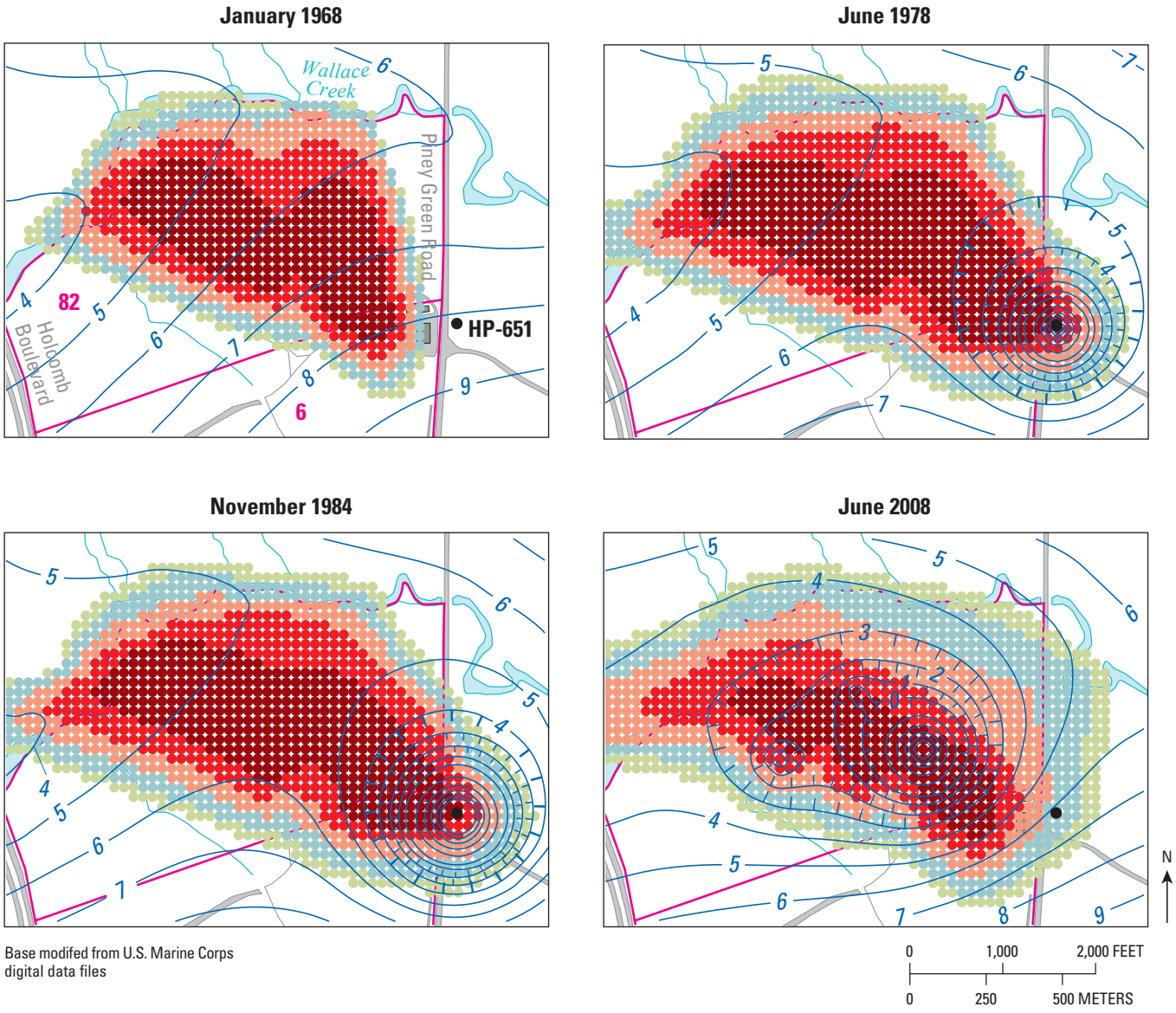


Figure A6.3. Reconstructed (simulated) water levels and distribution of trichloroethylene (TCE) within the Hadnot Point landfill area fate and transport model subdomain, model layer 5, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1968, June 1978, November 1984, and June 2008.

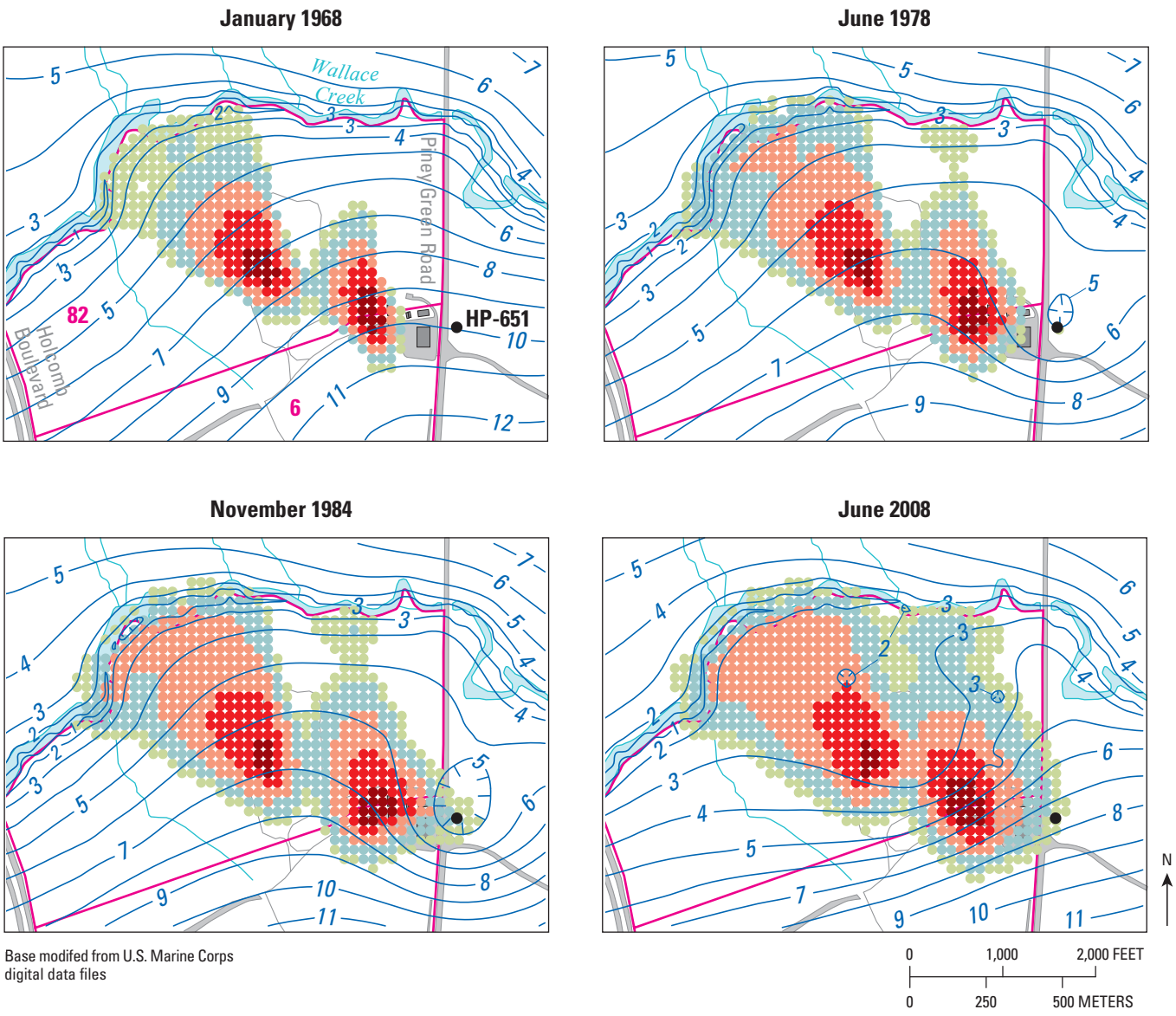


Figure A6.4. Reconstructed (simulated) water levels and distribution of tetrachloroethylene (PCE) within the Hadnot Point landfill area fate and transport model subdomain, model layer 1, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1968, June 1978, November 1984, and June 2008.

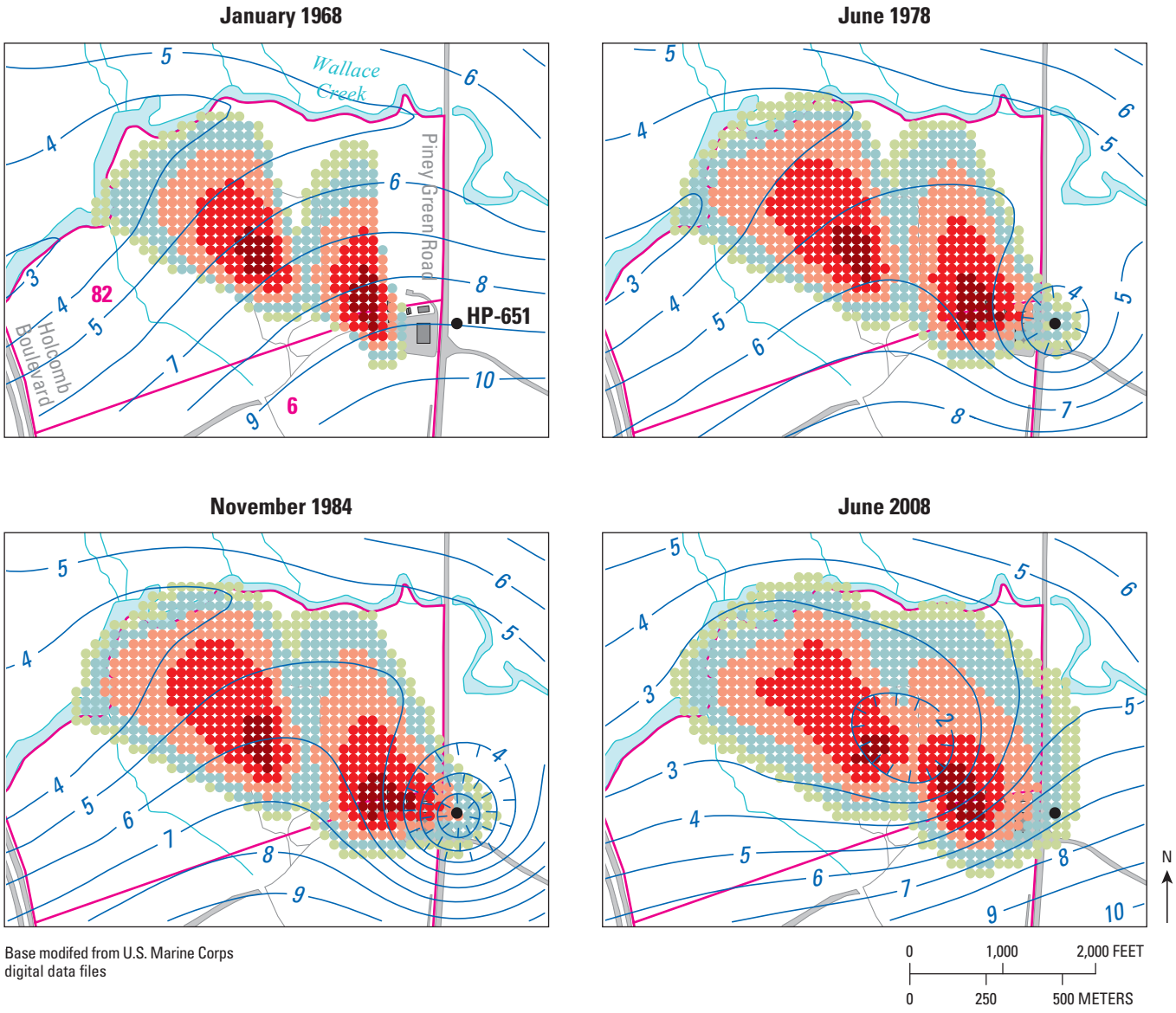


Figure A6.5. Reconstructed (simulated) water levels and distribution of tetrachloroethylene (PCE) within the Hadnot Point landfill area fate and transport model subdomain, model layer 3, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1968, June 1978, November 1984, and June 2008.

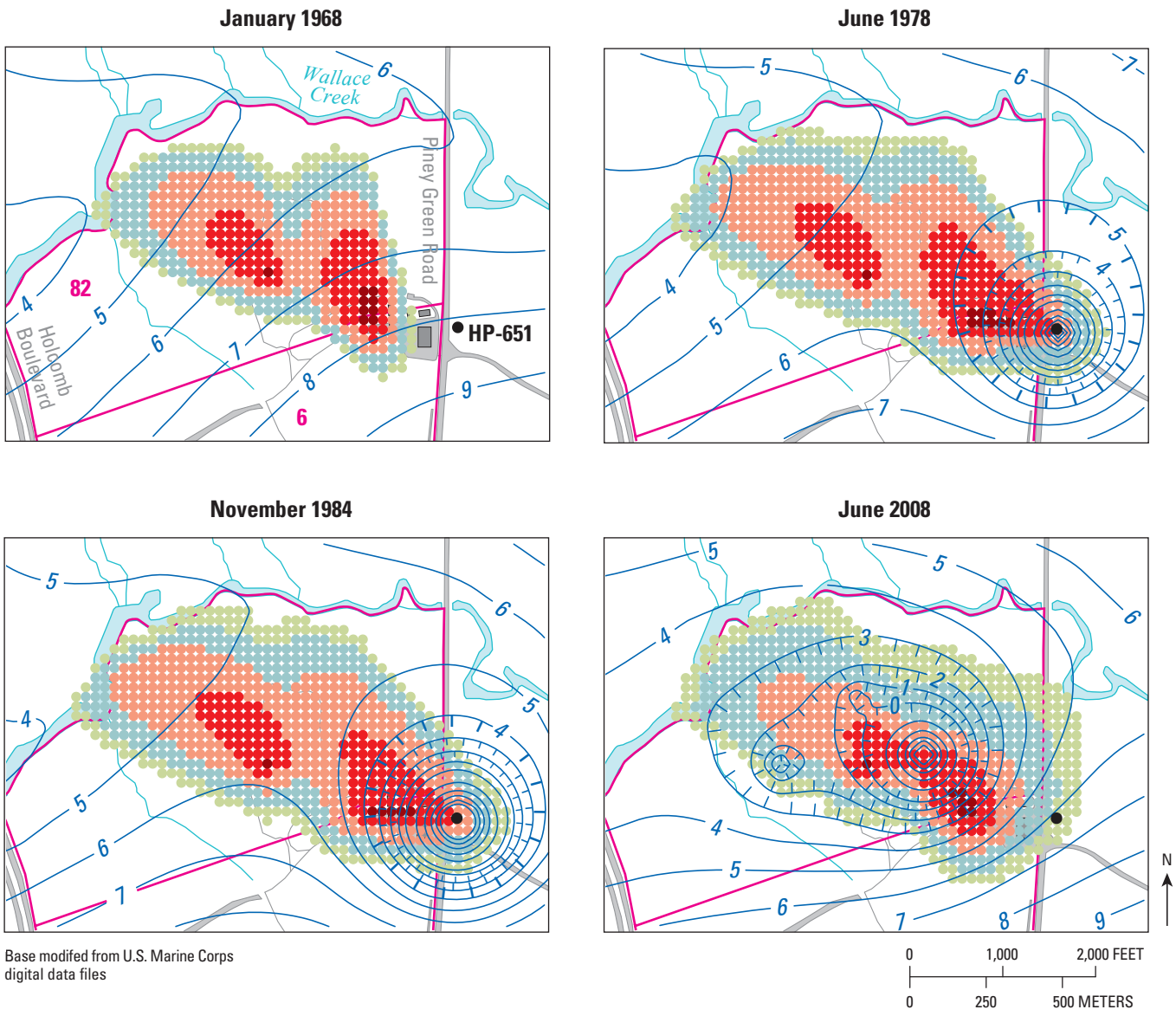


Figure A6.6. Reconstructed (simulated) water levels and distribution of tetrachloroethylene (PCE) within the Hadnot Point landfill area fate and transport model subdomain, model layer 5, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1968, June 1978, November 1984, and June 2008.

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard Study Area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
1–6	Jan.–June 1942	—	—	—	—	—
7–12	July–Dec. 1942	0	0	*	*	0
13–120	Jan. 1943–Dec. 1951	0	0	0	0	0
121	Jan. 1952	0	1	0	0	0
122	Feb. 1952	0	0	0	0	0
123	Mar. 1952	0	0	0	0	0
124	Apr. 1952	0	1	0	0	0
125	May 1952	0	1	0	0	0
126	June 1952	0	1	0	0	0
127	July 1952	0	1	0	0	0
128	Aug. 1952	0	2	0	0	0
129	Sept. 1952	0	2	0	0	0
130	Oct. 1952	0	2	0	0	0
131	Nov. 1952	0	3	0	0	0
132	Dec. 1952	0	3	0	0	0
133	Jan. 1953	0	4	0	0	0
134	Feb. 1953	0	3	0	0	0
135	Mar. 1953	0	3	0	0	0
136	Apr. 1953	0	5	0	0	0
137	May 1953	0	4	0	0	0
138	June 1953	0	3	0	0	0
139	July 1953	0	4	0	0	0
140	Aug. 1953	0	6	0	0	0
141	Sept. 1953	0	5	0	0	0
142	Oct. 1953	0	4	0	0	0
143	Nov. 1953	0	7	0	0	0
144	Dec. 1953	0	6	0	0	0
145	Jan. 1954	0	6	0	0	0
146	Feb. 1954	0	5	0	0	0
147	Mar. 1954	0	4	0	0	0
148	Apr. 1954	0	7	0	0	0
149	May 1954	0	5	0	0	0
150	June 1954	0	7	0	0	0
151	July 1954	0	7	0	0	0
152	Aug. 1954	0	10	0	0	0
153	Sept. 1954	0	9	0	0	0
154	Oct. 1954	0	8	0	0	0
155	Nov. 1954	0	14	0	0	0
156	Dec. 1954	0	11	0	0	0

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.— Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
157	Jan. 1955	0	12	0	0	0
158	Feb. 1955	0	9	0	0	0
159	Mar. 1955	0	7	0	0	0
160	Apr. 1955	0	14	0	0	0
161	May 1955	0	11	0	0	0
162	June 1955	0	10	0	0	0
163	July 1955	0	10	0	0	0
164	Aug. 1955	0	14	0	0	0
165	Sept. 1955	0	13	0	0	0
166	Oct. 1955	0	11	0	0	0
167	Nov. 1955	0	19	0	0	0
168	Dec. 1955	0	14	0	0	0
169	Jan. 1956	0	15	0	0	0
170	Feb. 1956	0	11	0	0	0
171	Mar. 1956	0	8	0	0	0
172	Apr. 1956	0	17	0	0	0
173	May 1956	0	13	0	0	0
174	June 1956	0	11	0	0	0
175	July 1956	0	12	0	0	0
176	Aug. 1956	0	16	0	0	0
177	Sept. 1956	0	14	0	0	0
178	Oct. 1956	0	13	0	0	0
179	Nov. 1956	0	21	0	0	0
180	Dec. 1956	0	17	0	0	0
181	Jan. 1957	0	17	0	0	0
182	Feb. 1957	0	12	0	0	0
183	Mar. 1957	0	9	0	0	0
184	Apr. 1957	0	19	0	0	0
185	May 1957	0	14	0	0	0
186	June 1957	0	12	0	0	0
187	July 1957	0	12	0	0	0
188	Aug. 1957	0	16	0	0	0
189	Sept. 1957	0	14	0	0	0
190	Oct. 1957	0	12	0	0	0
191	Nov. 1957	0	20	0	0	0
192	Dec. 1957	0	16	0	0	0

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
193	Jan. 1958	0	17	0	0	0
194	Feb. 1958	0	12	0	0	0
195	Mar. 1958	0	9	0	0	0
196	Apr. 1958	0	18	0	0	0
197	May 1958	0	14	0	0	0
198	June 1958	0	12	0	0	0
199	July 1958	0	13	0	0	0
200	Aug. 1958	0	18	0	0	0
201	Sept. 1958	0	15	0	0	0
202	Oct. 1958	0	13	0	0	0
203	Nov. 1958	0	22	0	0	0
204	Dec. 1958	0	17	0	0	0
205	Jan. 1959	0	18	0	0	0
206	Feb. 1959	0	13	0	0	0
207	Mar. 1959	0	9	0	0	0
208	Apr. 1959	0	19	0	0	0
209	May 1959	0	14	0	0	0
210	June 1959	0	13	0	0	0
211	July 1959	0	13	0	0	0
212	Aug. 1959	0	18	0	0	0
213	Sept. 1959	0	15	0	0	0
214	Oct. 1959	0	14	0	0	0
215	Nov. 1959	0	22	0	0	0
216	Dec. 1959	0	17	0	0	0
217	Jan. 1960	0	16	0	0	0
218	Feb. 1960	0	11	0	0	0
219	Mar. 1960	0	9	0	0	0
220	Apr. 1960	0	16	0	0	0
221	May 1960	0	13	0	0	0
222	June 1960	0	12	0	0	0
223	July 1960	0	12	0	0	0
224	Aug. 1960	0	15	0	0	0
225	Sept. 1960	0	14	0	0	0
226	Oct. 1960	0	13	0	0	0
227	Nov. 1960	0	18	0	0	0
228	Dec. 1960	0	14	0	0	0

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.— Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
229	Jan. 1961	0	16	0	0	0
230	Feb. 1961	0	12	0	0	0
231	Mar. 1961	0	10	0	0	0
232	Apr. 1961	0	18	0	0	0
233	May 1961	0	15	0	0	0
234	June 1961	0	14	0	0	0
235	July 1961	0	14	0	0	0
236	Aug. 1961	0	19	0	0	0
237	Sept. 1961	0	17	0	0	0
238	Oct. 1961	0	17	0	0	0
239	Nov. 1961	0	19	0	0	0
240	Dec. 1961	0	15	0	0	0
241	Jan. 1962	0	16	0	0	0
242	Feb. 1962	0	14	0	0	0
243	Mar. 1962	0	12	0	0	0
244	Apr. 1962	0	19	0	0	0
245	May 1962	0	16	0	0	0
246	June 1962	0	15	0	0	0
247	July 1962	0	16	0	0	0
248	Aug. 1962	0	21	0	0	0
249	Sept. 1962	0	18	0	0	0
250	Oct. 1962	0	19	0	0	0
251	Nov. 1962	0	22	0	0	1
252	Dec. 1962	0	20	0	0	0
253	Jan. 1963	0	20	0	0	0
254	Feb. 1963	0	20	0	0	0
255	Mar. 1963	0	17	0	0	0
256	Apr. 1963	0	24	0	0	1
257	May 1963	0	19	0	0	0
258	June 1963	0	19	0	0	0
259	July 1963	0	19	0	0	0
260	Aug. 1963	0	24	0	0	1
261	Sept. 1963	0	21	0	0	0
262	Oct. 1963	0	22	0	0	0
263	Nov. 1963	0	24	0	0	1
264	Dec. 1963	0	21	0	0	1

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
265	Jan. 1964	0	22	0	0	1
266	Feb. 1964	0	21	0	0	0
267	Mar. 1964	0	18	0	0	0
268	Apr. 1964	0	25	0	0	1
269	May 1964	0	21	0	0	1
270	June 1964	0	20	0	0	0
271	July 1964	0	21	0	0	0
272	Aug. 1964	0	25	0	0	1
273	Sept. 1964	0	22	0	0	1
274	Oct. 1964	0	24	0	0	1
275	Nov. 1964	0	25	0	0	1
276	Dec. 1964	0	23	0	0	1
277	Jan. 1965	0	22	0	0	1
278	Feb. 1965	0	23	0	0	1
279	Mar. 1965	0	19	0	0	0
280	Apr. 1965	0	26	0	0	1
281	May 1965	0	21	0	0	1
282	June 1965	0	21	0	0	1
283	July 1965	0	21	0	0	1
284	Aug. 1965	0	25	0	0	1
285	Sept. 1965	0	22	0	0	1
286	Oct. 1965	0	23	0	0	1
287	Nov. 1965	0	23	0	0	1
288	Dec. 1965	0	21	0	0	1
289	Jan. 1966	0	21	0	0	1
290	Feb. 1966	0	22	0	0	1
291	Mar. 1966	0	19	0	0	0
292	Apr. 1966	0	26	0	0	1
293	May 1966	0	21	0	0	1
294	June 1966	0	21	0	0	1
295	July 1966	0	21	0	0	1
296	Aug. 1966	0	26	0	0	1
297	Sept. 1966	0	23	0	0	1
298	Oct. 1966	0	25	0	0	1
299	Nov. 1966	0	26	0	0	1
300	Dec. 1966	0	26	0	0	1

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.— Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
301	Jan. 1967	0	25	0	0	1
302	Feb. 1967	0	26	0	0	1
303	Mar. 1967	0	23	0	0	1
304	Apr. 1967	0	30	0	0	1
305	May 1967	0	24	0	0	1
306	June 1967	0	24	0	0	1
307	July 1967	0	25	0	0	1
308	Aug. 1967	0	31	0	0	1
309	Sept. 1967	0	26	0	0	1
310	Oct. 1967	0	29	0	0	1
311	Nov. 1967	0	29	0	0	1
312	Dec. 1967	0	28	0	0	1
313	Jan. 1968	0	27	0	0	1
314	Feb. 1968	0	26	0	0	1
315	Mar. 1968	0	23	0	0	1
316	Apr. 1968	0	30	0	0	1
317	May 1968	0	24	0	0	1
318	June 1968	0	24	0	0	1
319	July 1968	0	25	0	0	1
320	Aug. 1968	0	32	0	0	1
321	Sept. 1968	0	28	0	0	1
322	Oct. 1968	0	31	0	0	1
323	Nov. 1968	0	31	0	0	2
324	Dec. 1968	0	29	0	0	1
325	Jan. 1969	0	28	0	0	1
326	Feb. 1969	0	28	0	0	1
327	Mar. 1969	0	23	0	0	1
328	Apr. 1969	0	32	0	0	2
329	May 1969	0	26	0	0	1
330	June 1969	0	26	0	0	1
331	July 1969	0	24	0	0	1
332	Aug. 1969	0	18	0	0	1
333	Sept. 1969	0	8	0	0	1
334	Oct. 1969	0	8	0	0	1
335	Nov. 1969	0	24	0	0	2
336	Dec. 1969	0	24	0	0	2

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
337	Jan. 1970	0	23	0	0	2
338	Feb. 1970	0	23	0	0	2
339	Mar. 1970	0	19	0	0	1
340	Apr. 1970	0	26	0	0	2
341	May 1970	0	20	0	0	2
342	June 1970	0	20	0	0	2
343	July 1970	0	20	0	0	2
344	Aug. 1970	0	24	0	0	2
345	Sept. 1970	0	21	0	0	2
346	Oct. 1970	0	23	0	0	2
347	Nov. 1970	0	25	0	0	3
348	Dec. 1970	0	22	0	0	2
349	Jan. 1971	0	22	0	0	2
350	Feb. 1971	0	21	0	0	2
351	Mar. 1971	0	17	0	0	2
352	Apr. 1971	0	24	0	0	3
353	May 1971	0	19	0	0	2
354	June 1971	0	19	0	0	2
355	July 1971	0	19	0	0	2
356	Aug. 1971	0	24	0	0	3
357	Sept. 1971	0	21	0	0	2
358	Oct. 1971	0	22	0	0	2
359	Nov. 1971	0	25	0	0	3
360	Dec. 1971	0	22	0	0	3
361	Jan. 1972	0	22	0	0	3
362	Feb. 1972	0	21	0	0	2
363	Mar. 1972	0	17	0	0	2
364	Apr. 1972	0	24	0	0	3
365	May 1972	0	19	0	0	3
366	June 1972	0	19	0	0	3
367	July 1972	0	16	3	0	2
368	Aug. 1972	0	20	38	1	3
369	Sept. 1972	0	18	50	1	2
370	Oct. 1972	0	18	12	0	3
371	Nov. 1972	0	25	133	3	3
372	Dec. 1972	0	32	146	3	2

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.— Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
373	Jan. 1973	0	27	74	2	3
374	Feb. 1973	0	34	113	3	2
375	Mar. 1973	0	38	123	3	2
376	Apr. 1973	0	38	80	2	3
377	May 1973	0	43	104	3	3
378	June 1973	0	57	131	4	3
379	July 1973	1	73	149	5	3
380	Aug. 1973	1	109	184	7	3
381	Sept. 1973	1	96	143	5	3
382	Oct. 1973	0	31	26	1	3
383	Nov. 1973	2	187	249	10	3
384	Dec. 1973	3	201	230	10	2
385	Jan. 1974	1	106	106	5	3
386	Feb. 1974	2	152	151	7	2
387	Mar. 1974	3	163	155	7	2
388	Apr. 1974	2	116	97	5	3
389	May 1974	2	142	122	6	2
390	June 1974	3	179	149	8	2
391	July 1974	4	209	166	9	2
392	Aug. 1974	5	274	203	12	3
393	Sept. 1974	4	217	155	9	3
394	Oct. 1974	1	50	28	2	3
395	Nov. 1974	8	399	273	17	3
396	Dec. 1974	8	369	239	15	3
397	Jan. 1975	4	179	109	7	3
398	Feb. 1975	6	252	155	11	3
399	Mar. 1975	6	261	159	11	2
400	Apr. 1975	4	174	99	7	3
401	May 1975	5	211	124	9	3
402	June 1975	7	260	151	11	2
403	July 1975	8	294	168	13	3
404	Aug. 1975	10	368	205	16	3
405	Sept. 1975	8	285	156	12	3
406	Oct. 1975	1	61	28	2	3
407	Nov. 1975	14	503	274	23	3
408	Dec. 1975	13	451	240	20	3

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
409	Jan. 1976	7	227	116	10	3
410	Feb. 1976	10	317	164	14	3
411	Mar. 1976	10	323	166	15	2
412	Apr. 1976	6	212	104	9	4
413	May 1976	8	257	130	12	3
414	June 1976	10	314	158	15	3
415	July 1976	12	348	174	16	3
416	Aug. 1976	15	436	214	20	4
417	Sept. 1976	11	336	163	16	3
418	Oct. 1976	2	70	29	3	3
419	Nov. 1976	19	543	264	26	4
420	Dec. 1976	19	520	249	25	3
421	Jan. 1977	9	249	116	12	4
422	Feb. 1977	13	346	164	17	3
423	Mar. 1977	13	342	162	17	2
424	Apr. 1977	8	218	99	11	4
425	May 1977	10	264	123	13	3
426	June 1977	12	320	149	17	3
427	July 1977	14	355	164	19	3
428	Aug. 1977	17	440	199	23	4
429	Sept. 1977	13	338	152	18	4
430	Oct. 1977	2	69	27	3	4
431	Nov. 1977	22	544	245	30	4
432	Dec. 1977	21	513	229	28	4
433	Jan. 1978	10	250	109	14	4
434	Feb. 1978	14	348	154	19	3
435	Mar. 1978	15	352	157	20	3
436	Apr. 1978	9	231	99	13	5
437	May 1978	12	278	123	16	4
438	June 1978	14	333	148	19	3
439	July 1978	17	388	172	23	3
440	Aug. 1978	20	475	209	28	4
441	Sept. 1978	16	364	159	22	4
442	Oct. 1978	3	74	28	4	4
443	Nov. 1978	24	544	240	33	5
444	Dec. 1978	24	546	240	33	4

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.— Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
445	Jan. 1979	12	268	117	16	6
446	Feb. 1979	17	370	163	23	5
447	Mar. 1979	17	378	165	24	5
448	Apr. 1979	11	230	101	15	4
449	May 1979	13	274	119	18	3
450	June 1979	15	320	138	21	3
451	July 1979	17	361	152	23	3
452	Aug. 1979	22	483	201	31	0
453	Sept. 1979	17	358	148	23	3
454	Oct. 1979	3	71	27	4	4
455	Nov. 1979	23	507	207	33	6
456	Dec. 1979	23	504	205	33	6
457	Jan. 1980	12	264	104	17	7
458	Feb. 1980	17	378	152	24	6
459	Mar. 1980	20	433	175	28	6
460	Apr. 1980	12	273	108	17	8
461	May 1980	15	322	131	21	6
462	June 1980	18	394	163	26	6
463	July 1980	20	415	173	27	6
464	Aug. 1980	23	496	206	33	7
465	Sept. 1980	18	388	162	26	7
466	Oct. 1980	3	88	32	5	8
467	Nov. 1980	25	524	222	35	7
468	Dec. 1980	26	541	229	37	6
469	Jan. 1981	14	295	122	19	8
470	Feb. 1981	18	387	163	26	7
471	Mar. 1981	19	397	169	27	6
472	Apr. 1981	12	266	109	17	9
473	May 1981	15	322	135	22	7
474	June 1981	18	380	161	26	7
475	July 1981	21	436	185	30	6
476	Aug. 1981	30	631	270	44	8
477	Sept. 1981	25	516	231	36	7
478	Oct. 1981	5	115	50	8	5
479	Nov. 1981	36	748	362	54	8
480	Dec. 1981	37	753	370	54	8

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
481	Jan. 1982	19	406	199	29	9
482	Feb. 1982	26	529	266	38	7
483	Mar. 1982	27	556	285	41	6
484	Apr. 1982	18	376	189	27	10
485	May 1982	21	438	227	32	8
486	June 1982	25	505	266	38	7
487	July 1982	27	551	293	42	7
488	Aug. 1982	33	670	355	51	9
489	Sept. 1982	29	588	311	44	9
490	Oct. 1982	6	138	64	9	9
491	Nov. 1982	34	706	379	55	10
492	Dec. 1982	35	721	388	56	8
493	Jan. 1983	19	389	206	30	8
494	Feb. 1983	26	526	284	42	7
495	Mar. 1983	29	588	319	47	6
496	Apr. 1983	18	372	196	29	10
497	May 1983	22	449	243	36	8
498	June 1983	27	546	298	45	7
499	July 1983	30	618	337	51	7
500	Aug. 1983	32	659	357	54	9
501	Sept. 1983	26	543	292	45	9
502	Oct. 1983	5	134	61	9	10
503	Nov. 1983	39	783	435	67	10
504	Dec. 1983	34	688	381	59	9
505	Jan. 1984	21	427	233	36	11
506	Feb. 1984	27	560	303	47	8
507	Mar. 1984	28	587	320	50	7
508	Apr. 1984	18	400	206	33	12
509	May 1984	23	491	262	42	10
510	June 1984	22	471	256	41	7
511	July 1984	24	507	278	45	7
512	Aug. 1984	26	539	295	48	8
513	Sept. 1984	21	443	241	39	8
514	Oct. 1984	3	94	40	6	8
515	Nov. 1984	31	639	358	59	8
516	Dec. 1984	2	43	26	4	2

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.— Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
517	Jan. 1985	16	324	163	31	4
518	Feb. 1985	0	0	0	0	3
519	Mar. 1985	0	0	0	0	3
520	Apr. 1985	0	0	0	0	4
521	May 1985	0	0	0	0	3
522	June 1985	0	0	0	0	3
523	July 1985	0	0	0	0	3
524	Aug. 1985	0	0	0	0	3
525	Sept. 1985	0	0	0	0	3
526	Oct. 1985	0	0	0	0	3
527	Nov. 1985	0	0	0	0	3
528	Dec. 1985	0	0	0	0	3
529	Jan. 1986	0	0	0	0	3
530	Feb. 1986	0	0	0	0	3
531	Mar. 1986	0	0	0	0	3
532	Apr. 1986	0	0	0	0	4
533	May 1986	0	0	0	0	3
534	June 1986	0	0	0	0	3
535	July 1986	0	0	0	0	3
536	Aug. 1986	0	0	0	0	3
537	Sept. 1986	0	0	0	0	3
538	Oct. 1986	0	0	0	0	3
539	Nov. 1986	0	0	0	0	3
540	Dec. 1986	0	0	0	0	3
541	Jan. 1987	0	0	0	0	2
542	Feb. 1987	0	0	0	0	3
543	Mar. 1987	0	0	0	0	2
544	Apr. 1987	0	0	0	0	3
545	May 1987	0	0	0	0	2
546	June 1987	0	0	0	0	2
547	July 1987	0	0	0	0	3
548	Aug. 1987	0	0	0	0	3
549	Sept. 1987	0	0	0	0	3
550	Oct. 1987	0	0	0	0	3
551	Nov. 1987	0	0	0	0	2
552	Dec. 1987	0	0	0	0	2

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
553	Jan. 1988	0	0	0	0	3
554	Feb. 1988	0	0	0	0	3
555	Mar. 1988	0	0	0	0	3
556	Apr. 1988	0	0	0	0	4
557	May 1988	0	0	0	0	3
558	June 1988	0	0	0	0	3
559	July 1988	0	0	0	0	3
560	Aug. 1988	0	0	0	0	3
561	Sept. 1988	0	0	0	0	3
562	Oct. 1988	0	0	0	0	3
563	Nov. 1988	0	0	0	0	3
564	Dec. 1988	0	0	0	0	3
565	Jan. 1989	0	0	0	0	3
566	Feb. 1989	0	0	0	0	3
567	Mar. 1989	0	0	0	0	3
568	Apr. 1989	0	0	0	0	3
569	May 1989	0	0	0	0	3
570	June 1989	0	0	0	0	3
571	July 1989	0	0	0	0	3
572	Aug. 1989	0	0	0	0	3
573	Sept. 1989	0	0	0	0	3
574	Oct. 1989	0	0	0	0	3
575	Nov. 1989	0	0	0	0	3
576	Dec. 1989	0	0	0	0	3
577	Jan. 1990	0	0	0	0	3
578	Feb. 1990	0	0	0	0	3
579	Mar. 1990	0	0	0	0	3
580	Apr. 1990	0	0	0	0	3
581	May 1990	0	0	0	0	3
582	June 1990	0	0	0	0	3
583	July 1990	0	0	0	0	3
584	Aug. 1990	0	0	0	0	3
585	Sept. 1990	0	0	0	0	3
586	Oct. 1990	0	0	0	0	3
587	Nov. 1990	0	0	0	0	2
588	Dec. 1990	0	0	0	0	3

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.— Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
589	Jan. 1991	0	0	0	0	2
590	Feb. 1991	0	0	0	0	3
591	Mar. 1991	0	0	0	0	3
592	Apr. 1991	0	0	0	0	3
593	May 1991	0	0	0	0	3
594	June 1991	0	0	0	0	3
595	July 1991	0	0	0	0	3
596	Aug. 1991	0	0	0	0	3
597	Sept. 1991	0	0	0	0	3
598	Oct. 1991	0	0	0	0	3
599	Nov. 1991	0	0	0	0	2
600	Dec. 1991	0	0	0	0	3
601	Jan. 1992	0	0	*	0	2
602	Feb. 1992	0	0	*	0	3
603	Mar. 1992	0	0	*	0	3
604	Apr. 1992	0	0	*	0	3
605	May 1992	0	0	*	0	3
606	June 1992	0	0	*	0	3
607	July 1992	0	0	*	0	3
608	Aug. 1992	0	0	*	0	3
609	Sept. 1992	0	0	*	0	3
610	Oct. 1992	0	0	*	0	3
611	Nov. 1992	0	0	*	0	3
612	Dec. 1992	0	0	*	0	3
613	Jan. 1993	0	0	*	0	3
614	Feb. 1993	0	0	*	0	3
615	Mar. 1993	0	0	*	0	3
616	Apr. 1993	0	0	*	0	4
617	May 1993	0	0	*	0	3
618	June 1993	0	0	*	0	3
619	July 1993	0	0	*	0	3
620	Aug. 1993	0	0	*	0	4
621	Sept. 1993	0	0	*	0	3
622	Oct. 1993	0	0	*	0	4
623	Nov. 1993	0	0	*	0	3
624	Dec. 1993	0	0	*	0	3

Appendix A7. Reconstructed (simulated) monthly mean concentrations in finished water for tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1942–June 2008.—Continued

[Concentrations in finished water computed using mixing-model approach; —, water treatment plant not operating; *, model simulations not conducted]

Stress period	Month and year	Concentrations in finished water, in micrograms per liter				
		Tetrachloroethylene (PCE)	Trichloroethylene (TCE)	*Trans*-1,2-dichloroethylene (1,2,-tDCE)	Vinyl chloride (VC)	Benzene
625	Jan. 1994	0	0	*	0	3
626	Feb. 1994	0	0	*	0	4
627	Mar. 1994	0	0	*	0	3
628	Apr. 1994	0	0	*	0	4
629	May 1994	0	0	*	0	3
630	June 1994	0	0	*	0	4
631	July 1994	0	0	*	0	4
632	Aug. 1994	0	0	*	0	4
633	Sept. 1994	0	0	*	0	4
634	Oct. 1994	0	0	*	0	4
635	Nov. 1994	0	0	*	0	3
636	Dec. 1994	0	0	*	0	4
637	Jan. 1995	0	0	*	0	3
638	Feb. 1995	0	0	*	0	4
639	Mar. 1995	0	0	*	0	4
640	Apr. 1995	0	0	*	0	4
641	May 1995	0	0	*	0	3
642	June 1995	0	0	*	0	4
643	July 1995	0	0	*	0	4
644	Aug. 1995	0	0	*	0	4
645	Sept. 1995	0	0	*	0	4
646	Oct. 1995	0	0	*	0	4
647	Nov. 1995	0	0	*	0	3
648	Dec. 1995	0	0	*	0	3
649	Jan. 1996	0	0	*	0	3
650	Feb. 1996	0	0	*	0	4
651	Mar. 1996	0	0	*	0	3
652	Apr. 1996	0	0	*	0	4
653	May 1996	0	0	*	0	3
654–798	June 1996–June 2008	0	0	*	0	0

Appendix A8. Reconstructed (simulated) monthly mean concentrations of tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene in finished water distributed to Holcomb Boulevard family housing areas, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina,1972–1985

Table A8.1. Reconstructed (simulated) monthly mean tetrachloroethylene (PCE) concentrations in finished water distributed to Holcomb Boulevard family housing areas for interconnection events, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, 1972–1985.[1]

[PP, Paradise Point; MP, Midway Park; BM, Berkeley Manor; WV, Watkins Village; —, not applicable; concentration in micrograms per liter (µg/L)]

Month	[2]1972				1973				1974				1975				1976			
	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV
Jan.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Feb.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Mar.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Apr.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
May	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
June	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
July	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Aug.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Sept.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Oct.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Nov.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Dec.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—

Month	1977				1978				1979				1980				1981			
	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV
Jan.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Feb.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mar.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Apr.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1
May	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
June	0	0	0	—	0	1	2	2	0	0	0	0	0	0	1	1	0	0	0	0
July	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aug.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sept.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oct.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nov.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dec.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Month	1982				1983				1984				[4]1985				1986			
	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV
Jan.	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2				
Feb.	0	0	0	0	0	0	0	0	0	0	0	0	3	3	3	3				
Mar.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Apr.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
May	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0				
June	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0				
July	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0				
Aug.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Sept.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Oct.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Nov.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Dec.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				

[1] Derived from multiplying monthly mean concentrations in finished water from the Hadnot Point water treatment plant (Appendix A7) by average percentage (unrounded) of Hadnot Point water distributed through Booster Pump 742 (Table A20); current maximum contaminant level (MCL) for PCE is 5 µg/L

[2] Prior to June 1972 when Holcomb Boulevard water treatment plant came online, 100 percent of Hadnot Point water was delivered to Holcomb Boulevard family housing areas (see Appendix A7 for January–May 1972)

[3] Watkins Village housing was not built and occupied until about 1978 (Faye et al. 2010), and the first documented interconnection occurs during May 1978 (U.S. Marine Corps Camp Lejeune Water Documents CLW #7023, #7031, and #7033)

[4] For period of January 28–February 4, 1985, booster pump 742 operated continuously due to shutdown of Holcomb Boulevard water treatment plant; this continuous event is not included in the Markov Chain analysis

Table A8.2. Reconstructed (simulated) monthly mean trichloroethylene (TCE) concentrations in finished water distributed to Holcomb Boulevard family housing areas for interconnection events, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, 1972–1985.[1]

[PP, Paradise Point; MP, Midway Park; BM, Berkeley Manor; WV, Watkins Village; —, not applicable; concentration in micrograms per liter (µg/L)]

Month	[2]1972				1973				1974				1975				1976			
	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV
Jan.	22	22	22	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Feb.	21	21	21	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Mar.	17	17	17	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Apr.	24	24	24	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
May	19	19	19	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
June	19	19	19	—	0	0	1	—	0	0	0	—	0	0	0	—	1	2	3	—
July	1	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Aug.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Sept.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Oct.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Nov.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Dec.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—

Month	1977				1978				1979				1980				1981			
	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV
Jan.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Feb.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mar.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Apr.	0	1	2	—	0	0	0	0	0	1	2	1	0	0	0	0	0	4	39	28
May	1	1	3	—	0	2	6	4	0	1	3	2	0	0	0	0	0	4	13	10
June	1	2	3	—	3	23	51	38	0	2	6	4	2	8	17	13	0	4	10	7
July	1	2	3	—	0	0	1	1	0	1	4	2	0	0	0	0	0	2	4	3
Aug.	1	2	4	—	0	0	0	0	0	2	5	3	0	0	0	0	0	2	6	4
Sept.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oct.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nov.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dec.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Month	1982				1983				1984				[4]1985				1986			
	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV
Jan.	0	0	0	0	0	0	0	0	0	0	0	0	34	31	32	34				
Feb.	0	0	0	0	0	0	0	0	0	0	0	0	66	53	54	56				
Mar.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Apr.	0	3	9	7	0	0	0	0	0	2	5	3	0	0	0	0				
May	1	6	20	13	1	5	14	10	0	0	0	0	0	0	0	0				
June	0	4	10	7	0	0	2	2	0	0	0	0	0	0	0	0				
July	0	4	12	8	0	0	3	2	0	0	0	0	0	0	0	0				
Aug.	1	3	6	4	0	2	5	3	0	0	0	0	0	0	0	0				
Sept.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Oct.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Nov.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Dec.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				

[1] Derived from multiplying monthly mean concentrations in finished water from the Hadnot Point water treatment plant (Appendix A7) by average percentage (unrounded) of Hadnot Point water distributed through Booster Pump 742 (Table A20); current maximum contaminant level (MCL) for PCE is 5 µg/L

[2] Prior to June 1972 when Holcomb Boulevard water treatment plant came online, 100 percent of Hadnot Point water was delivered to Holcomb Boulevard family housing areas (see Appendix A7 for January–May 1972)

[3] Watkins Village housing was not built and occupied until about 1978 (Faye et al. 2010), and the first documented interconnection occurs during May 1978 (U.S. Marine Corps Camp Lejeune Water Documents CLW #7023, #7031, and #7033)

[4] For period of January 28–February 4, 1985, booster pump 742 operated continuously due to shutdown of Holcomb Boulevard water treatment plant; this continuous event is not included in the Markov Chain analysis

Table A8.3. Reconstructed (simulated) monthly mean *trans*-1,2-dichloroethylene (1,2-tDCE) concentrations in finished water distributed to Holcomb Boulevard family housing areas for interconnection events, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, 1972–1985.[1]

[PP, Paradise Point; MP, Midway Park; BM, Berkeley Manor; WV, Watkins Village; —, not applicable; concentration in micrograms per liter (µg/L)]

Month	[2]1972				1973				1974				1975				1976			
	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV
Jan.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Feb.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Mar.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Apr.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
May	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
June	0	0	0	—	0	1	1	—	0	0	0	—	0	0	0	—	0	1	2	—
July	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Aug.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Sept.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Oct.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Nov.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Dec.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—

Month	1977				1978				1979				1980				1981			
	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV
Jan.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Feb.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mar.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Apr.	0	1	1	—	0	0	0	0	0	1	1	1	0	0	0	0	0	2	16	12
May	0	1	1	—	0	1	3	2	0	0	1	1	0	0	0	0	0	2	6	4
June	0	1	1	—	2	10	22	17	0	1	3	2	1	3	7	5	0	2	4	3
July	0	1	2	—	0	0	0	0	0	0	1	1	0	0	0	0	0	1	2	1
Aug.	0	1	2	—	0	0	0	0	0	1	2	1	0	0	0	0	0	1	3	2
Sept.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oct.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nov.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dec.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Month	1982				1983				1984				[4]1985				1986			
	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV
Jan.	0	0	0	0	0	0	0	0	0	0	0	0	17	16	16	17				
Feb.	0	0	0	0	0	0	0	0	0	0	0	0	33	27	27	28				
Mar.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Apr.	0	2	4	3	0	0	0	0	0	1	2	2	0	0	0	0				
May	0	3	10	7	0	3	8	5	0	0	0	0	0	0	0	0				
June	0	2	6	4	0	0	1	1	0	0	0	0	0	0	0	0				
July	0	2	6	4	0	0	2	1	0	0	0	0	0	0	0	0				
Aug.	0	2	3	2	0	1	3	2	0	0	0	0	0	0	0	0				
Sept.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Oct.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Nov.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Dec.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				

[1] Derived from multiplying monthly mean concentrations in finished water from the Hadnot Point water treatment plant (Appendix A7) by average percentage (unrounded) of Hadnot Point water distributed through Booster Pump 742 (Table A20); current maximum contaminant level (MCL) for PCE is 5 µg/L

[2] Prior to June 1972 when Holcomb Boulevard water treatment plant came online, 100 percent of Hadnot Point water was delivered to Holcomb Boulevard family housing areas (see Appendix A7 for January–May 1972)

[3] Watkins Village housing was not built and occupied until about 1978 (Faye et al. 2010), and the first documented interconnection occurs during May 1978 (U.S. Marine Corps Camp Lejeune Water Documents CLW #7023, #7031, and #7033)

[4] For period of January 28–February 4, 1985, booster pump 742 operated continuously due to shutdown of Holcomb Boulevard water treatment plant; this continuous event is not included in the Markov Chain analysis

Table A8.4. Reconstructed (simulated) monthly mean vinyl chloride (VC) concentrations in finished water distributed to Holcomb Boulevard family housing areas for interconnection events, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, 1972–1985.[1]

[PP, Paradise Point; MP, Midway Park; BM, Berkeley Manor; WV, Watkins Village; —, not applicable; concentration in micrograms per liter (µg/L)]

Month	[2]1972				1973				1974				1975				1976			
	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV
Jan.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Feb.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Mar.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Apr.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
May	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
June	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
July	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Aug.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Sept.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Oct.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Nov.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Dec.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—

Month	1977				1978				1979				1980				1981			
	PP	MP	BM	[3]WV	PP	MP	BM	[3]WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV
Jan.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Feb.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mar.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Apr.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2
May	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
June	0	0	0	—	0	1	3	2	0	0	0	0	0	1	1	1	0	0	1	0
July	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aug.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sept.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oct.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nov.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dec.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Month	1982				1983				1984				[4]1985				1986			
	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV
Jan.	0	0	0	0	0	0	0	0	0	0	0	0	3	3	3	3				
Feb.	0	0	0	0	0	0	0	0	0	0	0	0	6	5	5	5				
Mar.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Apr.	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0				
May	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0				
June	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0				
July	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0				
Aug.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Sept.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Oct.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Nov.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Dec.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				

[1] Derived from multiplying monthly mean concentrations in finished water from the Hadnot Point water treatment plant (Appendix A7) by average percentage (unrounded) of Hadnot Point water distributed through Booster Pump 742 (Table A20); current maximum contaminant level (MCL) for PCE is 5 µg/L

[2] Prior to June 1972 when Holcomb Boulevard water treatment plant came online, 100 percent of Hadnot Point water was delivered to Holcomb Boulevard family housing areas (see Appendix A7 for January–May 1972)

[3] Watkins Village housing was not built and occupied until about 1978 (Faye et al. 2010), and the first documented interconnection occurs during May 1978 (U.S. Marine Corps Camp Lejeune Water Documents CLW #7023, #7031, and #7033)

[4] For period of January 28–February 4, 1985, booster pump 742 operated continuously due to shutdown of Holcomb Boulevard water treatment plant; this continuous event is not included in the Markov Chain analysis

Table A8.5. Reconstructed (simulated) monthly mean benzene concentrations in finished water distributed to Holcomb Boulevard family housing areas for interconnection events, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, 1972–1985.[1]

[PP, Paradise Point; MP, Midway Park; BM, Berkeley Manor; WV, Watkins Village; —, not applicable; concentration in micrograms per liter (µg/L)]

Month	[2]1972			[3]WV	1973			[3]WV	1974			[3]WV	1975			[3]WV	1976			[3]WV
	PP	MP	BM		PP	MP	BM		PP	MP	BM		PP	MP	BM		PP	MP	BM	
Jan.	3	3	3	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Feb.	3	3	3	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Mar.	2	2	2	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Apr.	3	3	3	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
May	3	3	3	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
June	3	3	3	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
July	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Aug.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Sept.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Oct.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Nov.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—
Dec.	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—	0	0	0	—

Month	1977			[3]WV	1978			[3]WV	1979			WV	1980			WV	1981			WV
	PP	MP	BM		PP	MP	BM		PP	MP	BM		PP	MP	BM		PP	MP	BM	
Jan.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Feb.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mar.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Apr.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
May	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
June	0	0	0	—	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
July	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aug.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sept.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oct.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nov.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dec.	0	0	0	—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Month	1982				1983				1984				[4]1985				1986			
	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV	PP	MP	BM	WV
Jan.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Feb.	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1				
Mar.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Apr.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
June	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
July	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Aug.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Sept.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Oct.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Nov.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Dec.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				

[1] Derived from multiplying monthly mean concentrations in finished water from the Hadnot Point water treatment plant (Appendix A7) by average percentage (unrounded) of Hadnot Point water distributed through Booster Pump 742 (Table A20); current maximum contaminant level (MCL) for PCE is 5 µg/L

[2] Prior to June 1972 when Holcomb Boulevard water treatment plant came online, 100 percent of Hadnot Point water was delivered to Holcomb Boulevard family housing areas (see Appendix A7 for January–May 1972)

[3] Watkins Village housing was not built and occupied until about 1978 (Faye et al. 2010), and the first documented interconnection occurs during May 1978 (U.S. Marine Corps Camp Lejeune Water Documents CLW #7023, #7031, and #7033)

[4] For period of January 28–February 4, 1985, booster pump 742 operated continuously due to shutdown of Holcomb Boulevard water treatment plant; this continuous event is not included in the Markov Chain analysis

Appendix A9. Questions and answers

What is the purpose of the ATSDR health studies?

The three distribution systems of interest to this study—Tarawa Terrace, Hadnot Point, and Holcomb Boulevard—have historically supplied drinking water to the majority of family housing units at the U.S. Marine Corps Base (USMCB) Camp Lejeune, North Carolina. Groundwater within the Tarawa Terrace water treatment plant (WTP) service area was contaminated mostly with tetrachloroethylene (PCE). Groundwater within the Hadnot Point WTP (HPWTP) service area was contaminated mostly with trichloroethylene (TCE), as well as PCE and refined petroleum products, such as benzene, toluene, ethylbenzene, and xylenes (BTEX). Groundwater within the Holcomb Boulevard WTP (HBWTP) service area remained largely uncontaminated with the exception of intermittent supply by contaminated Hadnot Point water during 1972–1985. The contaminated Hadnot Point wells were continuously used until 1985. The ATSDR health studies are evaluating the potential for health effects from exposures to volatile organic compounds (VOCs) such as PCE, TCE, *trans*,1-2,dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene in drinking water at USMCB Camp Lejeune.

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

Only a few studies have looked at the risk of adverse health effects from these volatile organic compounds (VOCs) such as TCE and PCE in drinking water. These studies are unique because they will estimate monthly levels of drinking-water contaminants to determine exposures.

What is in the ATSDR reports about the Hadnot Point and Holcomb Boulevard drinking-water systems?

Chapter A provides a summary of detailed technical findings for the HPWTP and HBWTP service areas that are presented in Chapters B, C, and D and 8 supplemental information texts that provide details on water-modeling analyses . Included with Chapter A is a compact disc, read-only memory (CD-ROM) that contains all chapter reports (A–D), supplemental information texts (Chapter A, Supplements 1–8), selected calibrated model input files, and selected simulated water-supply well and finished-water concentrations. Information from the water-modeling analyses will be given to researchers conducting the health study.

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

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

What is a water model?

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

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

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

The historical reconstruction process required information and data pertinent to the physical characteristics of the groundwater-flow system, conservation principles that describe the flow system, the specific data on the contaminants such as PCE, TCE, vinyl chloride (VC), and benzene, and the waterdistribution systems. The following specific data needs were required:

- aquifer characteristics: geohydrologic, hydraulic, water production, fate, transformation, and transport;
- chemical properties characteristics: physical, fate, transformation, and transport;
- water-supply well characteristics: construction dates, operating schedules, and dates taken out of service; and
- water-distribution system characteristics: pipeline characteristics, storage-tank geometry, pumps, water-production data, and water-quality parameters.

Information and data used to conduct the historical reconstruction analysis were obtained from a variety of sources. These sources included ATSDR, U.S. Environmental Protection Agency, Environmental Management Division of USMCB Camp Lejeune, U.S. Geological Survey, private consulting organizations, published scientific literature, and community groups representing former marines and their families. Searchable electronic databases—on DVD format—of information and data sources used to conduct the historical reconstruction analysis are available by request from the ATSDR Camp Lejeune Web site.

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

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

Why is ATSDR providing simulated VOC concentrations in finished water at the HPWTP rather than at locations of specific housing units for Hadnot Point?

ATSDR did in-depth reviews of historical data, including water-supply well and WTP operational data when available. ATSDR concluded that the Hadnot Point water-distribution system—including the HPWTP—was *not* interconnected with other water-distribution systems at Camp Lejeune for any time longer than 2 weeks. All water arriving at the HPWTP was obtained solely from supply wells providing water to the HPWTP. Also, water provided by all wells to the HPWTP was mixed prior to delivery to residents of Hadnot Point and other facilities. On a monthly basis, the concentration of VOCs delivered to specific housing units and other facilities within the HPWTP service area was assumed to be the same as the simulated concentration of VOCs in finished water at the HPWTP.

During the selected months of June 1972–February 1985, the HPWTP did provide contaminated finished water to Holcomb Boulevard housing areas. During these brief periods, a more sophisticated water model was necessary to determine the VOC concentrations in finished water at different housing areas throughout the Holcomb Boulevard water-distribution system.

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

No. The available data are not specific enough to accurately estimate daily levels of VOCs (PCE, TCE, 1,2-tDCE, VC, and benzene) in the Hadnot Point–Holcomb Boulevard (HPHB) study area. The modeling approach used by ATSDR provides a high level of detail to estimate monthly VOC concentrations in finished water at the HPWTP and Holcomb Boulevard housing areas. It is assumed that simulated monthly concentrations of VOCs represent a typical day during a month. The actual level that a person may have been exposed to could have been lower or higher than the estimated average.

Were my family and I exposed to other contaminants besides PCE, TCE, or benzene in finished water while living in family housing at Hadnot Point or Holcomb Boulevard?

Yes. At Hadnot Point, some of the TCE degraded in the groundwater to 1,2-tDCE and VC. Degradation by-products of TCE were found in water samples from Hadnot Point water-supply wells, and these data are reported in the Chapter C and Chapter D reports. Historical reconstruction analyses conducted by ATSDR and its partners provide simulated monthly concentrations of PCE, TCE, 1,2-tDCE, VC, and benzene.

How can I get a list of the monthly VOC concentrations in finished water that my family and I were exposed to at Hadnot Point or Holcomb Boulevard?

A list of reconstructed (estimated) monthly concentrations for contaminants of concern to the ATSDR health studies are provided in the HPHB Chapter A report, which is available on the ATSDR Camp Lejeune Web site.

ATSDR's historical reconstruction analysis documents that HPWTP finished water was contaminated with TCE that most likely first exceeded the maximum contaminant level (MCL) of 5 micrograms per liter (µg/L) during August 1953 and reached a maximum value of 783 µg/L during November 1983. What does this mean in terms of my family's health?

ATSDR's exposure estimates cannot be used alone to determine whether you, or your family, suffered any health effects as a result of past exposure to TCE-contaminated drinking water at USMCB Camp Lejeune. The studies that the ATSDR is conducting may help determine if there are associations between certain health effects and exposures to contaminated drinking water. Epidemiological studies such as these help improve scientific knowledge of the health effects of these chemicals.

The U.S. Environmental Protection Agency in 2011 classified TCE as "carcinogenic in humans by all routes of exposure," and in 2012 classified PCE as "likely carcinogenic in humans by all routes of exposure." However, the lowest levels of TCE and PCE in finished water at which health effects begin to occur is unknown. The MCL for TCE was set at 5 µg/L (or 5 parts per billion) in 1989, and the MCL for PCE was set at 5 µg/L in 1992 because, given the technology at that time, 5 µg/L was the lowest level that water systems could be required to achieve. In addition, VC and benzene are known to cause cancers in humans.

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

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

How certain is ATSDR that finished water exceeding the MCL for TCE was delivered from the HPWTP beginning August 1953?

Historical data on the levels of contaminants in the drinking water are very limited. That is why there is uncertainty and variability concerning when the MCL of 5 µg/L was reached at the HPWTP. Therefore, ATSDR conducted simulations to estimate ranges of dates for exceeding the MCLs because of data limitations and modeling uncertainty.

How does ATSDR know where all of the Hadnot Point and Holcomb Boulevard water-supply wells were located if some have been destroyed? What is the accuracy of this information?

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

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

Throughout this investigation, ATSDR has sought external expert input and review. Activities included convening an expert review panel and submitting individual chapter reports and supplemental information texts to outside national and international experts for technical reviews. For example, during April 29–30, 2009, ATSDR convened an external expert panel to review the approach used in conducting the historical reconstruction analysis. The panel also provided input and recommendations on preliminary analyses and modeling. ATSDR also used technical comments from outside expert reviewers when finalizing reports on HPHB water-modeling analyses.

Where and how can I get a copy of this ATSDR report and the information and data that were used in the Hadnot Point–Holcomb Boulevard water-modeling analyses?

A limited number of printed copies of this report (Chapter A) and other HPHB chapter (C and D) will be available to interested parties and placed in public repositories. Electronic versions of all chapter reports and supplemental information texts will be available on the ATSDR Camp Lejeune Web site at *http://www.atsdr.cdc.gov/sites/lejeune/index.html*.

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Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina—Chapter A: Summary and Findings