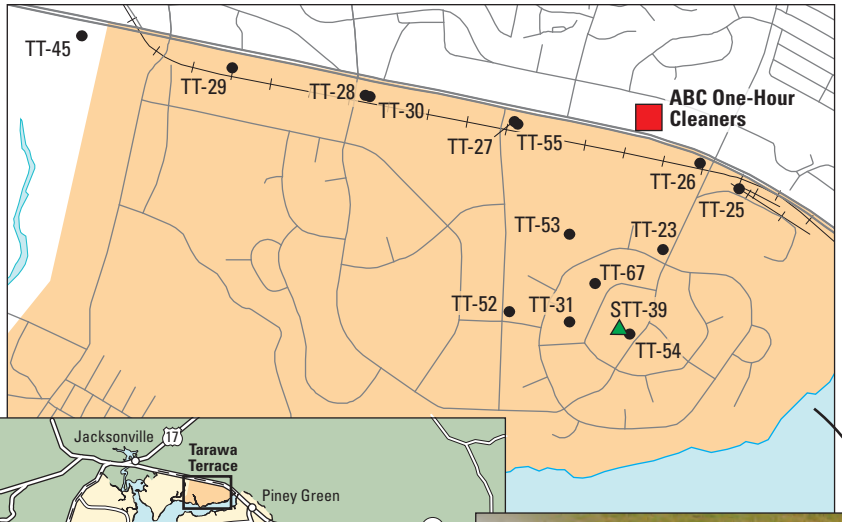
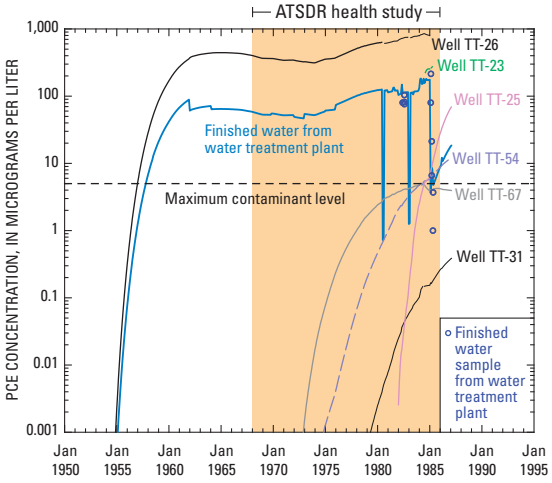
Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions

Chapter E: Occurrence of Contaminants in Groundwater





DEPARTMENT OF HEALTH & HUMAN SERVICES • USA

ATSDR
AGENCY FOR TOXIC SUBSTANCES AND DISEASE REGISTRY

Atlanta, Georgia–December 2007

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

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

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

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

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

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Chapter E: Occurrence of Contaminants in Groundwater

By Robert E. Faye and Joseph W. Green, Jr.

Agency for Toxic Substances and Disease Registry
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Foreword

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

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

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

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

An electronic version of this report, *Chapter E: Occurrence of Contaminants in Groundwater*, will be made available on the ATSDR Camp Lejeune Web site at *http://www.atsdr.cdc.gov/sites/lejeune/index.html*. Readers interested solely in a summary of this report or any of the other reports should refer to *Chapter A: Summary of Findings* that also is available at the ATSDR Web site.

Contents

Figures

Tables

Conversion Factors

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
million gallons (MG)	3,785	cubic meter (m^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
million gallons per day (MGD)	3,785	cubic meters per day (m^3/d)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

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

Altitude, as used in this report, refers to distance above the vertical datum.

Concentration Conversion Factors

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

Glossary and Abbreviations

ATSDR	Agency for Toxic Substances and Disease Registry
BTEX	benzene, toluene, ethylene, and xylene
DCE	DCE dichloroethylene 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
GIS	Geographic Information System
NCDNRCD	North Carolina Department of Natural Resources and Community Development
ND	not detected
PCE	tetrachloroethene, tetrachloroethylene, 1,1,2,2-tetrachloroethylene, or perchloroethylene; also known as PERC® or PERK®
TCE	1,1,2-trichloroethene, 1,1,2-trichloroethylene, or trichloroethylene
USEPA	U.S. Environmental Protection Agency
VOCs	volatile organic compounds
WTP	water treatment plant

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

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

By Robert E. Faye[1] and Joseph W. Green, Jr.[2]

Abstract

Two of three water-distribution systems that have historically supplied drinking water to family housing at U.S. Marine Corps Base Camp Lejeune, North Carolina, were contaminated with volatile organic compounds (VOCs). Tarawa Terrace was contaminated mostly with tetrachloroethylene (PCE), and Hadnot Point was contaminated mostly with trichloroethylene (TCE). Because scientific data relating to the harmful effects of VOCs on a child or fetus are limited, the Agency for Toxic Substances and Disease Registry (ATSDR), an agency of the U.S. Department of Health and Human Services, is conducting an epidemiological study to evaluate potential associations between in utero and infant (up to 1 year of age) exposures to VOCs in contaminated drinking water at Camp Lejeune and specific birth defects and childhood cancers. The study includes births occurring during the period 1968–1985 to women who were pregnant while they resided in family housing at Camp Lejeune. Because limited measurements of contaminant and exposure data are available to support the epidemiological study, ATSDR is using modeling techniques to reconstruct historical conditions of groundwater flow, contaminant fate and transport, and the distribution of drinking water contaminated with VOCs delivered to family housing areas. This report, Chapter E, describes the occurrence and distribution of tetrachloroethylene and related contaminants within the Upper Castle Hayne aquifer system at and in the vicinity of the Tarawa Terrace housing area. There also is a brief description of the occurrence and distribution of benzene and toluene.

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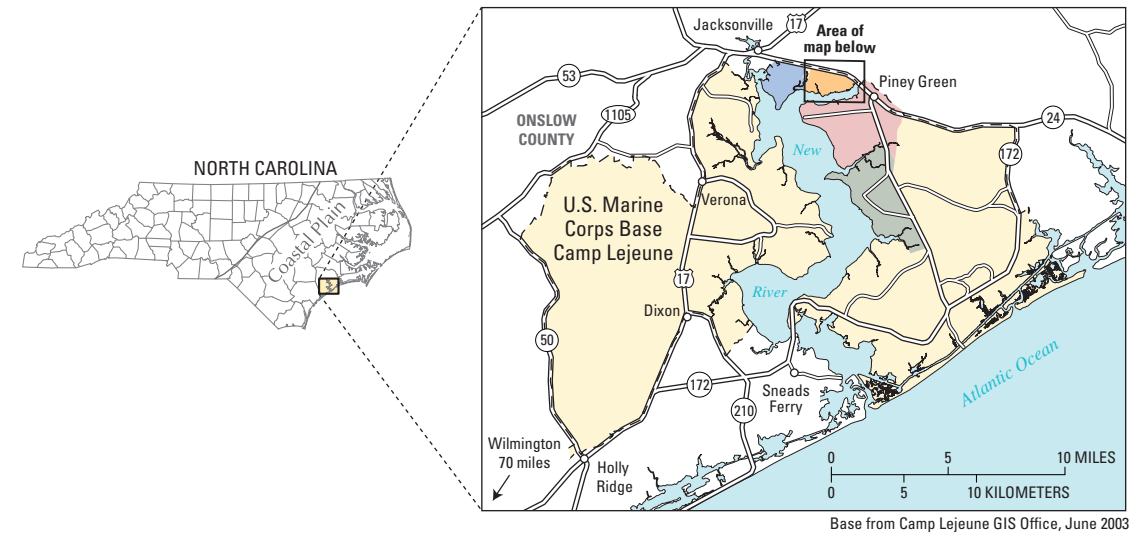
[2]Oak Ridge Institute for Science and Education, Agency for Toxic Substances and Disease Registry, Atlanta, Georgia.

Background

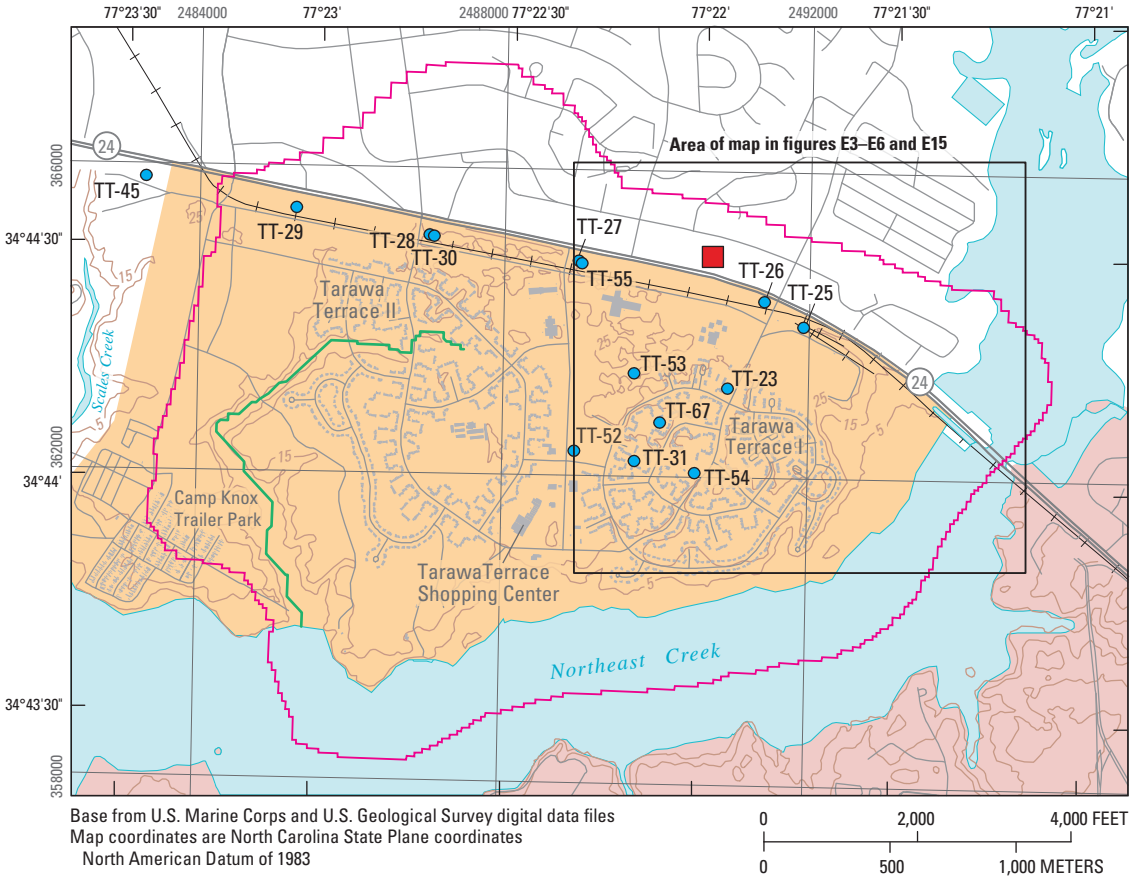
U.S. Marine Corps Base Camp Lejeune is located in the Coastal Plain of North Carolina, in Onslow County, south of the City of Jacksonville and about 70 miles northeast of the City of Wilmington, North Carolina. The major cultural and geographic features of Camp Lejeune are shown in Figure E1. A major focus of this investigation is the water-supply and distribution network at Tarawa Terrace, a noncommissioned officers' housing area located near the northwest corner of the base (Figure E1). Tarawa Terrace was constructed during 1951 and was subdivided into housing areas I and II. Areas I and II originally contained a total of 1,846 housing units described as single, duplex, and multiplex, and accommodated a resident population of about 6,000 persons (Sheet 3 of 18, Map of Tarawa Terrace II Quarters, June 30, 1961; Sheet 7 of 34, Tarawa Terrace I Quarters, July 31, 1984). The general area of Tarawa Terrace is bordered on the east by Northeast Creek, to the south by New River and Northeast Creek, and generally to the west and north by drainage boundaries of these streams.

Groundwater is the source of contaminants that occurred in the water-distribution system at Tarawa Terrace and was supplied to the distribution system via water-supply wells open to one or several water-bearing zones of the Castle Hayne aquifer system (Table E1). Faye (2007a) provides a complete description of the geohydrologic framework at and in the vicinity of Tarawa Terrace, including data and maps that summarize the geometry of individual aquifers and confining units.

Contamination of groundwater by a halogenated hydrocarbon—tetrachloroethylene (PCE)—was first detected in water supplies at Tarawa Terrace during 1982 (Grainger Laboratories, Camp Lejeune water document CLW 0592, written communication, August 10, 1982). The source of contamination was later determined to be ABC One-Hour Cleaners, located on State Route 24 (SR 24) and west and slightly north of several Tarawa Terrace water-supply wells (Shiver 1985, Figure 4). Production at water-supply wells TT-26 and TT-23 (Figure E1)



Base from Camp Lejeune GIS Office, June 2003



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

EXPLANATION

Historical water-supply areas of Camp Lejeune Military Reservation

- Montford Point
- Tarawa Terrace
- Holcomb Boulevard
- Hadnot Point
- **Other areas of Camp Lejeune Military Reservation**

- **Model boundary**—Active domain
- **Frenchmans Creek**
- TT-26 **Water-supply well and identification**
- **ABC One-Hour Cleaners**

Figure E1. U.S. Marine Corps Base Camp Lejeune, Tarawa Terrace water-supply wells, Tarawa Terrace Shopping Center, and ABC One-Hour Cleaners, Onslow County, North Carolina.

Table E1. Geohydrologic units and unit thickness, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[Units are listed shallowest to deepest and youngest to oldest; N/A, not applicable]

Geohydrologic unit	Thickness range, in feet
Tarawa Terrace aquifer	8 to 30
Tarawa Terrace confining unit	8 to 20
Castle Hayne Aquifer System	
Upper Castle Hayne aquifer–River Bend unit	16 to 56
Local confining unit	7 to 17
Upper Castle Hayne aquifer–Lower unit	8 to 30
Middle Castle Hayne confining unit	12 to 28
Middle Castle Hayne aquifer	32 to 90
Lower Castle Hayne confining unit	18 to 30
Lower Castle Hayne aquifer	41 to 64
Beaufort confining unit	N/A

was terminated during February 1985 because of contamination by PCE and related degradation products—trichloroethylene (TCE) and dichloroethylene (DCE) (Table E2). TCE degrades to DCE and its related isomers 1,1-dichloroethylene, *trans*-1,2-dichloroethylene (1,2-tDCE) and *cis*-1,2-dichloroethylene (1,2-cDCE), all of which ultimately degrade to vinyl chloride. The majority of analyses for DCE available for this study were reported as 1,2-tDCE and, unless otherwise noted, are similarly reported herein.[3]

Historical reconstruction characteristically includes the application of simulation tools, such as models, to re-create or represent past conditions. At Camp Lejeune, historical reconstruction methods include linking materials mass balance (mixing) and water-distribution system models to groundwater fate and transport models. Groundwater fate and transport models are based to a large degree on groundwater-flow velocities or specific discharges simulated by a groundwater-flow model. The groundwater-flow model is characterized by the vertical and spatial distribution of aquifers and confining units and their respective hydraulic characteristics, such as hydraulic conductivity and specific storage. Calibration of fate and transport models requires knowledge of temporal, spatial, and vertical occurrences of specific contaminant constituents within water-bearing units open to supply and other observation wells. This report describes these contaminant occurrences to the extent possible, given available data, and provides much of the basic information necessary to calibrate the fate and transport model.[4]

[3]A detailed discussion of the properties, degradation pathways, and degradation by-products of volatile organic (nontrihalomethane) compounds commonly detected in groundwater in the United States is provided in the Chapter D report (Lawrence 2007).

[4]Detailed discussions and descriptions of the calibration of groundwater-flow and fate and transport models are provided in the Chapter C (Faye and Valenzuela 2007) and Chapter F (Faye 2007b) reports, respectively.

Purpose of Study

This study describes the occurrence and distribution of PCE and related contaminants within the Castle Hayne aquifer system at and in the vicinity of the Tarawa Terrace housing area, U.S. Marine Corps Base Camp Lejeune, North Carolina. Calibration of the fate and transport model used for historical reconstruction was partly based on spatial, temporal, and vertical occurrences of PCE contamination described herein. The occurrence and distribution of benzene and toluene in groundwater at Tarawa Terrace, within possible capture zones of water-supply wells, also are briefly described in the "Previous Investigations" section. This study also describes the occurrence of PCE, benzene, and related constituents in finished water supplied by the Tarawa Terrace water treatment plant (WTP).

Geohydrologic Framework

A total of nine aquifers and confining units that occur between land surface and the top of the Beaufort Formation in the vicinity of Tarawa Terrace were identified and named after local cultural features where the units were first identified or as subdivisions of the Castle Hayne Formation. From shallowest to deepest, and youngest to oldest, these units are the Tarawa Terrace aquifer, Tarawa Terrace confining unit, Upper Castle Hayne aquifer–River Bend unit, Local confining unit, Upper Castle Hayne aquifer–Lower unit, Middle Castle Hayne confining unit, Middle Castle Hayne aquifer, Lower Castle Hayne confining unit, and Lower Castle Hayne aquifer. The base of the Lower Castle Hayne aquifer is at the top of the Beaufort confining unit and corresponds to the base of freshwater flow of interest to this study. The Beaufort confining unit is at the top of the Beaufort Formation. The River Bend unit of the Upper Castle Hayne aquifer is so named to conform to the upper part of the "Castle Hayne aquifer" described by Cardinell et al. (1993). As defined for this study, the River Bend unit probably includes sediments of the Castle Hayne Formation but only at the base, if at all. The Local confining unit separates the River Bend and Lower units of the Upper Castle Hayne aquifer and conforms in areal extent and thickness to the clay or sandy clay which approximates the top of the Castle Hayne Formation, as defined by Faye (2007a). The aquifers and confining units, ranging from the top of the Upper Castle Hayne aquifer–River Bend unit to the top of the Beaufort confining unit, are inclusive of the Castle Hayne aquifer system, as defined for this study. The water table fluctuates seasonally and generally occurs near the top of the Upper Castle Hayne aquifer–River Bend unit. Available water-level data from paired wells, which are individually open to the Upper Castle Hayne aquifer–River Bend and Lower units in the vicinity of ABC One-Hour Cleaners and northern Tarawa Terrace (Figures E4 and E5), indicate little or no head difference between the aquifers or a slightly downward gradient from the River Bend to the Lower unit (Roy F. Weston, Inc. 1992, 1994). Aquifers of the Castle

Table E2. Summary of selected analyses for tetrachloroethylene (PCE), trichloroethylene (TCE), and *trans*-1,2-dichloroethylene (1,2-tDCE) in water samples collected at water-supply wells during ABC One-Hour Cleaners Operable Units 1 and 2, by the North Carolina Department of Natural Resources and Community Development, and by the U.S. Navy, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter; —, constituent not determined; ND, not detected; J, estimated value; #, *cis*-1,2-dichloroethylene]

Site name	Date	PCE concentration, in µg/L	TCE concentration, in µg/L	1,2-tDCE concentration, in µg/L
[1]RW1	7/12/1991	[2]ND	[2]ND	[2]ND#
[1]RW2	7/12/1991	[2]760	[2]ND	[2]ND#
[1]RW3	7/12/1991	[2]ND	[2]ND	[2]ND#
[3,4]TT-23	7/1984	—	[5]37.0	—
	1/16/1985	[6]132	[6]5.8	[6]11
	2/12/1985	[6]37.0	[6]1.8	[6]1.9
	2/19/1985	[2]26.2	[2]53.5	[2]Trace
	2/19/1985	[6]ND	[6]ND	[6]13
	3/11/1985	**[2]14.9**	**[2]ND**	**[2]ND**
	3/11/1985	**[6]16**	**[6]1.3**	**[6]1.2**
	3/12/1985	**[2]40.6**	**[2]ND**	**[2]ND**
	3/12/1985	**[6]48**	**[6]2.4**	**[6]2.8**
	4/9/1985	[2]ND	[2]ND	[2]ND
	9/25/1985	[2]4.0	[2]0.2	—
	7/11/1991	[7]ND	[7]ND	[7]ND#
[3]TT-25	7/1984	—	[5]Trace	—
	2/5/1985	[6]ND	[6]ND	[6]ND
	4/9/1985	[2]ND	[2]ND	[2]ND
	9/25/1985	[2]0.43	—	—
	10/29/1985	[6]ND	[6]ND	[6]ND
	11/4/1985	[6]ND	[6]ND	[6]ND
	11/12/1985	[6]ND	[6]ND	[6]ND
	12/3/1985	[6]ND	[6]ND	[6]ND
	7/11/1991	[7]23	[7]5.8	[7]1.4J#
[3]TT-26	7/1984	—	[5]3.9	—
	1/16/1985	[6]1,580	[6]57	[6]92.0
	2/12/1985	[6]3.8	[6]ND	[6]ND
	2/19/1985	[2]55.2	[2]3.9	[2]Trace
	2/19/1985	[6]64	[6]4.1	[6]9.5
	4/9/1985	[2]630	[2]18	[2]1.4
	6/24/1985	[2]1,160	[2]24	[2]5
	9/25/1985	[2]1,100	[2]27	[2]1.6
	7/11/1991	[7]340	[7]56J	[7]ND#
	7/11/1991	[7]360	[7]62J	[7]15J#
[3]TT-30	2/6/1985	[6]ND	[6]ND	[6]ND
[3]TT-31	7/1984	—	[5]ND	—
	2/6/1985	[6]ND	[6]ND	[6]ND
[3]TT-52	2/6/1985	[6]ND	[6]ND	[6]ND
[3]TT-54	2/6/1985	[6]ND	[6]ND	[6]ND
	7/11/1991	[7]ND	[7]ND	[7]ND
[3]TT-67	2/6/1985	[6]ND	[6]ND	[6]ND

[1]See Figure E3 for location

[2]Detection limit = 2 µg/L

[3]See Figure E1 for location

[4]Well TT-23 was operated for 2 hours prior to sampling on 3/11/1985 and 22 hours prior to sampling on 3/12/1985 (bold)

[5]Detection limit unknown

[6]Detection limit = 10 µg/L

[7]Detection limit = 5 µg/L

Hayne aquifer system are composed largely of fine silty and clayey sand. Confining units are clay, sandy clay, or silty clay. For detailed descriptions of well and geohydrologic data used to develop the geohydrologic framework of the Castle Hayne aquifer system at Tarawa Terrace and vicinity, refer to Chapter B (Faye 2007a).

Previous Investigations

During August 1982, routine gas chromatograph/mass-spectrometer (GC/MS) analyses for trihalomethane in water samples collected from the Tarawa Terrace and Hadnot Point WTPs at U.S. Marine Corps Base Camp Lejeune were interrupted by interference from constituents in the water samples thought to be halogenated hydrocarbons (Grainger Laboratories, Camp Lejeune water document CLW 0592, written communication, August 10, 1982; Elizabeth A. Betz, written communication, August 19, 1982; AH Environmental Consultants, Inc., written communication, June 18, 2004; Camp Lejeune water documents CLW 592–595 and 606–607). Subsequent analyses confirmed the presence of PCE in samples of finished water supplies from both locations, ranging in concentration from 76 to 104 micrograms per liter (µg/L) at Tarawa Terrace and from 15 µg/L to not detected (ND) at Hadnot Point. Concentrations of TCE determined in samples from the Hadnot Point WTP ranged from 19 to 1,400 µg/L. Samples analyzed were collected during May and July 1982.

During July 1984, routine sampling and analyses of community water-supply wells at Camp Lejeune as a part of the Base Naval Assessment and Control of Installation Pollutants Program indicated the occurrence of TCE in samples obtained from wells TT-23 (37 µg/L), TT-25 (trace), and TT-26 (3.9 µg/L) (Maslia et al. 2007). Well TT-26 is open only to the Upper Castle Hayne aquifer; wells TT-23 and TT-25 are open to both the Upper and Middle Castle Hayne aquifers (Faye 2007a).

Beginning January 1985 and continuing into September 1985, the North Carolina Department of Natural Resources and Community Development (NCDNRCD) periodically sampled water-supply wells TT-23, TT-25, and TT-26 and water treated at the Tarawa Terrace WTP for PCE and its degradation products, TCE, 1,2-tDCE, and vinyl chloride (McMorris 1987). On occasion, NCDNRCD and JTC Environmental Consultants, Inc., analyzed duplicate samples (Shiver 1985; R.A. Tiebout, Memorandum for the Commanding General, Chief of Staff, written communication, November 6, 1985; J.R. Bailey to U.S. Environmental Protection Agency, written communication, April 25, 1986; Camp Lejeune water documents CLW 1338–1339, 1475–1483). Concentrations of PCE in samples from well TT-26 ranged from an estimated 3.8 to 1,580 µg/L in seven samples collected during this period (Table E2). Concentrations in 10 samples from well TT-23 ranged from not detected to 132 µg/L. Concentrations also were detected for TCE, 1,2-tDCE, and vinyl chloride. Tarawa Terrace water-supply wells TT-30, TT-31, TT-52, TT-54, and TT-67 also were sampled once during this period, and subsequent analyses detected no concentrations of PCE or related degradation products at these wells (JTC Environmental Consultants Report 85-047, Report 19, written communication, February 5–6, 1985). JTC Environmental Consultants, however, detected benzene at a concentration of 6.3 µg/L in a sample collected at well TT-23 on February 19, 1985 (JTC Environmental Consultants Report 85-072, Report 37, written communication, March 1, 1985). An estimated concentration of 0.43 µg/L of PCE was determined in a sample from well TT-25 during September 1985 (Table E2).

The sampling and analyses for VOCs during January and February 1985 caused wells TT-23 and TT-26 to be removed from service during February 1985. Well TT-26 was closed permanently at this time; however, well TT-23 was used to deliver water to the Tarawa Terrace WTP for several days during March and April 1985 (Camp Lejeune water document 1182; Camp Lejeune water document CLW 1193, "Direction to Operators at Tarawa Terrace," April 30, 1985; Camp Lejeune water document CLW 1194, "Procedures for operating the 'New Well' at Tarawa Terrace," date unknown).

At the time of discovery of PCE and related contaminants at Tarawa Terrace water-supply wells, the Tarawa Terrace WTP provided drinking water to approximately 6,200 people in the service area (McMorris 1987). A summary of analyses of water samples collected at Tarawa Terrace and nearby water-supply wells is listed in Table E2. Location coordinates of Tarawa Terrace and nearby water-supply wells are listed in Table E3.

During April 1985, the NCDNRCD began a field investigation to determine the source or sources of PCE and related constituents occurring at water-supply wells TT-23 and TT-26. Samples were collected at these wells and at well TT-25 for analyses of VOCs. Three monitor wells were installed in the "Water Table aquifer" northwest of well TT-26 and parallel to SR 24 to collect additional samples and water-level data (Shiver 1985; wells X24B4, X24B5, X24B6[5]; Tables E4 and E5). Results of analyses of samples collected at water-supply and monitor wells were sufficient to delineate a highly generalized plume of PCE in groundwater of the aquifer. The northwest apex of the plume was located at monitor well X24B6, immediately opposite the entrance of ABC One-Hour Cleaners at 2127 Lejeune Boulevard (SR 24). The PCE concentration determined in the sample from this well was 12,000 µg/L. These and ancillary water-level data indicating the direction of groundwater flow to the southeast pinpointed ABC One-Hour Cleaners as the source of PCE in Tarawa Terrace water-supply wells (Shiver 1985, Figure 4).

ABC One-Hour Cleaners always used PCE in its dry-cleaning operations, beginning during 1953, when the business opened (Hopf & Higley, P.A., "Deposition of Victor John Melts," written communication, April 12, 2001). A primary pathway of contaminants from the dry-cleaning operations at ABC One-Hour Cleaners to the soil and subsequently to groundwater was apparently through a septic

[5] Shown as B4, B5, and B6, respectively, on Plate 1 in the Chapter A report (Maslia et al. 2007). Plate 1 also is available on the ATSDR Camp Lejeune Web site at *http://www.atsdr.cdc.gov/sites/lejeune/docs/Camp_Lejeune_master_plate.pdf*

Table E3. Location coordinates of water-supply wells, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[AKA, also known as]

Site name	Location coordinates[1]	
	North	East
[2]2A	364625	2489025
[3]#6	369730	2481720
[3]#7	370500	2481530
[4]RW1	365150	2489880
[4]RW2	364930	2490770
[4]RW3	364170	2493350
[5]TT-23	363208	2491024
[5]TT-25	364042	2491984
[5]TT-26, AKA #1	364356	2491461
[5]TT-27, AKA #2B	364794	2489026
[5]TT-28, AKA #3	365058	2487071
[5]TT-29, AKA #4	365352	2485328
[5]TT-30, AKA #13	365044	2487130
[5]TT-31, AKA #14	362224	2489843
[5]TT-45, AKA #5	365688	2483352
[5]TT-52, AKA #9	362321	2489060
[5]TT-53, AKA #10	363360	2489800
[5]TT-54, AKA #11	362090	2490630
[5]TT-55, AKA #8	364767	2489070
[5]TT-67, AKA #12	362730	2490160

[1]Location coordinates are North Carolina State Plane coordinates, North American Datum of 1983

[2]See Plate 1, Chapter A report, for location (Maslia et al. 2007)

[3]Out of map area, location not shown. North Carolina State Plane coordinates: #6 (highly approximate) North 369730, East 2481720; #7 (highly approximate) North 370500, East 2481530

[4]See Figure E3 for location

[5]See Figure E1 for location

tank–soil absorption system to which ABC One-Hour Cleaners discharged waste and wastewater. Shiver (1985) reports that an inspection of the PCE storage area at ABC One-Hour Cleaners indicated that PCE releases can and did enter the septic system through a floor drain, probably as a result of spillage in the storage area (Roy F. Weston, Inc. 1994). In addition, spent PCE was routinely reclaimed using a filtration-distillation process that produced dry "still bottoms," which, until about 1982 (Hopf & Higley, P.A., "Deposition of Victor John Melts," written communication, April 12, 2001) or 1984/1985 (McMorris 1987), were disposed of onsite, generally by filling potholes in a nearby alleyway. When ABC One-Hour Cleaners totally discontinued the use of the floor drain and the onsite disposal of still bottoms is not known exactly, but such practices probably terminated completely during 1985.

The disposal of dry-cleaning solvents to the septic system and subsequently to groundwater placed ABC One-Hour Cleaners in violation of various State laws and statutes. During January 1986, the owners were ordered by the State of North Carolina to cease such disposal and propose a plan to restore the quality of affected ground water to an acceptable level as determined by the State (Roy F. Weston, Inc. 1994). Pursuant to this plan, ABC One-Hour Cleaners hired Law Engineering and Testing Company, Inc., to investigate the septic tank and the surrounding soil for contaminant content. Samples collected and analyzed by Law Engineering and Testing Company, Inc., indicated PCE concentrations of the septic tank sludge were as high as 1,400 milligrams per liter (mg/L) and that soil 4 feet (ft) below the tank contained PCE concentrations as high as 400 milligrams per kilogram (mg/kg) (Law Engineering and Testing Company, Inc. 1986a). Subsequently Law Engineering and Testing Company, Inc., conducted additional investigations to determine the vertical and horizontal extent of contamination within the soil profile. These investigations were completed by December 1986 and indicated the depth of PCE contamination in the vicinity of the septic tank to be in excess of 16 ft. A PCE concentration at a depth of 8 ft was 860 mg/kg (Law Engineering and Testing Company, Inc. 1986b; Roy F. Weston, Inc. 1992). A summary of PCE concentrations in soil in the vicinity of ABC One-Hour Cleaners is listed in Table E4.

By March or April 1987, all water-supply wells at Tarawa Terrace were removed from service. During March 1989, the ABC One-Hour Cleaners site was placed on the National Priority List (Final List). During June 1990, the U.S. Environmental Protection Agency (USEPA) hired Roy F. Weston, Inc., to conduct a remedial investigation at the site aimed at determining the areal and vertical extent of contaminant plumes (Operable Unit 1) and characterizing the source of contaminants in the unsaturated soils beneath and in the vicinity of the septic disposal system at ABC One-Hour Cleaners (Operable Unit 2) (Roy F. Weston, Inc. 1992, 1994).

Operable Unit 1 of the remedial investigation included the installation of eight soil borings to depths ranging from 16 to 20 ft surrounding and in the immediate vicinity of ABC One-Hour Cleaners (SB-1–SB-6, SB-10, and SB12; Figure E2, Table E4). These borings occurred entirely within the unsaturated zone. Ten shallow and five deep monitor wells also were installed during Operable Unit 1, not only in the immediate vicinity of ABC One-Hour Cleaners but also northwest of the site as well as proximate to water-supply wells TT-26 and TT-25. Several monitor wells were located between SR 24 (Lejeune Boulevard) and Tarawa Terrace housing (Figure E3). The shallow wells, S1–S10, were constructed to depths ranging from 28 to 40 ft and were open at the base of the well to the Upper Castle Hayne aquifer–River Bend unit (Faye 2007a). Four of the deep wells—C1, C2, C3, and C5—ranged in depth from about 90 to 100 ft and were open at the base to the Upper Castle Hayne aquifer–Lower unit.

Table E4. Summary of selected analyses for tetrachloroethylene (PCE) in soil samples collected at ABC One-Hour Cleaners by Law Engineering and Testing Company, Inc., and during ABC One-Hour Cleaners Operable Units 1 and 2.

[µg/kg, microgram per kilogram; ND, not detected; detection limits are unknown; data source: Roy F. Weston, Inc. 1994, Table 2-4, Figures 2-4, 3-1, and 5-2]

Site name	Location coordinates[1]		Date	Sample depth, in feet	PCE concentration, in µg/kg
	North	East			
[2]Law #3	364918	2490707	9/10/1986	8.00	5,900
[2]Law #9	364932	2490717	9/10/1986	4.00	106,000
				8.00	450,000
				12.00	22,000
				16.00	12,000
[2]Law #10	364927	2490703	9/10/1986	4.00	1,300
				8.00	110
[2]Law #11	364927	2490731	9/10/1986	4.00	450,000
				8.00	170,000
[2]Law #12	364918	2490717	9/10/1986	4.00	720,000
				8.00	860,000
				10.00	820,000
[2]Law #13	364914	2490731	9/10/1986	4.00	630,000
				8.00	260,000
[2]Law #14	364906	2490731	9/10/1986	4.00	24,000
				8.00	280,000
[2]Law #15	364901	2490724	9/10/1986	4.00	12,000
				8.00	18,000
[2]Law #17	364893	2490719	9/10/1986	4.00	5,600
				8.00	5,800
[2]Law #18	364901	2490707	9/10/1986	4.00	17,000
				8.00	6,000
[3]SB-1	364874	2490691	6/26/1991	6.00	640
				10.00	37
				14.00	440
[3]SB-2	364930	2490697	6/26/1991	2.00	10
				6.00	19
				10.00	27
				14.00	ND
[3]SB-3	364981	2490754	6/27/1991	6.00	ND
				10.00	ND
				14.00	ND
[3]SB-4	364985	2490736	6/27/1991	12.00	ND
				16.00	ND
[3]SB-5	364795	2490714	6/27/1991	6.00	3
				12.00	ND
[3]SB-6	364798	2490696	6/27/1991	12.00	ND
				14.00	ND
[3]SB-10	364857	2490750	6/30/1991	6.00	2,100
				10.00	210
				14.00	90
[3]SB-12	364922	2490767	6/30/1991	4.00	ND
				6.00	ND
				12.00	ND

Table E4. Summary of selected analyses for tetrachloroethylene (PCE) in soil samples collected at ABC One-Hour Cleaners by Law Engineering and Testing Company, Inc., and during ABC One-Hour Cleaners Operable Units 1 and 2.—Continued

[µg/kg, microgram per kilogram; ND, not detected; detection limits are unknown; data source: Roy F. Weston, Inc. 1994, Table 2-4, Figures 2-4, 3-1, and 5-2]

Site name	Location coordinates[1]		Date	Sample depth, in feet	PCE concentration, in µg/kg
	North	East			
[3]SB-13	364841	2490658	9/9/1993	1.00	ND
				4.00	ND
				9.00	ND
				14.00	ND
[3]SB-14	364930	2490664	9/9/1993	1.00	90
				4.00	570
				9.00	210
				14.00	ND
[3]SB-15	364938	2490675	9/9/1993	1.00	20
				4.00	ND
				9.00	ND
				14.00	ND
[3]SB-16	364855	2490726	9/10/1993	1.00	49,000
				4.00	27,000
				9.00	200
				14.00	390
[3]SB-17	364834	2490744	9/12/1993	1.00	14
				4.00	1,400
				9.00	650
				14.00	1,400
[3]SB-18	364859	2490753	9/12/1993	1.00	2,100,000
				4.00	110,000
				9.00	Not sampled
				14.00	Not sampled
[3]SB-19	364886	2490731	9/15/1993	1.00	300,000
				4.00	4,900
				9.00	16
				14.00	5,100
[3]SB-20	364918	2490695	9/16/1993	1.00	56
				4.00	Not sampled
				9.00	Not sampled
				14.00	Not sampled
[3]SB-21	364859	2490703	9/16/1993	1.00	170
				4.00	Not sampled
				9.00	Not sampled
				14.00	Not sampled
[3]SB-22	364909	2490705	9/17/1993	1.00	580,000
				4.00	210,000
				9.00	26,000
				14.00	2,900
[3]SB-23	364933	2490738	9/18/1993	1.00	41,600
				4.00	120
				9.00	20
				14.00	44

Table E4. Summary of selected analyses for tetrachloroethylene (PCE) in soil samples collected at ABC One-Hour Cleaners by Law Engineering and Testing Company, Inc., and during ABC One-Hour Cleaners Operable Units 1 and 2.—Continued

[µg/kg, microgram per kilogram; ND, not detected; detection limits are unknown; data source: Roy F. Weston, Inc. 1994, Table 2-4, Figures 2-4, 3-1, and 5-2]

Site name	Location coordinates[1]		Date	Sample depth, in feet	PCE concentration, in µg/kg
	North	East			
[3]SB-24	364889	2490752	9/21/1993	1.00	ND
				4.00	ND
				9.00	ND
				14.00	ND
[3]SPM1	364906	2490730	9/17/1993	1.00	49,000
				4.00	7,500
				9.00	7,100
				14.00	8,900
[3]SPM2	364910	2490730	9/15/1993	1.00	4,400
				4.00	14,000
				9.00	15,000
				14.00	6,000
[3]SPM5	364902	2490716	9/14/1993	1.00	43,000
				4.00	11,000
				9.00	3,000
				14.00	13,000
[3]V1	364899	2490730	9/17/1993	1.00	Not sampled
				4.00	Not sampled
				9.00	33,000
				14.00	180,000
[3]V2	364929	2490730	9/17/1993	1.00	180,000
				4.00	5,400
				9.00	2,300
				14.00	800

[1]Location coordinates are North Carolina State Plane coordinates, North American Datum of 1983

[2]Roy F. Weston, Inc. 1994, Table 2-4, Figure 2-4

[3]See Figure E2 for location

Well C4 was constructed to a depth of about 200 ft and was open to the Middle Castle Hayne aquifer.

Operable Unit 2 included the construction of shallow well (S11) approximately 1,000 ft northwest of ABC One-Hour Cleaners. Two deep wells, C9 and C10, also were constructed east and south of the cleaners. Well C11 was located in the northeast part of Tarawa Terrace housing area I (Figure E3). Depths of wells C9 and C10 ranged from about 75 to 175 ft. Wells C9 and C11 were open to the Upper Castle Hayne aquifer–Lower unit. Well C10 was open to the Middle Castle Hayne aquifer. Also installed as part of Operable Unit 2 were 6 piezometers, 3 shallow (PZ-02, -04, -06) and 3 deep (PZ-01, -03, -05), in the immediate vicinity of ABC One-Hour Cleaners and open to the Upper Castle Hayne aquifer–River Bend and Lower units, respectively. The depths of PZ-02, -04, and -06 ranged from 29.5 to 34.5 ft. Depths of PZ-01, -03, and -05 ranged from 74.5 to 79.5 ft.

Results of analyses of periodic water samples obtained from monitor wells during Operable Units 1 and 2 are summarized in Table E5. Concentrations of PCE ranged from not detected at several wells to 5,400 µg/L at well S3. Samples from monitor wells also were analyzed for various metals and "semivolatile" compounds. Location coordinates of monitor wells and piezometers constructed during Operable Units 1 and 2 are listed in Table E6.

During Operable Unit 2, similar constituent-analysis schedules were used during analyses of effluent from the septic tank at ABC One-Hour Cleaners and of soil samples obtained from the unsaturated zone in the vicinity of the tank. PCE concentration in the tank effluent was 6,800 µg/L during June 1991. Concentrations of PCE in soil borings at various depths in the immediate vicinity of ABC One-Hour Cleaners ranged from not detected to more than 2,000,000 micrograms per kilogram (µg/kg) (Figure E2, Table E4).

Table E5. Summary of selected analyses for tetrachloroethylene (PCE), trichloroethylene (TCE), and total dichloroethylene (DCE) in water samples collected at monitor wells during ABC One-Hour Cleaners Operable Units 1 and 2 and by the North Carolina Department of Natural Resources and Community Development, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter; ND, not detected; J, estimated value; #, *cis*-1,2-dichloroethylene; —, constituent not determined]

Site name[1]	Date	PCE concentration, in µg/L	TCE concentration, in µg/L	Total DCE concentration, in µg/L
C1	4/24/1992	ND	ND	ND
	9/21/1993	ND	ND	ND
C2	4/23/1992	1J	3J	9J
	10/21/1993	ND	ND	ND
C3	4/29/1992	7J	28	14
	9/23/1993	120	43	21
C4	4/22/1992	ND	ND	ND
	9/22/1993	ND	ND	ND
C5	4/23/1992	ND	17J	ND
	9/22/1993	ND	ND	ND
C9	9/29/1993	0.2J	0.1J	—
C10	10/15/1993	4.8J	ND	ND
C11	10/15/1993	0.64J	ND	ND
S1	4/24/1992	10	ND	ND
	9/20/1993	27	0.6J	0.2J#
S2	4/23/1992	880	690	1,200
	10/21/1993	490	280	467
S3	4/29/1992	5,400	640	1,200
	9/23/1993	380	24	46J
S4	4/22/1992	ND	ND	ND
	9/20/1993	ND	ND	—
S5	4/23/1992	3	3	ND
	9/22/1993	0.8J	ND	—
S6	4/29/1992	4J	ND	ND
	9/29/1993	0.5J	0.1J	—
S7	4/28/1992	ND	ND	ND
	9/28/1993	0.2J	ND	ND
S8	4/24/1992	ND	ND	ND
	9/28/1993	ND	ND	ND
S9	4/22/1992	ND	ND	ND
	9/23/1993	ND	ND	ND
S10	4/28/1992	ND	ND	ND
	9/22/1993	ND	ND	—
S11	9/29/1993	0.3J	46	ND
[2]X24B4	9/25/1985	2.2	—	—
[2]X24B5	9/25/1985	4.9	0.98	—
[2]X24B6	9/25/1985	12,000	2.7	—

[1]See Plate 1, Chapter A report, for location (Maslia et al. 2007)

[2]Shown as B4, B5, and B6, respectively, on Plate 1, Chapter A report, (Maslia et al. 2007)

Detection limit at "C" and "S" sites = 10 µg/L, 5 µg/L, or 1 µg/L

Detection limit at "X24" sites = 2 µg/L

Table E6. Location coordinates of monitor wells installed during ABC One-Hour Cleaners Operable Units 1 and 2 and by the North Carolina Department of Natural Resources and Community Development, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Site name[1]	Location coordinates[2]	
	North	East
C1	365232	2490503
C2	364902	2490793
C3	364437	2491433
C4	364045	2492080
C5	364107	2491233
C9	364800	2491730
C10	364360	2491380
C11	362300	2492130
S1	365251	2490534
S2	364883	2490787
S3	364357	2491413
S4	364065	2492060
S5	364081	2491244
S6	364938	2490617
S7	364753	2490732
S8	364938	2491312
S9	364593	2491682
S10	363818	2491922
S11	365390	2489710
[3]X24B4	364530	2491570
[3]X24B5	364640	2491050
[3]X24B6	364810	2490710

[1]See Plate 1, Chapter A report, for location (Maslia et al. 2007)

[2]Location coordinates are North Carolina State Plane coordinates, North American Datum of 1983

[3]Shown as B4, B5, and B6, respectively, on Plate 1, Chapter A report, (Maslia et al. 2007)

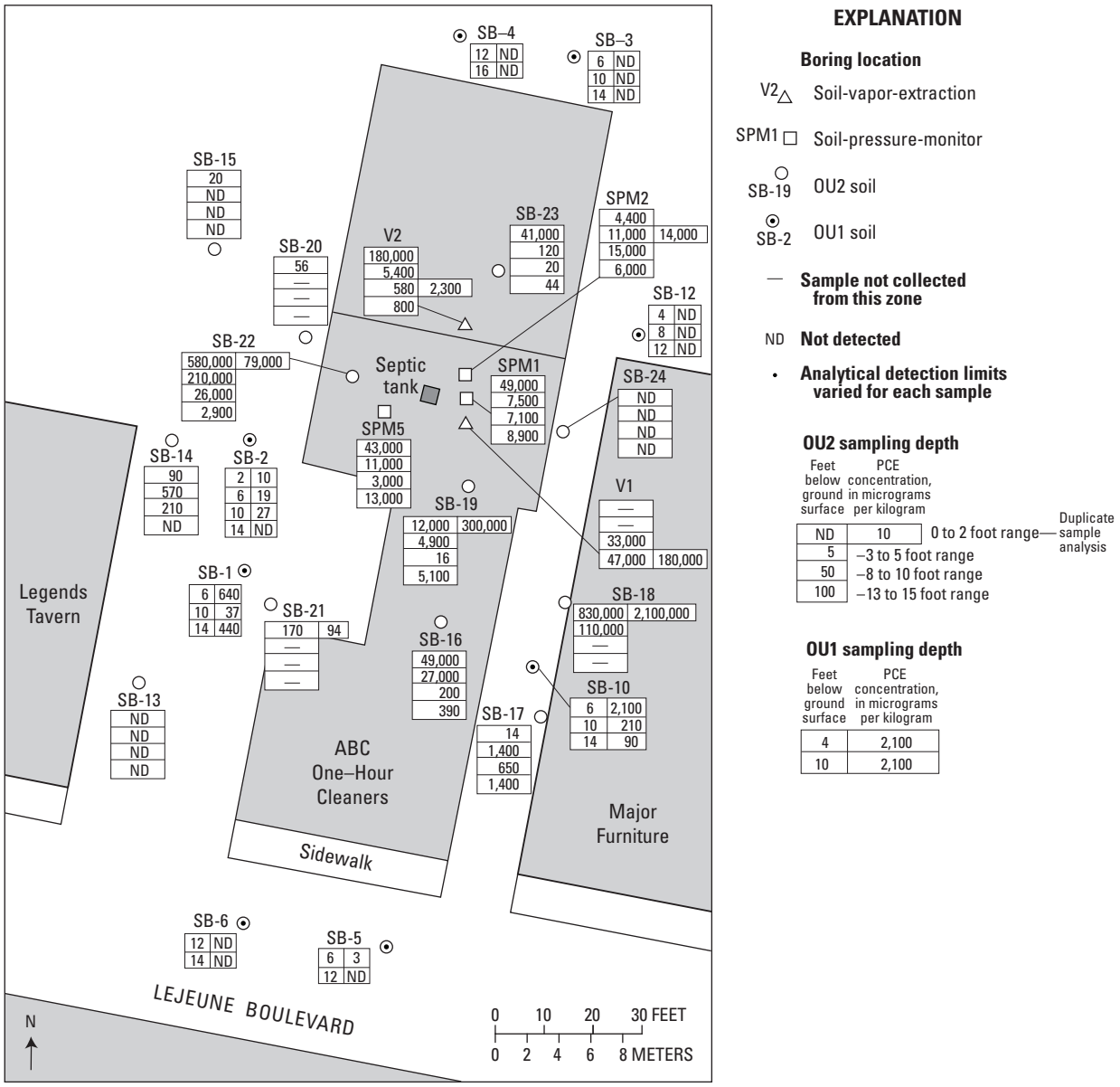
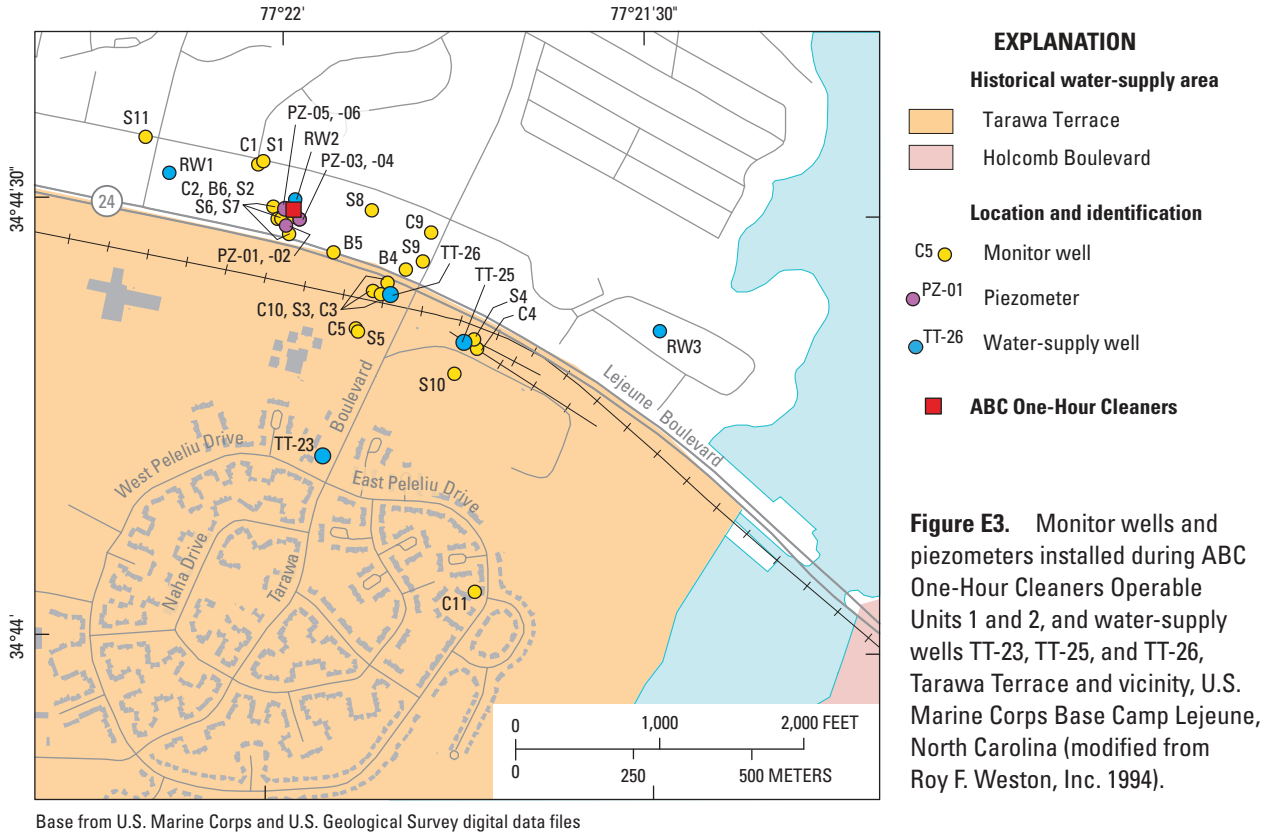


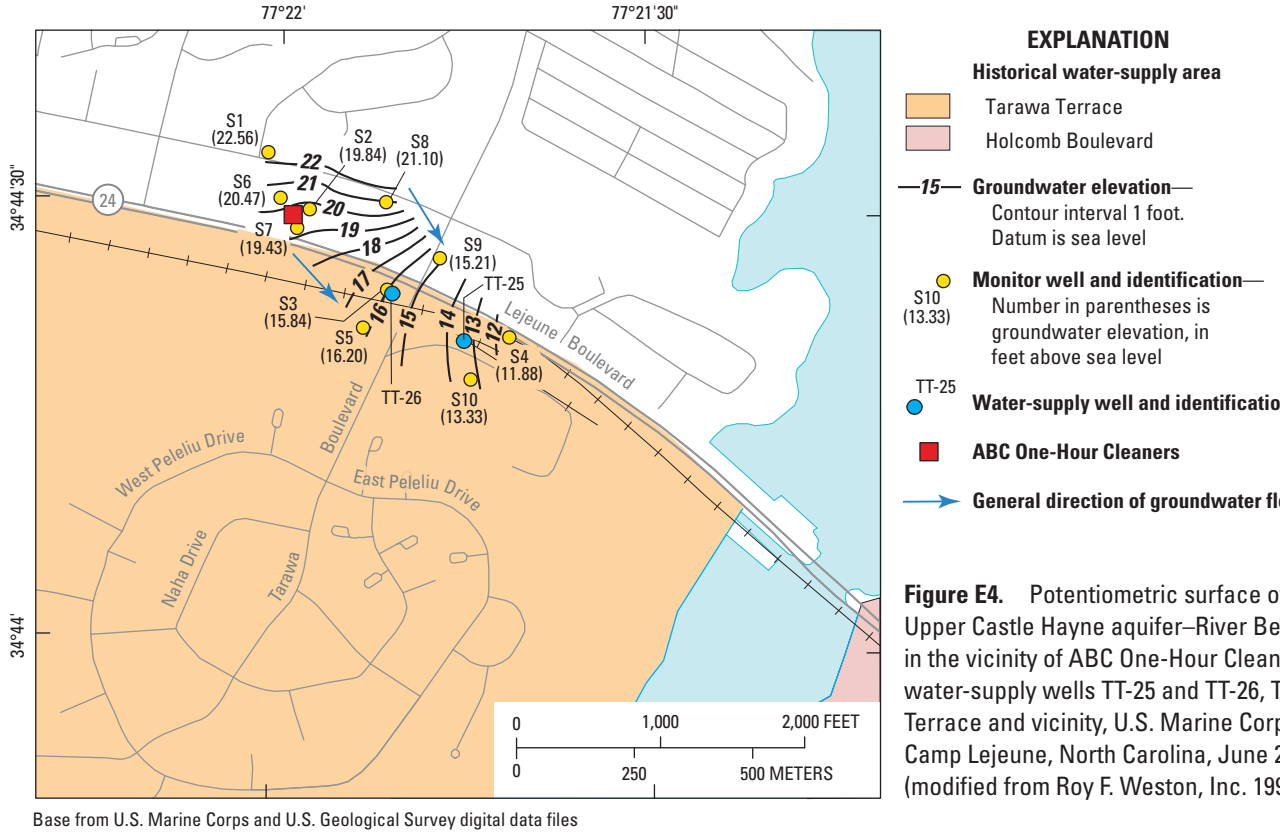
Figure E2. Soil borings and related tetrachloroethylene (PCE) concentrations, ABC One-Hour Cleaners Operable Units 1 and 2, U.S. Marine Corps Base Camp Lejeune, North Carolina (modified from Roy F. Weston, Inc. 1994).

Deep monitor wells C1–C5 were paired with their respective shallow well counterparts S1–S5. Piezometers with odd and even numbers were likewise paired, in an effort to determine vertical hydraulic gradients. Potentiometric levels at paired wells and piezometers were measured to hundredths of a foot periodically during 1992 and 1993. Vertical head gradients were downward at all paired wells at all times with the exception of slightly upward gradients at PZ-01 and -02 and PZ-03 and -04 during November 1993. A maximum head difference of 2.23 ft occurred at paired wells S1/C1 during April 1992. Head differences between the Upper Castle Hayne aquifer–River Bend unit and the Middle Castle Hayne aquifer were always less than 2 ft. These and similar water-level measurements at all monitor wells were used to map local potentiometric surfaces in the vicinity and downgradient of ABC One-Hour Cleaners. Potentiometric-surface maps of the Upper Castle Hayne aquifer–River Bend and Lower units are shown in Figures E4 and E5. Potentiometric levels in the aquifers are similar and range from about 23 to 10 ft, National Geodetic Vertical Datum of 1929 (NGVD 29). Potentiometric levels trend from northwest to southeast, from greater to lesser, and generally correspond to groundwater-flow directions. The potentiometric gradient of the Upper Castle Hayne aquifer–River Bend unit is from about 0.006 to 0.007 foot per foot (ft/ft) (Roy F. Weston, Inc. 1992). Corresponding gradients for the Upper Castle Hayne aquifer–Lower unit are from 0.005 to 0.006 ft/ft. Aquifer tests were conducted in conjunction with several monitor wells. Test results indicated values



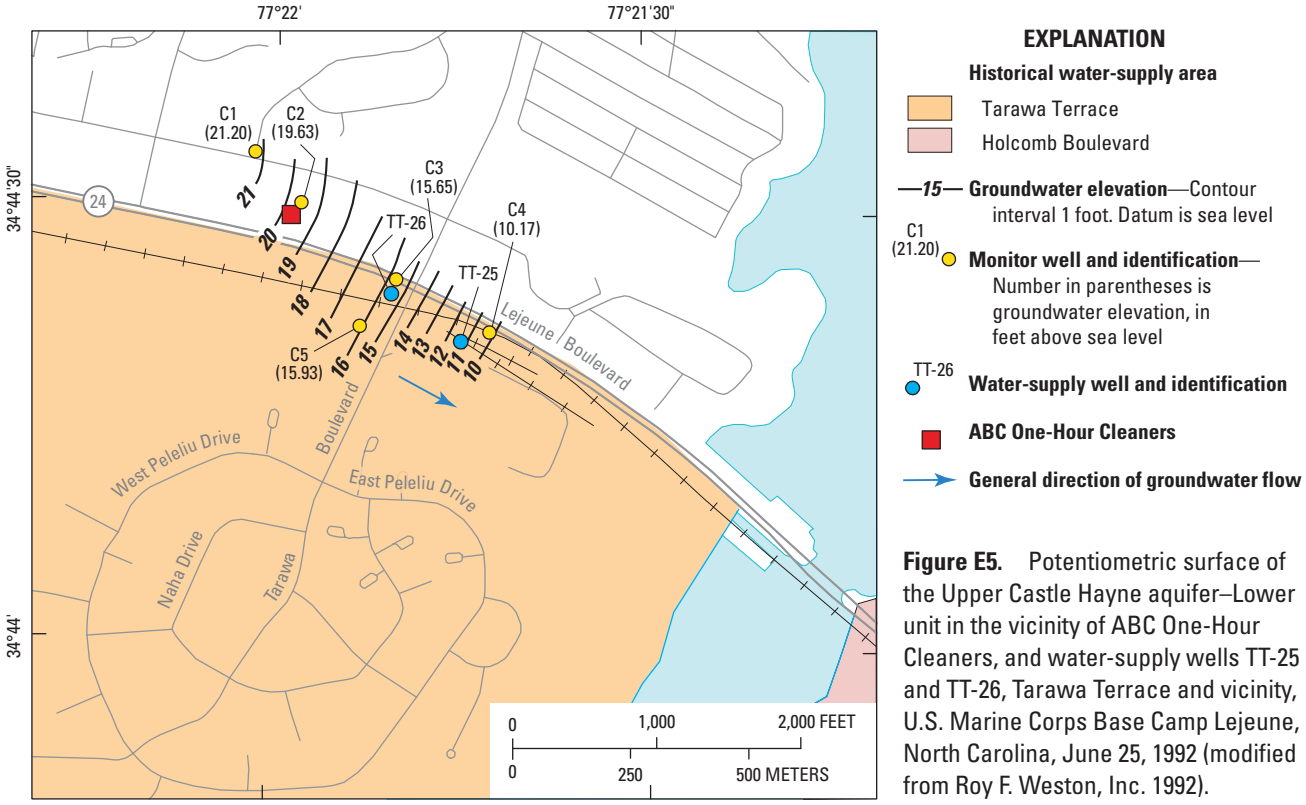
Base from U.S. Marine Corps and U.S. Geological Survey digital data files

Figure E3. Monitor wells and piezometers installed during ABC One-Hour Cleaners Operable Units 1 and 2, and water-supply wells TT-23, TT-25, and TT-26, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina (modified from Roy F. Weston, Inc. 1994).



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

Figure E4. Potentiometric surface of the Upper Castle Hayne aquifer–River Bend unit in the vicinity of ABC One-Hour Cleaners, and water-supply wells TT-25 and TT-26, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina, June 25, 1992 (modified from Roy F. Weston, Inc. 1992).



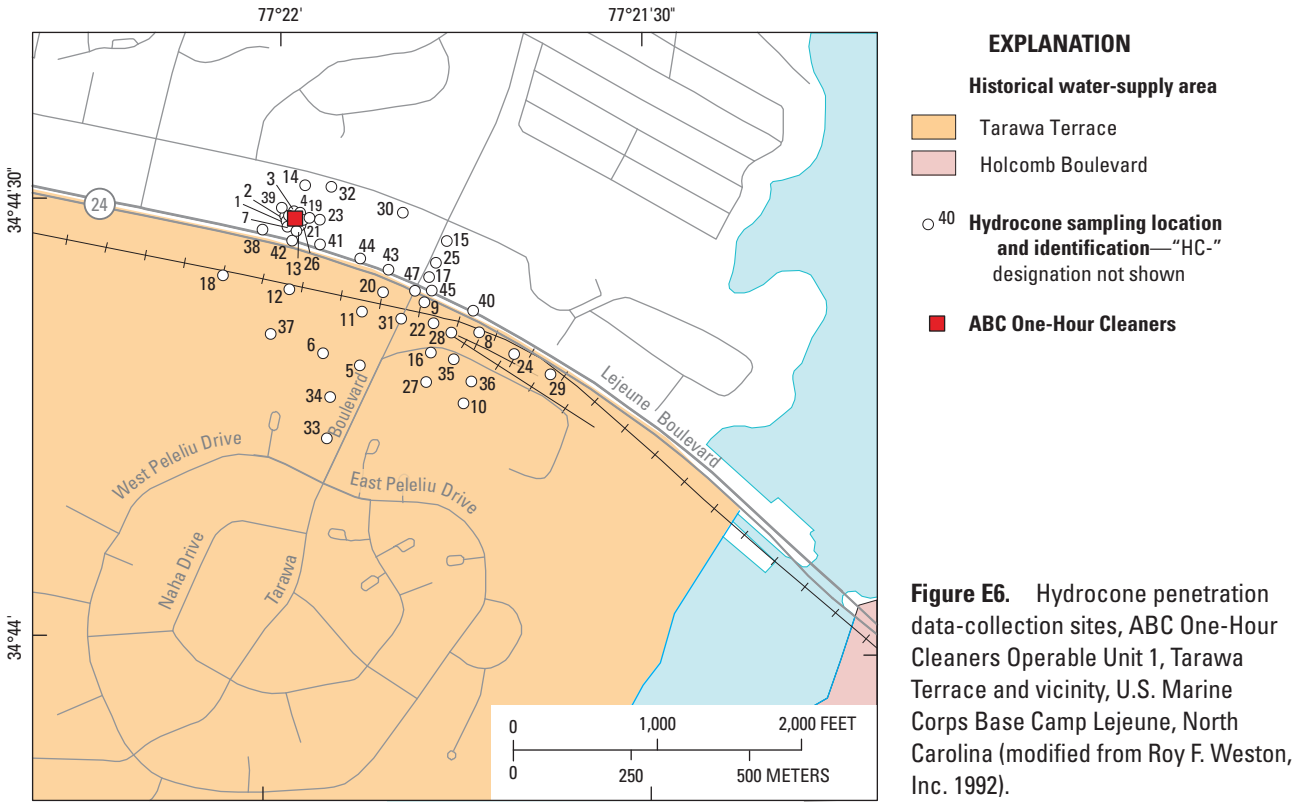
Base from U.S. Marine Corps and U.S. Geological Survey digital data files

Figure E5. Potentiometric surface of the Upper Castle Hayne aquifer–Lower unit in the vicinity of ABC One-Hour Cleaners, and water-supply wells TT-25 and TT-26, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina, June 25, 1992 (modified from Roy F. Weston, Inc. 1992).

of horizontal hydraulic conductivity ranged from about 10 to 30 feet per day (ft/d) for the "surficial aquifer" (Upper Castle Hayne aquifer–River Bend unit). Corresponding storativity ranged from magnitude 10^{-4} to 10^{-3}.

In order to characterize the depth, areal extent, and water quality of the contaminant plumes emanating from the vicinity of ABC One-Hour Cleaners, hydrocone penetrations using direct-push technology were accomplished at 47 sites near, east, and south of the cleaners (Figure E6). Two levels of samples were collected at each site, generally at about 20 and 40 ft, respectively. The constituent analysis schedule used for hydrocone samples included PCE, TCE, 1,2-tDCE, and vinyl chloride, which have been mentioned in conjunction with previous investigations, as well as 1,1,1-trichloroethane (1,1,1-TCA), 1,1- and 1,2-dichloroethane (1,1-, 1,2-DCA), and carbon tetrachloride. Samples were analyzed in the field using a mobile laboratory. Several duplicate samples were submitted to "CLP" laboratories for comparison of results. Although not defined in the respective Operable Unit reports, CLP probably refers to "Clinical Laboratory Program," a process that inspects State and Federal public health laboratories for purposes of certification. The CLP laboratories also determined concentrations of carbon disulfide, benzene, ethylbenzene, and total xylenes. Benzene and related toluene, ethylbenzene, and total xylenes (BTEX constituents) were detected infrequently in the hydrocone samples. Benzene concentrations ranged from not detected to 12 µg/L. Results of mobile and CLP laboratory analyses were not highly consistent (Roy F. Weston, Inc. 1992, Table 5-12); however, most constituents were noted in one or more samples. PCE was detected most frequently and was found in 75 samples at concentrations ranging from 1 to 30,000 µg/L. The maximum depth of PCE occurrence determined by hydrocone penetration was 64 ft (sample HC-6-64) and probably occurred near the base of the Upper Castle Hayne aquifer–River Bend unit. Results of selected analyses of water samples collected during hydrocone penetration investigations are summarized in Table E7. Location coordinates of hydrocone penetration sites are listed in Table E8. The sampling depth at each site is the last number of the site name. For example, site designation HC-6-64 indicates a sample was collected at site 6 at a depth of 64 ft.

During 1990, ATSDR completed an assessment of public health effects related to groundwater contamination at ABC One-Hour Cleaners and expressed a public health concern that offsite (namely Tarawa Terrace) exposure of contaminants to humans had occurred through the groundwater pathway. During 1997, ATSDR conducted a comprehensive Public Health Assessment of U.S. Marine Corps Base Camp Lejeune, which included an assessment of human exposure to contaminated groundwater at Tarawa Terrace. Maximum contaminant concentrations for PCE (215 µg/L), TCE (8 µg/L), and DCE (12 µg/L) determined from samples obtained within the Tarawa Terrace water-distribution system were listed, and a definitive exposure timeframe was identified for the period 1982–1985. The period 1954–1982 was identified as an unknown exposure timeframe (Agency for Toxic Substances and Disease Registry 1997).



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

Figure E6. Hydrocone penetration data-collection sites, ABC One-Hour Cleaners Operable Unit 1, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina (modified from Roy F. Weston, Inc. 1992).

Investigations of groundwater contamination at and near Tarawa Terrace not related to ABC One-Hour Cleaners also have occurred since 1990, largely in conjunction with known or suspected releases to groundwater of refined petroleum products from underground and above-ground storage tanks. Six large (30,000 gallons [gal]) above-ground petroleum storage tanks (STT61–STT66) were located just west of Tarawa Terrace in the narrow strip of land between the railroad tracks and SR 24. Tarawa Terrace water-supply wells TT-27 and TT-55 were located just south and slightly west of these tanks (Figure E1). The tanks were constructed during 1942, and until about 1980, petroleum product deliveries were offloaded from railcars. About 1980, the tanks were converted to waste oil storage (O'Brien & Gere Engineers, Inc. 1993). Well TT-27 was installed during 1951 and was mostly out of service by 1962. Well TT-55 was installed during 1961 and was out of service by 1971. At least one spill is documented at the tank site—a spill from tank STT66 occurred about 1986 or 1987 (O'Brien & Gere Engineers, Inc. 1993).

Field investigations of groundwater conditions at and in the vicinity of the tanks included the installation of 20 monitor wells during 1991–1992 (Tables E9 and E10). Half the wells were installed to a depth of about 15 ft and the other half to a depth of about 30 ft. Ten-foot slotted screens were installed at the base of all wells. The shallow wells were open to the base of the Tarawa Terrace aquifer. The deep wells were open to the Upper Castle Hayne aquifer–River Bend unit. Water-level data collected in monitor wells indicate that groundwater flows in a generally southerly direction away from the tanks. Hydrocone samples obtained using direct-push techniques were collected at 10 additional sites approximately 4 ft below the water table. Samples obtained from each well and hydrocone site were analyzed for a variety of constituents. Most constituents are included in the Toxicity Characteristic Leaching Procedure (TCLP) protocols. Of major interest to this study were concentrations of benzene, which ranged from not detected to 23 µg/L. All occurrences of benzene were in the deep wells and may be the result of contamination transported to depth during drilling. Of the 20 monitor wells, only samples from 4 contained benzene. Benzene also was detected in three hydrocone samples and ranged in concentration from 7 to 22 µg/L. A highly generalized boundary of a benzene plume was constructed using these data representing conditions during 1993 and is shown in Figure E7. The elongated part of the plume is pointed almost directly south, corresponding to groundwater-flow directions (O'Brien & Gere Engineers, Inc. 1992, 1993).

A "strong gasoline type odor" was noted at water-supply well TT-53 (Figure E1) during October 1986 while U.S. Geological Survey (USGS) personnel conducted a routine well reconnaissance (U.S. Geological Survey well inventory, written communication, October 21, 1986). The well was out of service at the time, and the pump had been removed. This well is located about 1,500 ft southeast of the benzene plume depicted in Figure E7 and is the nearest most recently active Tarawa Terrace supply well to this plume.

Table E7. Summary of selected analyses for tetrachloroethylene (PCE), trichloroethylene (TCE), and *trans*-1,2-dichloroethylene (1,2-tDCE) in water samples collected at hydrocone penetration sites during ABC One-Hour Cleaners Operable Unit 1, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina, December 15, 1991.

[µg/L, microgram per liter; —, constituent not determined; J, estimated value; ND, not detected; unless noted by superscript "2," detection limit is unknown]

Site name[1]	PCE concentration, in µg/L	TCE concentration, in µg/L	1,2-tDCE concentration, in µg/L
HC-1-17.5	4	ND	—
HC-1-39	1.7	ND	—
HC-2-21.5	1.5J	0.13J	—
HC-2-44.5	5	ND	—
HC-3-21	2.5J	ND	—
HC-3-40.5	ND	ND	—
HC-4-19	ND	ND	—
HC-4-40	0.16J	ND	—
HC-5-25	0.38J	ND	—
HC-5-25	2J	ND	ND
HC-5-42.5	ND	ND	—
HC-6-30	5	ND	—
HC-6-41	9.4	ND	—
HC-6-64	0.6J	ND	—
HC-7-26.5	0.93J	ND	—
HC-7-26.5A	[2]4	[2]ND	[2]ND
HC-7-39	8.1	ND	—
HC-7-39	[2]2J	[2]ND	—
HC-8-28	5	ND	—
HC-8-35	6.8	ND	—
HC-8-35	[2]27	[2]3J	[2]ND
HC-9-31	175.7	ND	—
HC-9-36.5	6.3	ND	—
HC-10-24	2.5J	ND	—
HC-10-40	0.8J	ND	—
HC-10-40	[2]ND	[2]ND	[2]ND
HC-11-24	12.2	ND	—
HC-11-34	2.8J	ND	—
HC-11-34	[2]8J	[2]ND	[2]ND
HC-12-24	ND	ND	—
HC-12-24	[2]ND	[2]ND	[2]ND
HC-12-40	3.4J	ND	—
HC-13-19.5	0.76J	0.19J	—
HC-13-19.5	[2]2J	[2]ND	[2]ND
HC-13-32	0.4J	ND	—
HC-14-20	0.22J	ND	—
HC-14-20	[2]ND	[2]ND	[2]ND
HC-14-40	ND	ND	—
HC-14-40	[2]ND	[2]ND	[2]ND
HC-15-24	ND	ND	—
HC-15-24	[2]ND	[2]ND	[2]ND
HC-15-36.5	ND	2.8J	—
HC-15-36.5	[2]ND	[2]ND	[2]ND
HC-16-30	0.23J	ND	—
HC-17-24	ND	ND	—
HC-17-24	[2]ND	[2]ND	[2]ND
HC-17-44	ND	ND	—
HC-17-44	[2]ND	[2]ND	[2]ND
HC-18-24	1J	ND	—
HC-18-36	ND	ND	—
HC-18-36	[2]ND	[2]ND	[2]ND
HC-19-25	53.3	ND	—
HC-19-35.5	157	ND	—
HC-19-35.5	[2]200	[2]100	[2]170
HC-20-34	500	ND	—
HC-20-34	[2]30,000	[2]2,900	[2]5,700
HC-20-41	196	ND	—
HC-20-41	[2]43	[2]29	[2]89
HC-21-22	96	ND	—
HC-21-22	[2]6,900	[2]1,100	[2]2,300
HC-21-31.5	13.5	ND	—
HC-22A-30	740	ND	—
HC-22-41	5.2	ND	—
HC-23-19	2.2J	ND	—
HC-23-45	11	ND	—
HC-24-28	14	ND	—
HC-24-38	13	ND	—
HC-25-18	8.2	ND	—
HC-25-27	6	ND	—
HC-26-42	5	ND	—
HC-27-27	4	ND	—
HC-27-37.5	3.2	0.34J	—
HC-28-28	2.7J	ND	—
HC-28-41	2.2J	ND	—
HC-29-23	1.4J	ND	—
HC-29-26.5	5	ND	—
HC-30-24	2	0.2	—
HC-30-40	2J	ND	—

Table E7. Summary of selected analyses for tetrachloroethylene (PCE), trichloroethylene (TCE), and *trans*-1,2-dichloroethylene (1,2-tDCE) in water samples collected at hydrocone penetration sites during ABC One-Hour Cleaners Operable Unit 1, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina, December 15, 1991.—Continued

[µg/L, microgram per liter; —, constituent not determined; J, estimated value; ND, not detected; unless noted by superscript "2," detection limit is unknown]

Site name[1]	PCE concentration, in µg/L	TCE concentration, in µg/L	1,2-tDCE concentration, in µg/L
HC-31-29	1.2J	ND	—
HC-31-39	1.4J	ND	—
HC-32-26	1.3J	ND	—
HC-32-38	1.1J	ND	—
HC-33-28	2J	ND	—
HC-33-36	1.5J	ND	—
HC-34-21.5	2J	0.3J	—
HC-34-34	2J	ND	—
HC-35-30	133	ND	—
HC-35-42	7.5	ND	—
HC-36-30	ND	ND	—
HC-36-30	[2]ND	[2]ND	[2]ND
HC-36-41	1J	ND	—
HC-37-27	0.3J	ND	—
HC-37-48	1.4J	ND	—
HC-38-24	0.5J	ND	—
HC-38-40	1.2J	ND	—
HC-39-23	0.9J	ND	—
HC-39-23	[2]ND	[2]ND	[2]ND
HC-39-35	2.4J	ND	—
HC-40-26	ND	ND	—
HC-40-40	ND	ND	—
HC-41-27	82	ND	—
HC-41-27	[2]120	[2]4J	[2]4J
HC-41-45	2J	ND	—
HC-42-24	ND	ND	—
HC-42-40	ND	ND	—
HC-43-24	33	ND	—
HC-43-34	1,060	ND	—
HC-44-28	6	ND	—
HC-44-28	[2]13	[2]5J	[2]17
HC-44-39	12,860	ND	—
HC-45-28	ND	ND	—
HC-45-38	2J	ND	—
HC-47-26	18	ND	—
HC-47-38	30	ND	—

[1] See Figure E6 for location

[2] Detection limit = 10 µg/L

Site name key: Example HC-20-34
HC Hydrocone site
20 Site location number
34 Sample depth

Table E8. Location coordinates of hydrocone penetration sites, ABC One-Hour Cleaners Operable Unit 1, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Site name[1]	Location coordinates[2]	
	North	East
HC-1	364830	2490670
HC-2	364980	2490675
HC-3	365020	2490700
HC-4	365010	2490750
HC-5	363870	2491230
HC-6	363850	2490960
HC-7	364800	2490680
HC-8	364080	2492020
HC-9	364310	2491690
HC-10	363604	2491940
HC-11	364250	2491230
HC-12	364350	2490730
HC-13	364790	2490730
HC-14	365050	2490810
HC-15	364740	2491810
HC-16	363946	2491690
HC-17	364470	2491670
HC-18	364410	2490280
HC-19	364975	2490850
HC-20	364370	2491372
HC-21	364970	2490770
HC-22	364130	2491710
HC-23	364960	2490910
HC-24	363960	2492270
HC-25	364590	2491750
HC-26	364820	2490750
HC-27	363738	2491680
HC-28	363080	2491836
HC-29	363810	2492550
HC-30	364950	2491520
HC-31	364170	2491510
HC-32	365060	2490980
HC-33	363365	2491045
HC-34	363640	2491090
HC-35	363884	2491860
HC-36	363756	2491996
HC-37	364050	2490590
HC-38	364770	2490550
HC-39	365040	2490650
HC-40	364250	2492010
HC-41	364700	2490920
HC-42	364720	2490730
HC-43	364500	2491410
HC-44	364610	2491200
HC-45	364390	2491730
HC-47	364400	2491600

[1]See Figure E6 for location

[2]Location coordinates are North Carolina State Plane coordinates, North American Datum of 1983

Table E9. Summary of analyses of groundwater samples for benzene and toluene collected at water-supply wells, monitor wells, and hydrocone penetration sites during ABC One-Hour Cleaners Operable Units 1 and 2, by the North Carolina Department of Natural Resources and Community Development, and by the U.S. Navy during remedial or other investigations of spills or leaks of petroleum products to groundwater, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter; ND, not detected; —, constituent not determined; J, estimated value]

Site name	Date	Benzene concentration, in µg/L	Toluene concentration, in µg/L
C1	4/24/1992	ND	ND
	9/21/1993	[1]ND	[1]ND
C2	4/23/1992	ND	ND
	10/21/1993	[1]ND	[1]ND
C3	4/29/1992	ND	ND
	9/23/1993	[1]ND	[1]ND
C4	4/22/1992	ND	ND
	9/22/1993	[1]ND	[1]ND
C5	4/23/1992	18J	25J
	9/22/1993	[1]ND	[1]ND
C9	9/29/1993	[1]ND	0.7J
C10	10/15/1993	[2]ND	[2]ND
C11	10/15/1993	[2]ND	[2]ND
HC-5-25	12/15/1991	12	—
HC-7-26.5A	12/15/1991	1J	—
HC-7-39	12/15/1991	ND	—
HC-8-35	12/15/1991	1J	—
HC-10-40	12/15/1991	1J	—
HC-11-34	12/15/1991	ND	—
HC-12-24	12/15/1991	ND	—
HC-13-19.5	12/15/1991	ND	—
HC-14-20	12/15/1991	2J	—
HC-14-40	12/15/1991	ND	—
HC-15-24	12/15/1991	2J	—
HC-15-35.5	12/15/1991	ND	—
HC-17-24	12/15/1991	ND	—
HC-17-44	12/15/1991	ND	—
HC-18-36	12/15/1991	ND	—
HC-19-35.5	12/15/1991	ND	—
HC-20-34	12/15/1991	ND	—
HC-20-41	12/15/1991	ND	—
HC-21-22	12/15/1991	ND	—
HC-21-22	12/15/1991	ND	—
HC-36-30	12/15/1991	ND	—
HC-39-23	12/15/1991	1J	—
HC-41-27	12/15/1991	ND	—
HC-44-28	12/15/1991	ND	—
RW1	7/12/1991	ND	—
RW2	7/12/1991	ND	—
RW3	7/12/1991	ND	—
S1	4/24/1992	ND	ND
	9/20/1993	[1]ND	[1]ND
S2	4/23/1992	ND	1J
	10/2/1993	0.4J	2
S3	4/29/1992	ND	ND
	9/23/1993	[1]ND	[1]ND
S4	4/22/1992	ND	ND
	9/20/1993	[1]ND	[1]ND
S5	4/23/1992	2	4
	9/22/1993	[1]ND	[1]ND
S6	4/29/1992	2J	3J
	9/29/1993	0.4J	0.2J
S7	4/28/1992	ND	ND
	9/28/1993	ND	0.1J
S8	4/24/1992	ND	ND
	9/28/1993	[1]ND	[1]ND
S9	4/22/1992	ND	ND
	9/23/1993	[1]ND	[1]ND
S10	4/28/1992	ND	ND
	9/22/1993	[1]ND	[1]ND
S11	9/1/1993	—	0.1J
STT61to66-MW01	1/10/1992	[1]ND	[1]ND
STT61to66-MW02	1/10/1992	[1]ND	[1]ND
STT61to66-MW03	1/10/1993	[1]ND	[1]ND
STT61to66-MW04	1/10/1992	[1]ND	[1]ND
STT61to66-MW05	1/10/1992	[1]ND	[1]ND
STT61to66-MW06	1/10/1992	[1]ND	[1]ND
STT61to66-MW07	1/10/1992	[1]ND	[1]ND
STT61to66-MW08	1/10/1992	[1]ND	[1]ND
STT61to66-MW09	1/10/1992	[1]ND	[1]ND
STT61to66-MW10	1/10/1992	[1]14	[1]3
STT61to66-MW11	1/10/1992	[1]ND	[1]ND
STT61to66-MW12	1/10/1992	[1]ND	[1]ND
STT61to66-MW13	1/10/1992	[1]ND	[1]ND
STT61to66-MW14	1/10/1992	[1]23	[1]ND
STT61to66-MW15	12/14/1992	[1]ND	[1]9
STT61to66-MW16	12/14/1992	[1]ND	[1]ND
STT61to66-MW17	12/14/1992	[1]ND	[1]ND
STT61to66-MW18	12/14/1992	[1]7	[1]ND
STT61to66-MW19	12/14/1992	[1]ND	[1]ND
STT61to66-MW20	12/14/1992	[1]1	[1]ND
TT-23	1/16/1985	ND	ND
	2/12/1985	6.5	ND
	2/19/1985	ND	—
	2/19/1985	6.3	ND
	3/11/1985	6.7	—
	3/11/1985	4.3	—
	7/11/1991	ND	—
TT-25	2/5/1985	ND	ND
	10/29/1985	ND	ND
	11/4/1985	ND	ND
	11/13/1985	ND	ND
	12/3/1985	ND	ND
	7/11/1991	ND	—
TT-26	1/16/1985	ND	ND
	2/12/1985	ND	ND
	2/19/1985	ND	—
	2/19/1985	ND	—
	7/11/1991	ND	—
	7/11/1991	ND	—

Table E9. Summary of analyses of groundwater samples for benzene and toluene collected at water-supply wells, monitor wells, and hydrocone penetration sites during ABC One-Hour Cleaners Operable Units 1 and 2, by the North Carolina Department of Natural Resources and Community Development, and by the U.S. Navy during remedial or other investigations of spills or leaks of petroleum products to groundwater, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[µg/L, microgram per liter; ND, not detected; —, constituent not determined; J, estimated value]

Site name	Date	Benzene concentration, in µg/L	Toluene concentration, in µg/L
TT-30	2/6/1985	ND	ND
TT-31	2/6/1985	ND	ND
TT-52	2/6/1985	ND	ND
TT-54	2/6/1985	ND	ND
	7/11/1991	1.3J	—
TT-67	2/6/1985	ND	ND
TTUST-44-MW01	11/15/2001	[1]ND	[1]ND
TTUST-44-MW02	11/15/2001	[1]ND	[1]ND
TTUST-44-MW03	11/15/2001	[1]ND	[1]ND
TTUST-779-MW01	7/27/2002	[1]ND	[1]ND
TTUST-2254-MW01	7/25/2002	[1]ND	[1]ND
TTUST-2258-MW01	7/24/2002	[1]ND	[1]ND
TTUST-2302-MW01	7/24/2002	[1]ND	[1]ND
TTUST-2453-OB1	6/6–9/1989	[3]13,000	[3]44,000
TTUST-2453-OB2	6/6–9/1989	[3]12,000	[3]39,000
TTUST-2453-OB4	6/6–9/1989	[3]22,000	[3]38,000
TTUST-2453-OB11	6/6–9/1989	[3]<1,000	[3]17,000
TTUST-2453-RW	6/6–9/1989	[3]5,300	[3]7,900
TTUST-2455-3	10/7/1993	[3]ND	[3]ND
TTUST-2455-4	10/20/1993	[3]ND	[3]ND
TTUST-2455-5	10/7/1993	[3]ND	[3]ND
TTUST-2455-6	10/20/1993	[3]ND	[3]ND
TTUST-2455-7	10/7/1993	[3]1.4	[3]1.3
TTUST-2455-8	10/7/1993	[3]ND	[3]ND
TTUST-2455-9	10/20/1993	[3]ND	[3]ND
TTUST-2455-10	10/7/1993	[3]ND	[3]ND
TTUST-2455-11	10/7/1993	[3]ND	[3]0.7
TTUST-2455-12	10/7/1993	[3]0.6	[3]1.1
TTUST-2455-13	10/20/1993	[3]ND	[3]ND
TTUST-2455-14	10/20/1993	[3]ND	[3]ND
TTUST-2455-15	11/22/1993	[3]ND	[3]ND
TTUST-2455-16	10/20/1993	[3]ND	[3]ND
TTUST-TTSC-1	12/19/1994	[1]ND	[1]ND
TTUST-TTSC-2	12/19/1994	[1]0.7	[1]ND
TTUST-TTSC-3	12/19/1994	[1]0.8	[1]ND
TTUST-TTSC-4	12/19/1994	[1]0.7	[1]ND
TTUST-TTSC-5	12/19/1994	[1]0.7	[1]ND
TTUST-TTSC-6	12/19/1994	[1]11.1	[1]ND
TTUST-TTSC-7	12/19/1994	[1]0.8	[1]0.6
TTUST-TTSC-8	12/19/1994	[1]0.7	[1]ND
TTUST-TTSC-9	12/19/1994	[1]1.7	[1]ND
TTUST-TTSC-10	12/19/1994	[1]0.7	[1]ND
TTUST-TTSC-13	12/19/1994	[1]1	[1]1.2
TTUST-TTSC-14	12/19/1994	[1]0.8	[1]0.6
TTUST-TTSC-15	12/19/1994	[1]0.7	[1]ND
TTUST-TTSC-16	12/19/1994	[1]32.5	[1]58.7
TTUST-2477-MW01	10/18/1994	[2]4.3	[2]2.6
TTUST-2477-MW02	10/18/1994	[2]0.8	[2]2.3
TTUST-2477-MW03	10/18/1994	[2]ND	[2]ND
TTUST-2477-MW04	10/18/1994	[2]0.6	[2]ND
TTUST-2477-MW05	10/18/1994	[2]1.6	[2]2.8
TTUST-2477-MW06	11/22/1994	[2]ND	[2]ND
TTUST-2477-MW07	11/22/1994	[2]ND	[2]ND
TTUST-2477-MW08	11/22/1994	[2]ND	[2]ND
TTUST-2477-MW09	11/22/1994	[2]ND	[2]ND
TTUST-2477-MW10	11/22/1994	[2]ND	[2]ND
TTUST-2477-MW11	11/22/1994	[2]ND	[2]ND
TTUST-2477-MW12	11/23/1994	[2]ND	[2]ND
TTUST-2477-MW13	11/22/1994	[2]ND	[2]ND
TTUST-2477-MW14	11/22/1994	[2]ND	[2]ND
TTUST-2478-MW03	12/30/1993	[2]6,200	[2]13,000
TTUST-2478-MW05	12/30/1993	[2]8,800	[2]26,000
TTUST-2478-MW06	12/30/1993	[2]1,300	[2]530
TTUST-2478-MW08	12/30/1993	[2]ND	[2]ND
TTUST-2478-MW09	12/30/1993	[2]ND	[2]ND
TTUST-2478-MW10	12/29/1993	[2]ND	[2]ND
TTUST-2478-MW11	12/29/1993	[2]ND	[2]ND
TTUST-2478-MW11D	12/30/1993	[2]ND	[2]ND
TTUST-2478-MW12	12/29/1993	[2]ND	[2]ND
TTUST-2478-MW13	12/29/1993	[2]ND	[2]ND
TTUST-2478-MW14	12/29/1993	[2]290	[2]7.9
TTUST-2478-MW14D	12/30/1993	[2]ND	[2]ND
TTUST-2478-MW15	12/30/1993	[2]ND	[2]ND
TTUST-2478-MW16	12/29/1993	[2]ND	[2]ND
TTUST-2478-MW17	12/29/1993	[2]11	[2]ND
TTUST-2478-MW17D	12/29/1993	[2]ND	[2]ND
TTUST-2478-MW18	12/29/1993	[2]33	[2]ND
TTUST-2478-MW19	12/29/1993	[2]18	2.9
TTUST-2478-MW20	9/19/2000	[1]13	[1]2,580
TTUST-2478-MW21D	9/19/2000	[1]ND	[1]0.62
TTUST-2478-MW22	9/19/2000	[1]ND	[1]11.3
TTUST-2478-MW23	9/19/2000	[4]ND	[4]ND
TTUST-2478-MW24	9/19/2000	[1]ND	[1]ND
TTUST-2478-MW25	9/19/2000	[1]ND	[1]ND
TTUST-2634-MW01	11/29/2001	[1]ND	[1]ND
TTUST-3140-MW01	7/24/2002	[1]ND	[1]ND
TTUST-3165-MW01	7/24/2002	[1]ND	[1]ND
TTUST-3233-MW01	7/24/2002	[1]4	[1]ND
TTUST-3524-MW01	7/25/2992	[1]ND	[1]ND
TTUST-3546-MW01	7/25/2002	[1]ND	[1]2
X24B5	9/25/1985	2.3	—

[1] Detection/quantitation limit = 1 µg/L

[2] Detection/quantitation limit = 0.5 µg/L

[3] Detection/quantitation limit is unknown

[4] Detection/quantitation limit = 5 µg/L

NOTE: Unless otherwise noted by superscripts "1," "2," "3," or "4," the detection limit = 10 µg/L

Table E10. Location coordinates of monitor wells at sites undergoing remedial investigations or other investigations of leaks or spills of petroleum products to groundwater, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Site name[1]	Location coordinates[2]	
	North	East
STT61to66-MW01	364847	2489130
STT61to66-MW02	364847	2489130
STT61to66-MW03	364740	2489186
STT61to66-MW04	364740	2489186
STT61to66-MW05	364818	2489276
STT61to66-MW06	364818	2489276
STT61to66-MW07	364885	2489219
STT61to66-MW08	364885	2489219
STT61to66-MW09	364732	2489102
STT61to66-MW10	364732	2489102
STT61to66-MW11	364700	2489241
STT61to66-MW12	364700	2489241
STT61to66-MW13	364612	2489148
STT61to66-MW14	364612	2489148
STT61to66-MW15	364754	2489310
STT61to66-MW16	364603	2489247
STT61to66-MW17	364693	2489062
STT61to66-MW18	364616	2489072
STT61to66-MW19	364525	2489072
STT61to66-MW20	364554	2489135
TTDump-MW01	360343	2488970
TTDump-MW02	360623	2488230
TTDump-MW03	360230	2487690
[3]TTUST-44-MW01	360936	2488458
[3]TTUST-44-MW02	360962	2488506
[3]TTUST-44-MW03	360978	2488487
[3]TTUST-779-MW01	362251	2490046
[3]TTUST-2254-MW01	362204	2486721
[3]TTUST-2258-MW01	362175	2486658
[3]TTUST-2302-MW01	361702	2486831
[3]TTUST-2453-A1	361286	2488830
[3]TTUST-2453-A2	361090	2488716
[3]TTUST-2453-A3	361092	2488773
[3]TTUST-2453-A4	361187	2488760
[3]TTUST-2453-A5	361160	2488901
[3]TTUST-2453-A6	361102	2488864
[3]TTUST-2453-A7	361109	2488874
[3]TTUST-2453-A8	361092	2488868
[3]TTUST-2453-A9	361109	2488881
[3]TTUST-2453-A11	361104	2488897
[3]TTUST-2453-A13	361104	2488990
[3]TTUST-2453-A16	361093	2488944
[3]TTUST-2453-OB1	361111	2488903
[3]TTUST-2453-OB2	361104	2488812
[3]TTUST-2453-OB3	361061	2488867
[3]TTUST-2453-OB4	361166	2488864
[3]TTUST-2453-OB6	361127	2488864
[3]TTUST-2453-OB7	361228	2488907
[3]TTUST-2453-OB8	361002	2488849
[3]TTUST-2453-OB9	361099	2488852
[3]TTUST-2453-OB10	361067	2488814
[3]TTUST-2453-OB11	361181	2488817
[3]TTUST-2453-RW	361111	2488874
[3]TTUST-2455-1	361322	2488307
[3]TTUST-2455-2	361313	2488289
[3]TTUST-2455-3	361333	2488264
[3]TTUST-2455-4	361356	2488245
[3]TTUST-2455-5	361436	2488312
[3]TTUST-2455-6	361255	2488250
[3]TTUST-2455-7	361120	2488302
[3]TTUST-2455-8	361203	2488302
[3]TTUST-2455-9	361255	2488321
[3]TTUST-2455-10	361171	2488350
[3]TTUST-2455-11	361155	2488259
[3]TTUST-2455-12	361292	2488261
[3]TTUST-2455-13	361484	2488341
[3]TTUST-2455-14	361136	2488407
[3]TTUST-2455-15	360972	2488327
[3]TTUST-2455-16	361310	2488291
[3]TTUST-2455-18	361196	2488312
[3]TTUST-TTSC-1	361637	2488268
[3]TTUST-TTSC-2	361532	2488246
[3]TTUST-TTSC-3	361589	2488360
[3]TTUST-TTSC-4	361666	2488337
[3]TTUST-TTSC-5	361619	2488355
[3]TTUST-TTSC-6	361552	2488374

Table E10. Location coordinates of monitor wells at sites undergoing remedial investigations or other investigations of leaks or spills of petroleum products to groundwater, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

Site name	Location coordinates[1]	
	North	East
[3]TTUST-TTSC-7	361470	2488474
[3]TTUST-TTSC-8	361653	2488577
[3]TTUST-TTSC-9	361328	2488369
[3]TTUST-TTSC-10	361671	2488387
[3]TTUST-TTSC-13	361614	2488404
[3]TTUST-TTSC-14	361526	2488244
[3]TTUST-TTSC-15	361657	2488579
[3]TTUST-TTSC-16	361619	2488397
[3]TTUST-2477-MW01	361550	2488759
[3]TTUST-2477-MW02	361562	2488738
[3]TTUST-2477-MW03	361615	2488759
[3]TTUST-2477-MW04	361555	2488776
[3]TTUST-2477-MW05	361580	2488738
[3]TTUST-2477-MW06	361521	2488738
[3]TTUST-2477-MW07	361519	2488745
[3]TTUST-2477-MW08	361459	2488658
[3]TTUST-2477-MW09	361447	2488774
[3]TTUST-2477-MW10	361324	2488759
[3]TTUST-2477-MW11	361329	2488754
[3]TTUST-2477-MW12	361243	2488858
[3]TTUST-2477-MW13	361240	2488865
[3]TTUST-2477-MW14	361197	2488975
[3]TTUST-2478-MW01	361876	2488879
[3]TTUST-2478-MW02	361835	2488865
[3]TTUST-2478-MW03	361849	2488895
[3]TTUST-2478-MW04	361883	2488890
[3]TTUST-2478-MW05	361843	2488872
[3]TTUST-2478-MW06	361828	2488876
[3]TTUST-2478-MW07	361868	2488888
[3]TTUST-2478-MW08	362092	2488829
[3]TTUST-2478-MW09	361888	2488997
[3]TTUST-2478-MW10	361785	2488999
[3]TTUST-2478-MW11	361716	2489004
[3]TTUST-2478-MW11D	361716	2489004
[3]TTUST-2478-MW12	361540	2488990
[3]TTUST-2478-MW13	361718	2488764
[3]TTUST-2478-MW14	361780	2488898
[3]TTUST-2478-MW14D	361780	2488898
[3]TTUST-2478-MW15	361900	2488730
[3]TTUST-2478-MW16	361452	2488973
[3]TTUST-2478-MW17	361377	2488896
[3]TTUST-2478-MW17D	361377	2488896
[3]TTUST-2478-MW18	361425	2488824
[3]TTUST-2478-MW19	361528	2488819
[3]TTUST-2478-MW20	361093	2488831
[3]TTUST-2478-MW21D	361087	2488826
[3]TTUST-2478-MW22	360933	2489041
[3]TTUST-2478-MW23	360836	2488918
[3]TTUST-2478-MW24	360877	2488755
[3]TTUST-2478-MW25	361031	2488668
[3]TTUST-2478-PW01	361898	2488879
[3]TTUST-2634-MW01	363587	2487670
[3]TTUST-3140-MW01	364679	2486468
[3]TTUST-3140-SB05	364678	2486467
[3]TTUST-3165-MW01	364540	2485990
[3]TTUST-3233-MW01	363831	2485914
[3]TTUST-3524-MW01	362897	2485350
[3]TTUST-3546-MW01	362583	2485633

[1]See Plate 1, Chapter A report, for location (Maslia et al. 2007)

[2]Location coordinates are North Carolina State Plane coordinates, North American Datum of 1983

[3]Because of scale, not shown on Plate 1, Chapter A report (Maslia et al. 2007)

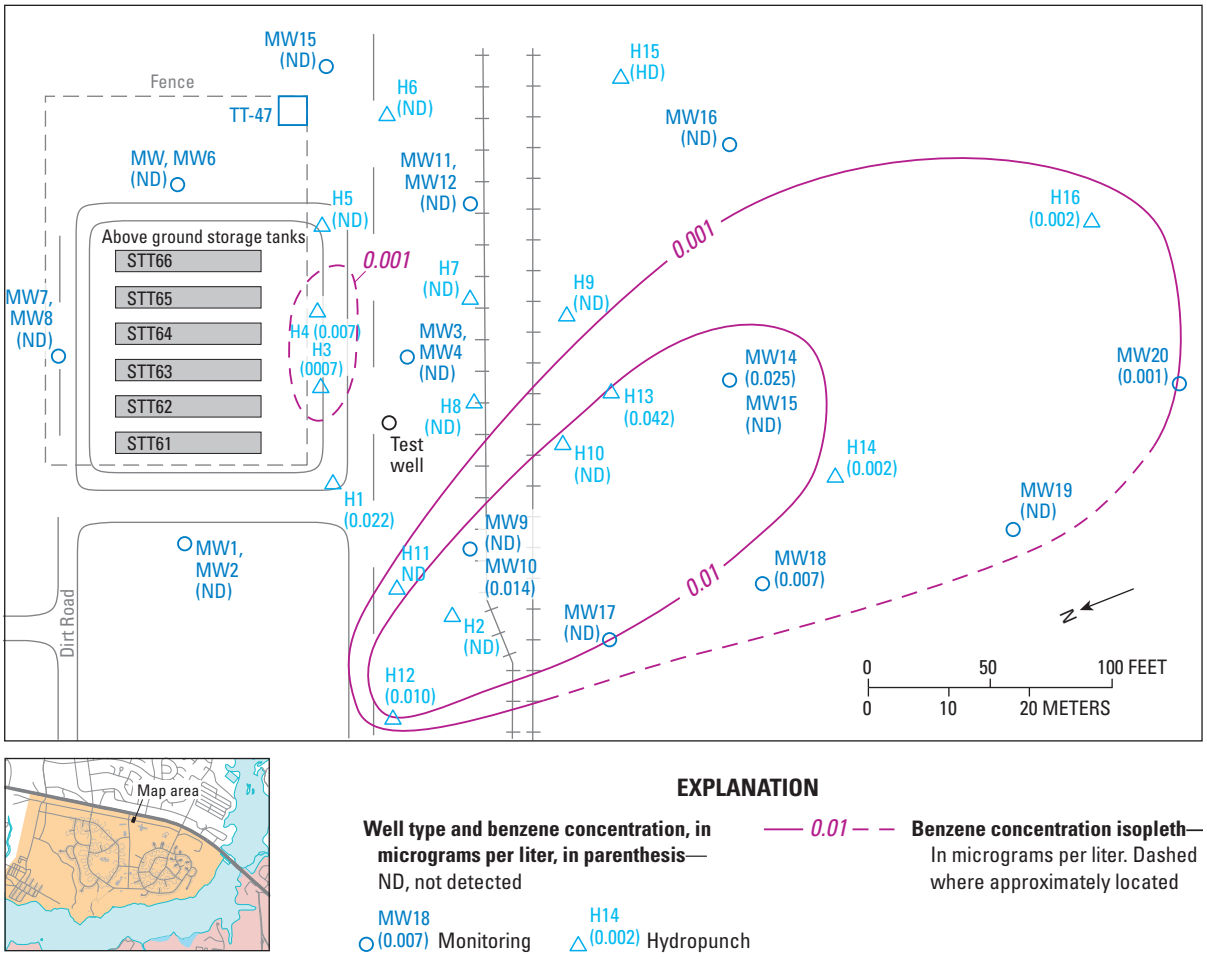


Figure E7. Highly generalized delineation of a benzene plume emanating from tank area STT61–STT66, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, 1992 (modified from O'Brien & Gere Engineers, Inc. 1993).

The Tarawa Terrace Shopping Center is located in the southern part of Tarawa Terrace north of the shoreline of Northeast Creek (Figure E1). Eleven buildings associated with the shopping center are numbered beginning at TT-2455 and ending at TT-2475. The construction date of the shopping center is unknown, but the major buildings and the name "Shopping Center" are shown on maps of Tarawa Terrace dated June 1961 (Sheet 3 of 18, Map of Tarawa Terrace II Quarters, June 30, 1961). Twelve underground storage tanks (USTs) ranging in capacity from 300 to 500 gal and several above-ground storage tanks were associated with various buildings at the shopping center. The installation and release history of these tanks is unknown; however, releases from two tanks were confirmed during 1994. Many of these tanks were abandoned by 1995 (Richard Catlin & Associates, Inc. 1994a,b, 1995a,b).

Adjacent or in close proximity to the shopping center are Buildings TT-2477, TT-2478, and TT-2453. Building TT-2477 was constructed during the 1950s as a full-service gasoline station. This building originally contained one 10,000-gal gasoline UST and one 550-gal UST for hydraulic/gear fluids. These tanks probably were installed at the time of construction of Building TT-2477. During 1992, the 550-gal tank was removed, and the 10,000-gal tank was abandoned in place (Law Engineering, Inc. 1995 a,b). The release history is unknown for both tanks.

Building TT-2478 is located approximately 250 ft north of Building TT-2477 and was constructed during 1986. Three 10,000-gal gasoline USTs were installed at the time of construction. By 1992, at least two of the tanks were determined to be leaking (Law Engineering, Inc. 1994a,b).

Building TT-2453, located slightly southeast of Building TT-2455 of the shopping center and about 450 ft south of Building TT-2477, was a gasoline station at one time. The installation and release history of tanks at Building TT-2453 is unknown, but this building is shown on maps of Tarawa Terrace dated June 1961 and is identified on some as a "filling station" (Sheet 3 of 18, Map of Tarawa Terrace II Quarters, June 30, 1961). DiGiano et al. (1988) summarized the results of gasoline-plume discovery and delineation at Building TT-2453 (Industrial Marine Services, Inc. 1985). The presence of gasoline in the subsurface at Building TT-2453 apparently originated from two sources: (1) a catastrophic tank failure on September 21, 1985, with a subsequent loss

of 4,400 gal of unleaded gasoline to the subsurface, and (2) a 3,000-gal tank of leaded gasoline discovered leaking on July 23, 1986. A release history by DiGiano et al. (1988, Table 3) indicates that small leaks of product probably occurred at this site beginning in the 1950s. As of May 4, 1987, more than 2 ft of "free product" was identified above the water table in the vicinity of Building TT-2453. Concentrations of benzene in groundwater samples collected at monitor wells in the vicinity of Building TT-2453 ranged from less than 1,000 to about 22,000 µg/L (Table E9). The contamination associated with Building TT-2453 was undergoing active remediation as of May 1987 (DiGiano et al. 1988).

As of about 1995, Buildings TT-2455, TT-2463, TT-2465, TT-2467, TT-2469, and TT-2471 of the shopping center were subjects of active investigations of groundwater contamination, as were UST sites associated with buildings TT-2477 and TT-2478 (Law Engineering, Inc. 1994a,b, 1995a,b; Law Engineering and Environmental Services, Inc. 1996; OHM Remediation Services Corp. 2001; Richard Catlin & Associates, Inc. 1994a,b, 1995a,b, 1996, 1998). Numerous monitor wells were installed during these investigations and were the locations of periodic collections of water-level data and water-quality samples (Tables E9 and E10). All wells were installed either in the Tarawa Terrace aquifer or the Upper Castle Hayne aquifer–River Bend unit (Faye 2007a).

Water-level measurements accurate to a hundredth of a foot were collected at paired wells in conjunction with investigations at Buildings TT-2477 and TT-2478 and indicated that vertical head gradients between depths of 15 and 50 ft were generally downward and ranged from 0 to order of magnitude 10^{-4} ft/ft (Law Engineering, Inc. 1994a). Water-level data also indicated the direction of groundwater flow in the shopping center area was southward. Water-table altitudes ranged from about 8 to 11 ft, NGVD 29 (Law Engineering, Inc. 1995a) (Figure E8).

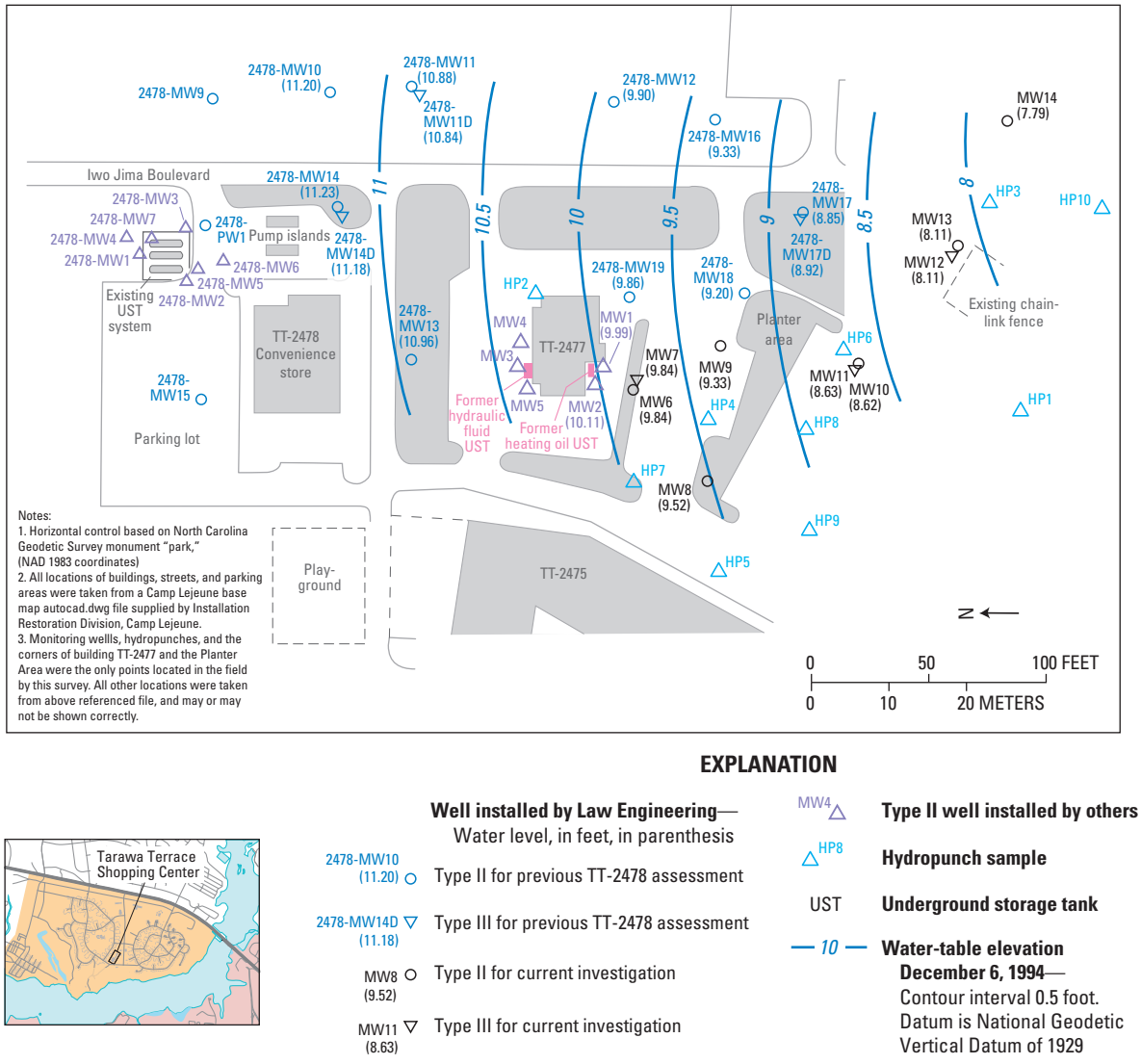
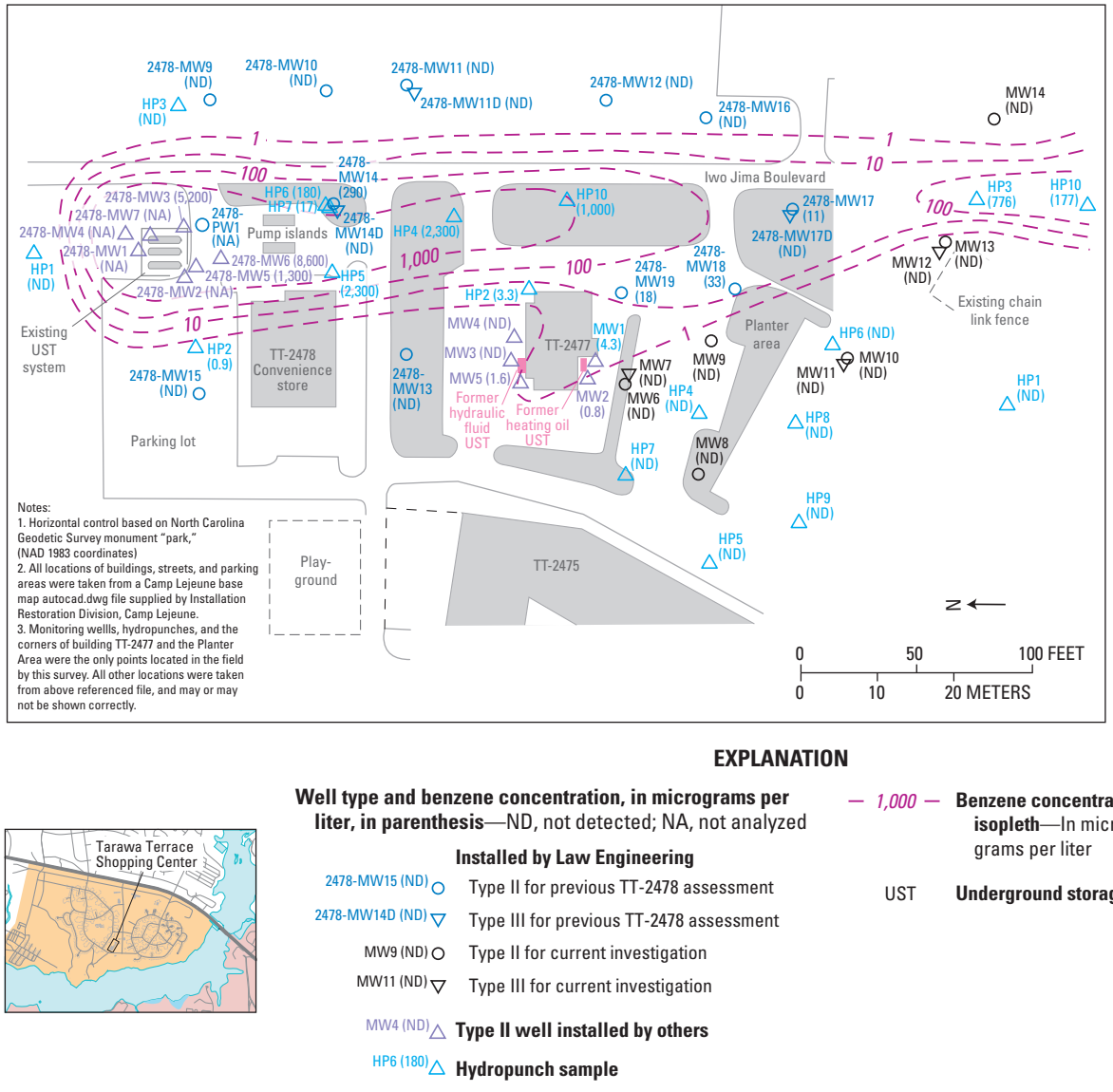


Figure E8. Potentiometric surface of the combined Tarawa Terrace aquifer and Upper Castle Hayne aquifer–River Bend unit in the vicinity of the Tarawa Terrace Shopping Center, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, October–December 1994 (modified from Law Engineering, Inc. 1995a).

Water-quality samples collected at monitor wells and at several hydrocone sampling sites were analyzed for all BTEX constituents. The approximate extent of a benzene plume delineated during 1994 in front of the shopping center is from about 600 ft north to south, as shown in Figure E9 (Law Engineering, Inc. 1995a). This plume possibly represents the merger of older plumes originally emanating from areas near Buildings TT-2477 and TT-2453. Benzene concentrations at the northern apex of the plume were in excess of 6,000 µg/L. This northern apex was located approximately 700 ft almost directly south of Tarawa Terrace water-supply well TT-52, which was placed in service during 1961 and removed from service during March 1987. Tarawa Terrace water-supply well TT-31 was located about 1,300 ft northeast of the plume's northern apex. Well TT-31 was placed in service during 1973 and also was removed from service during March 1987.

In addition to active remedial investigations at buildings of the shopping center and at the storage tanks, several other sites within the Tarawa Terrace housing areas were the subject of UST removal and related soil and groundwater investigations. The site designators at these locations correspond to Tarawa Terrace building addresses and include TT-44, TT-48, TT-779, TT-2254/2256, TT-2258/2260, TT-2302/2304, TT-2634, TT-3140/3142, TT-3165/3167, TT-3233/3235, TT-3524/3526, and TT-3546/3548 (Catlin Engineers and Scientists 2002a,b; Law Engineering and Environmental Services, Inc. 1998; Mid-Atlantic Associates, P.A. 2002a,b,c,d,e,f,g; Mid-Atlantic Associates, Inc. 2003a,b). Concentrations of benzene and toluene at monitor wells installed at these sites and at the shopping center and vicinity are listed in Table E9. Concentrations of benzene ranged from not detected to 290 µg/L



EXPLANATION

Well type and benzene concentration, in micrograms per liter, in parenthesis—ND, not detected; NA, not analyzed

— 1,000 — **Benzene concentration isopleth**—In micrograms per liter

UST **Underground storage tank**

Installed by Law Engineering

2478-MW15 (ND) Type II for previous TT-2478 assessment

2478-MW14D (ND) Type III for previous TT-2478 assessment

MW9 (ND) Type II for current investigation

MW11 (ND) Type III for current investigation

MW4 (ND) **Type II well installed by others**

HP6 (180) **Hydropunch sample**

Figure E9. Boundaries of benzene plume in the vicinity of the Tarawa Terrace Shopping Center, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, 1994 (modified from Law Engineering, Inc. 1995a).

at monitor well 14 (TTUST-2478-MW14 and TTUST-2478-MW14D) near Building TT-2478 in the vicinity of the shopping center. Benzene was not detected at the majority of sites. Location coordinates of monitor wells constructed during remedial investigations or investigations of leaks or spills of refined petroleum products to groundwater are listed in Table E10.

During 1991, Haliburton NUS Environmental Corporation (1992) conducted soil borings and installed several monitor wells at the Tarawa Terrace dump (TT-Dump) located immediately south of the shopping center and between it and Northeast Creek (Figure E1). Constituent concentrations of interest to this study were determined in soil samples from several locations and were generally low or not detected. Water-level data collected during this investigation indicated that all groundwater flow was entirely from the dump site toward Northeast Creek.

Occurrence of PCE and Related Constituents at Water-Supply Wells TT-23, TT-25, and TT-26

Water-supply well TT-26 was constructed during May 1951 (R.E. Peterson, "Public Works," written communication, May 31, 1951) and was probably placed in service at the first occupation of Tarawa Terrace, also during 1951 or 1952. Well TT-26 was a major supply well to the Tarawa Terrace WTP until it was removed from service during February 1985 because of contamination. Well TT-25 was constructed during November 1980 and was in service at least as early as January 1982. Well TT-25 was removed from service during March or April 1987. Well TT-23 was constructed prior to the 24-hour aquifer test conducted at the well on March 15, 1983 (North Carolina Department of Natural and Economic Resources–Ground Water Division, written communication, date unknown), and was placed in service probably prior to September 4, 1984, when Camp Lejeune personnel conducted a capacity test at the well and noted that the discharge pressure was "left set at 32 psi" (pounds per square inch) (Thomas and Brown, written communication, September 4, 1984). Well TT-23 definitely was in service during September 1984, based on two entries in the WTP "Check In Log" dated September 21 and September 29, 1984 (Camp Lejeune WTP Check In Log, written communication, August 16, 1984, to April 1, 1985; Camp Lejeune water documents CLW 7999 and CLW 8007, September 21, 1984 and September 29, 1984). Well TT-23 was removed from service during February 1985, also because of contamination, but was used periodically to supply the Tarawa Terrace WTP during March and April 1985 (Camp Lejeune water document CLW 1193—"Direction to Operators at Tarawa Terrace," April 30, 1985; Camp Lejeune water document CLW 1194—"Procedures for Operating the 'New Well' at Tarawa Terrace," date unknown).

Sampling and analyses for PCE concentrations at Tarawa Terrace water-supply wells TT-23, TT-25, and TT-26 occurred periodically during 1985. Additional sampling and analyses did not occur again at wells TT-23 and TT-26 until July 1991, during the investigations of ABC One-Hour Cleaners Operable Unit 1 (Table E2). Additional sampling and analyses at well TT-25 occurred between October 1985 and April 1986; however, most of these analyses were not available for this study (Department of the Navy, J.R. Bailey, by direction of the Commander, written communication, April 25, 1986; Camp Lejeune water documents CLW 1475–1483).

Concentrations of PCE at well TT-23 ranged from about 130 µg/L during January 1985 to not detected during July 1991 (Figure E10). After well TT-23 was removed from service during February 1985, PCE concentrations at that well declined from 48 µg/L during March 1985 to 4 µg/L during September 1985 (Table E2). Well TT-23 is not located on a natural advective pathway from ABC One-Hour Cleaners (Figures E3, E4, and E5), and, as such, PCE probably originally occurred at the well only because of pumping at other water-supply wells, particularly nearby wells TT-54 and TT-67. The rapid decline of PCE concentration at well TT-23 between March and September 1985 is difficult to explain because wells TT-54 and TT-67 continued pumping until March or April 1987. Degradation of PCE in groundwater typically occurs under anaerobic conditions by the microbially mediated process of reductive dechlorination (Wiedemeier et al. 1998). Hydrogen in the subsurface is used by the dechlorinating bacteria as an electron donor, and chlorinated hydrocarbons—such as PCE—act as electron receptors, thus becoming reduced; in this case, from PCE to TCE. Hydrogen in the terrestrial subsurface is produced by the fermentation of a variety of organic compounds including anthropogenic hydrocarbons such as BTEX. Benzene was detected in water from well TT-23 during February and March 1985 in concentrations ranging from about 4 to about 7 µg/L (Table E9; Camp Lejeune water document CLW 1482, April 25, 1986) and possibly was the source of hydrogen that facilitated, and possibly accelerated, the reductive dechlorination of PCE at well TT-23. Note that TCE concentrations also were determined in water samples collected from well TT-23 during February and March 1985 in estimated concentrations ranging from about 1.3 to 2.4 µg/L. Note also that benzene concentrations were not detected at any time in discharge waters from well TT-26, which also was contaminated with PCE (Table E9). Following the complete cessation of groundwater pumping at Tarawa Terrace during March or April 1987, PCE in the Tarawa Terrace and Upper Castle Hayne aquifers was no longer induced to flow toward well TT-23, and the already low PCE concentrations at the well apparently degraded to not detected by July 1991. Concentrations of TCE and DCE also were not detected during July 1991 at well TT-23.

Samples collected for PCE analyses at well TT-26 were nearly coincident with collections at well TT-23. Concentrations of PCE at well TT-26 during 1985 varied between 3.8 and about 1,600 µg/L (Table E2). After well TT-26 was removed from service during February 1985, PCE concentrations apparently decreased for a short period before beginning to increase again during April 1985 (Figure E11). Much of this

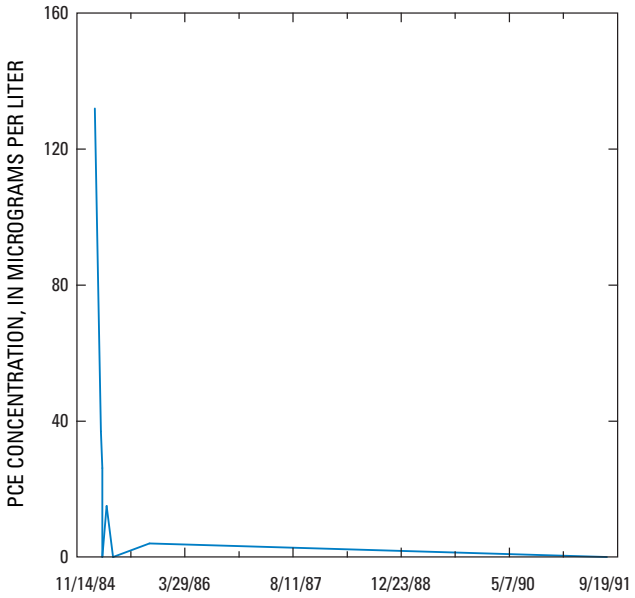


Figure E10. Tetrachloroethylene (PCE) concentrations at water-supply well TT-23, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1985–July 1991.

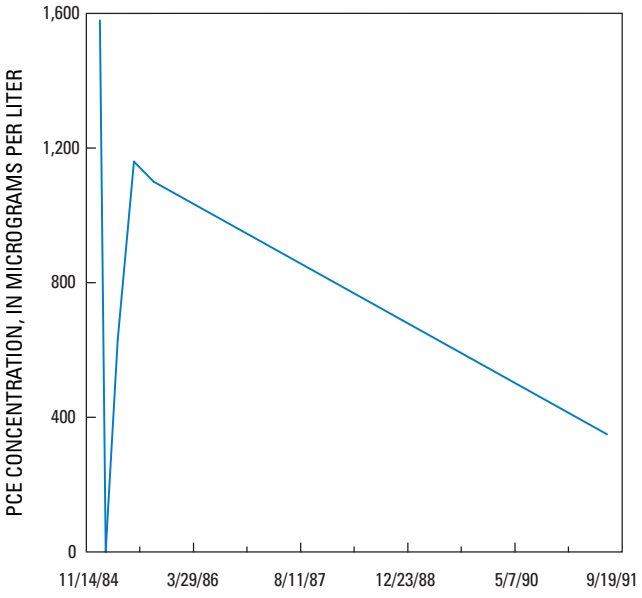


Figure E11. Tetrachloroethylene (PCE) concentrations at water-supply well TT-26, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1985–July 1991.

increase was possibly caused by continued pumping at well TT-25, which is open to the same interval of the Upper Castle Hayne aquifer–Lower unit as well TT-26 and is located only about 500 ft southwest and downgradient of well TT-26 (Figure E4). In addition, well TT-26 is located on a direct advective pathway from ABC One-Hour Cleaners, which partly explains the continued relatively high concentrations of PCE at the well during July 1991. A significant part of the decrease in PCE concentration at well TT-26 between September 1985 and July 1991 was possibly the result of microbial degradation.

PCE was first detected at well TT-25 during September 1985 at an estimated concentration of 0.43 µg/L (Table E2). This well was sampled again periodically until April 1986. Although only four of the latter analyses are available, all PCE concentrations reported for these analyses were not detected. After April 1986, this well is not known to have been sampled again until July 1991, at which time the PCE concentration was 23 µg/L. The PCE concentration at well TT-25 increased despite the well's removal from service during March or April 1987. High concentrations of PCE occurred at well TT-26 during 1985, and part of this PCE probably migrated toward well TT-25 between 1985 and 1991, partly by advection and partly along concentration gradients.

Trends in TCE concentration at wells TT-23 and TT-26 and DCE concentration at well TT-26 (Figures E12–E14, Table E2) are similar to those described for PCE. The TCE concentration at well TT-23 was relatively high during mid-1984 and early 1985, when the well was routinely operating, and declined rapidly when the well was removed from production during February 1985. TCE was not detected at well TT-23 during July 1991. At well TT-26, TCE concentrations also were high in early 1985 during routine operation. Concentrations declined rapidly after the well was removed from service and then increased between September 1985 and July 1991, possibly as a result of microbial degradation of PCE in the vicinity of the well and migration of TCE toward the well by advection and dispersion. Concentration trends of DCE at well TT-26 generally correspond to those of TCE for similar reasons. Concentrations of TCE and 1,2-cDCE at well TT-25 during July 1991 were about 6 and 1.4 µg/L, respectively (Table E2).

Reductions of PCE concentration reported at well TT-26 between September 1985 and July 1991 possibly occurred largely by microbially mediated degradation such as reductive dechlorination. Knowing the initial and final PCE concentrations at well TT-26 for this period and the number of days between measurements, a first-order degradation rate can be computed using the relation

$$C = C_0 e^{-kt}, \quad (1)$$

where

- C = the PCE concentration at well TT-26 on July 11, 1991;
- C_0 = the PCE concentration at well TT-26 on September 25, 1985;
- e = the base of Naperian or Natural logarithms;
- k = the degradation rate constant, in days^{-1}; and
- t = the elapsed time, in days.

The PCE concentrations at well TT-26 on September 25, 1985, and July 11, 1991, were 1,100 and 350 µg/L, respectively (Table E2), and the elapsed time was 2,151 days.

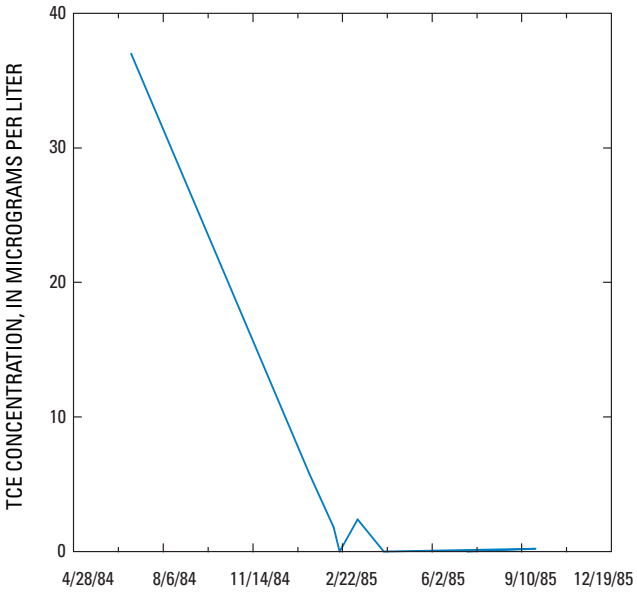


Figure E12. Trichloroethylene (TCE) concentrations at water-supply well TT-23, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, July 1984–October 1985.

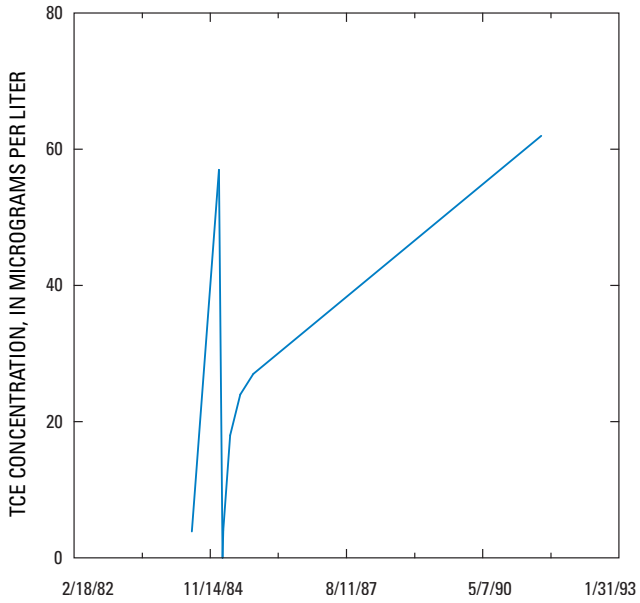


Figure E13. Trichloroethylene (TCE) concentrations at water-supply well TT-26, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1985–July 1991.

Applying these data to Equation 1, yields a degradation rate of 0.00053 per day. Potentiometric levels shown in Figures E4 and E5 indicate that well TT-26 (near monitor wells C3 and S3) is located on a direct advective pathway from ABC One-Hour Cleaners. Thus, PCE mass migrates down gradient toward and beyond well TT-26. To the extent that migration of PCE mass toward and away from well TT-26 occured at about

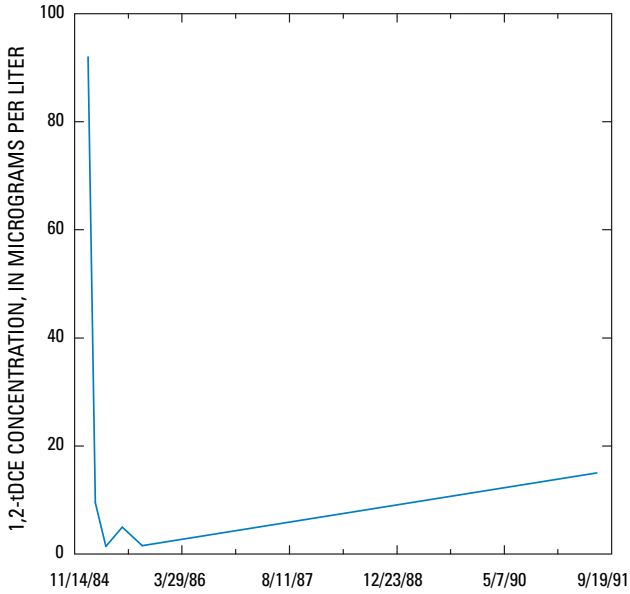


Figure E14. *Trans*-1,2-dichloroethylene (1,2-tDCE) concentrations at water-supply well TT-26, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1985–July 1991.

equal rates from 1985 to 1991, the computed degradation rate of 0.00053 per day approximates a long-term average rate. On the other hand, if a significant quantity of the PCE degraded in the vicinity of well TT-26 was replaced by advection, then the degradation rate computed using Equation 1 is probably a minimum rate.

Half-lives of PCE reported by Lucius et al. (1990) range from about 360 to 720 days. Applying these half lives to Equation 1 yields first-order degradation rates ranging between 0.001 and 0.002 per day, which is about two to four times the rate computed using concentrations at well TT-26. Aronson and Howard (1997) reported mean values of PCE degradation rates and half lives of 0.0029 per day and 239 days, respectively, determined from sample microcosms collected in situ during field investigations.

Equation 1 also can be applied to PCE concentrations determined at well TT-23 between March 11, 1985 (48 µg/L) and September 25, 1985 (4 µg/L), a period of 198 days (Table E2). A PCE degradation rate of about 0.5 per day is computed; this rate far exceeds the rate determined at well TT-26 and further indicates that the occurrence of BTEX in water-bearing units open to well TT-23 possibly accelerated the degradation process. Migration of PCE toward well TT-23 continued after the removal of the well from service after February 1985, indicating that the computed biodegradation rate might underestimate actual conditions. Conversely, dispersion and adsorption processes during migration would tend to reduce the September 1985 concentration below that of a conservative solute and cause an overestimate of the degradation rate.

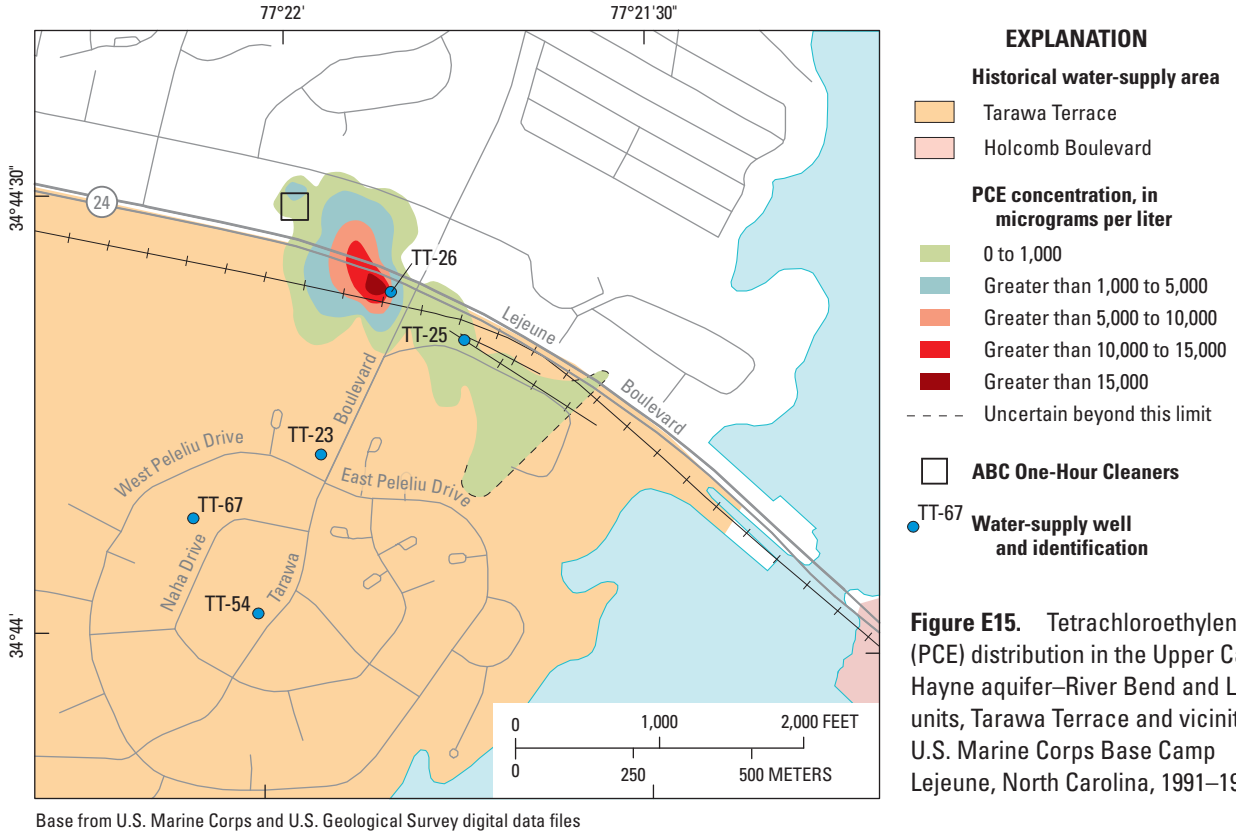
Constituent concentrations noted as not detected in Table E2 were converted to 0 µg/L to plot Figures E10–E14.

Occurrence of PCE in the Upper Castle Hayne Aquifer, 1991–1993

Concentrations of PCE determined at monitor wells during ABC One-Hour Cleaners Operable Units 1 and 2 and at hydrocone locations and abandoned Tarawa Terrace water-supply wells during Operable Unit 1 were used to spatially represent the distribution of PCE in the Upper Castle Hayne aquifer during 1991–1993 (Tables E2–E3, E5–E8; Figure E15). A mass of PCE with concentrations exceeding 15,000 µg/L occurs near and slightly upgradient of water-supply well TT-26 and is represented by the area of concentric closed contours in Figure E15. The high concentrations of PCE at the center of the closed contours are similar to the concentrations observed in the immediate proximity of ABC One-Hour Cleaners during 1985, and the location during 1991–1993 may represent the migration of that PCE mass. The State Plane coordinates of ABC One-Hour Cleaners and the location of the greatest concentration within the center of PCE mass during December 1991 (Table E7) are known. If a linear, horizontal migration path is assumed, then the center of mass migrated down the hydraulic gradient about 800 ft between 1985 and 1991, which represents an average migration-path velocity of about 0.3 ft/day. The small lobes of PCE mass extending south and southeast of ABC One-Hour Cleaners are either directly opposite or somewhat orthogonal to the hydraulic gradient within the Upper Castle Hayne aquifer (Figure E5) and may represent relict masses of PCE that migrated south of ABC One-Hour Cleaners because of pumping at Tarawa Terrace water-supply wells during their period of operation prior to March 1987.

Computation of PCE Mass in the Upper Castle Hayne Aquifer, 1991–1993

The concentrations of PCE at monitor wells, Tarawa Terrace water-supply wells, and at hydrocone locations determined by Roy F. Weston, Inc. (1992, 1994) during Operable Units 1 and 2 (Tables E2–E3, E5–E8) also were used to calculate the mass of PCE still contained in the Upper Castle Hayne aquifer at the time the Operable Units were in progress (1991–1993). With only three exceptions, the water samples collected by hydrocone penetration were collected at two depths at each location (Table E7). The collection depth for the majority of the "shallow" samples ranged from about 15 to 25 ft. These data and data from the shallow ("S") monitor wells were assigned to an "upper shell." The collection depth for the majority of the "deep" samples ranged from about 35 to 45 ft. These data and data from the deep ("C") monitor wells and Tarawa Terrace water-supply wells were assigned to a "lower shell." An altitude was assigned to each sampling interval. At monitor wells and Tarawa Terrace



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

Figure E15. Tetrachloroethylene (PCE) distribution in the Upper Castle Hayne aquifer–River Bend and Lower units, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina, 1991–1993.

water-supply wells, altitude was assigned at the midpoint of the open or screened interval. At hydrocone locations, altitude was assigned at the reported sample depth.

Using gridding and interpolation techniques, contour maps of PCE concentration and altitude were constructed for the upper and lower shells. The shell maps of PCE concentration closely resemble the map shown in Figure E15. The contour maps of altitude of the upper and lower shells were used to compute the volume of aquifer materials between shells. This volume equaled approximately 186 x 10^6 cubic feet (ft^3) or about 5.3 x 10^9 liters (L). The total volume of aquifer materials was multiplied by an effective porosity of 20 percent to estimate the volume of connected interstices between shells, which equaled about 1.1 x 10^9 L (Table E11).

The shell contour maps of PCE concentration first were used to determine contours of PCE concentration representing an average condition between the upper and lower shells, termed herein the average PCE shell. Contours representing the average PCE shell were constructed at concentration intervals of 2,000 µg/L of PCE. The area between each concentration contour was determined using Geographic Information System (GIS) techniques and is termed herein a subarea (Table E11). Nine subareas were determined, and a representative PCE concentration was assigned to each subarea corresponding to the average concentration of the two contours that bound the subarea. The product of each subarea and its representative concentration was then determined. These products were summed and the total divided by the total area of PCE

Table E11. Computation of tetrachloroethylene (PCE) mass in the Upper Castle Hayne aquifer, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina, 1991–1993.

[µg/L, microgram per liter; ft^2, square foot]

PCE contour range, in µg/L	Cumulative area, in ft^2	Subarea, in ft^2	Subarea PCE concentration, in µg/L	Subarea-weighted PCE concentration, in µg/L × ft^2
12,000+	2,536.4	2,536.4	12,000	30,436,342
10,000 to 12,000	8,327.7	5,791.3	11,000	63,704,515.1
8,000 to 10,000	19,214.3	10,886.6	9,000	97,979,539.6
6,000 to 8,000	46,394.4	27,180.1	7,000	190,260,492.8
4,000 to 6,000	103,822.4	57,428	5,000	287,139,951.1
2,000 to 4,000	238,065.4	134,243	3,000	402,730,048.4
0 to 2,000	1,793,827.4	1,555,762.1	1,000	1,555,762,094
2.2	1,812,259.5	18,432	2.2	40,660.3
3.4	1,834,571.1	22,311.6	3.4	75,859.4
Total area	**1,834,571.0**			
Total subarea		**1,834,571.0**		
Total area-weighted PCE concentration				**2,628,129,503**

Area-weighted PCE concentration = 1,433 µg/L = 0.0014 gram per liter (sum of PCE subarea-weighted concentrations/total area)

Aquifer volume between shells = 186,072,994 cubic feet

Aquifer volume between shells × effective porosity (20 percent) = 37,214,599 cubic feet

Volume of connected interstices, in liters = 1,053,173,152 (1 cubic foot = 28.3 liters)

PCE mass, in grams = 1,474,442 (product of area-weighted PCE concentration and volume of connected interstices)

PCE weight, in pounds = 3,244 (1 gram = 0.0022 pound)

PCE volume, in cubic feet = 32 (unit weight of PCE = 101 pounds/cubic foot)

PCE volume, in gallons = 240 (1 cubic foot = 7.5 gallons)

contamination represented by the average PCE shell, or about 42 acres. The result of this computation is an area-weighted average PCE concentration for the entire volume of aquifer material between the upper and lower shells, which equaled about 1.4×10^{-3} grams per liter. The product of this weighted average concentration and the estimated volume of connected interstices between the shells (1.1×10^{9} L) equals the estimated mass of PCE within the volume of aquifer materials between the upper and lower shells, or about 1.5×10^{6} grams. This mass in grams was converted to a weight of 3.2×10^{3} pounds (lbs), or 1.6 tons. The unit weight of PCE is about 1.6 that of water, or about 101 pounds per cubic feet (lbs/ft^3). Accordingly, the estimated volume of PCE within the aquifer materials between the upper and lower shells at Tarawa Terrace and vicinity equals about 32 ft^3, or about 240 gal. Considering that ABC One-Hour Cleaners began operation during 1953, used PCE as a dry-cleaning solvent during its entire period of operation, and was the single source of PCE to the Upper Castle Hayne aquifer at Tarawa Terrace and vicinity (Roy F. Weston, Inc. 1992, 1994; Shiver 1985), an average annual contribution of PCE to this aquifer from ABC One-Hour Cleaners between 1953 and 1985 is estimated at about 7 gal per year or about 120 grams per day. Pankow and Cherry (1996) indicate that computations of contaminant mass similar to those described in this section represent only a small part of the total contaminant mass in the subsurface of interest.

The effective porosity of a porous media is porosity that is directly related to the volume of connected interstices. Because porosity of unconsolidated sediments is largely primary, effective porosity is probably somewhat to substantially less than total porosity, particularly where silts and clays compose a significant percentage of the media. Effective porosity is closely related to laboratory determinations of specific yield and is equated with drainage porosity (Brady and Kunkel date unknown). Published data, primarily from Morris and Johnson (1967), were the sources of estimates of effective porosity for this study. The average specific yield of 287 samples of fine sand reported by Morris and Johnson (1967) was 33 percent. Specific yield of fine sand ranged from 1 to about 46 percent. Total porosity of 243 samples of fine sand ranged from 26 to about 53 percent and averaged 43 percent. Total porosity of 281 silt samples ranged from about 34 to 61 percent and averaged 46 percent. The specific yield of 266 silt samples ranged from about 1 to 39 percent and averaged 20 percent. The range and average specific yield of 27 clay samples were from about 1 to 18 percent and 6 percent, respectively. Total porosity of 74 clay samples ranged from about 34 to 57 percent and averaged 42 percent. Drainage porosity of fine sand, reported by Brady and Kunkel (date unknown), ranged from about 1 to 40 percent and averaged about 19 percent. The average drainage porosity of silt was about 14 percent and ranged from about 4 to 29 percent. The primary lithology of the sediments that compose the Upper Castle Hayne aquifer is fine silty and clayey sand. The mean of the average specific yield values reported for fine sand, silt, and clay by Morris and Johnson (1967) is about 20 percent. This value also closely corresponds to the average drainage porosity of fine sand (about 19 percent) reported by Brady and Kunkel (date unknown). Accordingly, an effective porosity of 20 percent was assigned to the computation of PCE mass in solution within the Upper Castle Hayne aquifer.

Computation of PCE Mass in the Unsaturated Zone in the Vicinity of ABC One-Hour Cleaners, 1987–1993

Shell computations similar to those described in the previous section were applied in conjunction with PCE concentration-depth data listed in Table E4 to estimate the PCE mass in the unsaturated zone at and in the vicinity of ABC One-Hour Cleaners from 1987 to 1993. Three data "shells" were created representing PCE concentrations at depths ranging from 1 to 4 ft, from 4 to 9 ft, and from 9 to 14 ft. The soil mass contained within each shell was computed as the product of the estimated volume of each shell and the unit weight of silty sand, estimated to be 170 lbs/ft^3 or about 77 kilograms per cubic foot. Subareas for the uppermost shell were computed based on PCE concentration contours plotted at intervals of 50,000 µg/kg. Subareas for the middle and bottom shells were computed using concentration contours plotted at intervals of 20,000 µg/kg. The computed area-weighted average PCE concentration within each shell was 156,900 µg/kg, 88,400 µg/kg, and 78,100 µg/kg, respectively. Total computed sediment volume of each shell was 29,640 ft^3, 52,860 ft^3, and 70,560 ft^3, respectively. Thus, total PCE mass occurring within the unsaturated zone in the vicinity of ABC One-Hour Cleaners was estimated to be about 2,500 lbs for the period of interest, or about 190 gal. This mass and the PCE mass computed previously in solution in groundwater represents a minimum loss of PCE to the subsurface of about 430 gal at ABC One-Hour Cleaners during the period 1953–1985. This volume represents a minimum total loss rate of PCE from ABC One-Hour Cleaners to the subsurface of about 13 gal per year, or about 230 grams per day. This contribution rate must necessarily be considered a minimum because (1) the quantity of PCE removed from the aquifers at Tarawa Terrace water-supply wells from 1953 to 1985 is unknown; (2) the mass of PCE degraded to TCE from 1953 to 1993 was probably large and was not accounted for by the foregoing computations of PCE mass; and (3) similarly, the mass of PCE sorbed onto the porous media from 1953 to 1993 also was probably substantial and was not accounted for by the computations of PCE mass described herein. Water-quality data applied to the computation of PCE mass refer only to PCE mass in solution in groundwater. Note that the PCE mass computations described for the Upper Castle Hayne aquifer and the unsaturated zone in the vicinity of ABC One-Hour Cleaners are necessarily highly interpretive and somewhat subjective because of poor data density and some uncertainty regarding analytical methods and results.

Occurrence of PCE and Related Constituents in Finished Water Delivered by the Tarawa Terrace Water Treatment Plant

Contaminated water delivered by supply wells to the Tarawa Terrace WTP was routinely processed at the WTP and delivered to residents of Tarawa Terrace and possibly to residents of the Camp Knox Trailer Park community located between Tarawa Terrace and Montford Point (Figure E1). Contaminants, mostly from water-supply well TT-26, were delivered to the WTP in unknown quantities prior to 1982, when the first indications of halogenated hydrocarbons in finished water at the WTP were noted at Tarawa Terrace (Grainger Laboratories, Camp Lejeune water document CLW 0592, written communication, August 10, 1982; Camp Lejeune water documents CLW 592–595; AH Environmental Consultants, Inc., written communication, June 18, 2004; Elizabeth A. Betz, written communication, August 19, 1982; Camp Lejeune water documents CLW 606–607). Well TT-26 continued to deliver water to the WTP subsequent to the first discovery of contaminants until February 1985, when the well was removed from service. Well TT-23 probably also delivered contaminated groundwater to the WTP during its short service period from about August 1984 to February 1985, and then periodically during March and April 1985 (Camp Lejeune water document CLW 1193, "Direction to Operators at Tarawa Terrace," April 30, 1985; Camp Lejeune water document CLW 1194, "Procedures for Operating the 'New Well' at Tarawa Terrace," date unknown). A summary of analyses for PCE, TCE, and 1,2-tDCE concentrations in finished water at the WTP is listed in Table E12. The range of PCE concentrations from 76 to 104 µg/L noted for samples collected on July 28, 1982, is probably the result of sample collection at different buildings (addresses) within the Tarawa Terrace housing areas. On March 11, 1985, a sample of finished water was collected from the WTP that contained a "nondetect" concentration of PCE. Water-supply well TT-23 was then operated for 24 hours. Immediately following the shutdown of well TT-23, a water sample was collected from the reservoir upstream of the treatment plant. This sample contained PCE at a concentration of 21.3 and 20 µg/L, respectively, based on analyses by the North Carolina Division of Human Resources, Division of Health Services, and JTC Environmental Consultants, Inc. The PCE concentration of the water downstream of the reservoir, after mixing, was 6.6 and 8.9 µg/L, respectively (Camp Lejeune water documents CLW 1182, March 14, 1985; 1183, March 19, 1985; 1482, April 25, 1986). These analyses represent the contribution of PCE to finished water at the WTP from just a single contaminated well pumping for 1 day. A PCE concentration of 215 µg/L was reported in water from storage tank STT-39A on February 11, 1985 (Table E12), and is the highest known concentration of PCE in WTP raw or finished water at Tarawa Terrace (JTC Environmental Consultants Report 85-080, Report 26, written

Table E12. Summary of selected analyses for tetrachloroethylene (PCE), trichloroethylene (TCE), and *trans*-1,2-dichloroethylene (1,2-tDCE) in water samples collected at the Tarawa Terrace water treatment plant and Tarawa Terrace addresses, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L micrograms per liter; TTWTP, Tarawa Terrace water treatment plant; bold text indicates that a note with additional information or qualification follows the analytical information; —, constituent not determined; ND, not detected]

Site name	Date	PCE concentration, in µg/L	TCE concentration, in µg/L	1,2-tDCE concentration, in µg/L
TTWTP Building TT-38	**5/27/1982**	[1]**80**	—	—
	Above sample from tap water at Building TT-2453			
	7/28/1982	[1]**104**		
	Above sample from tap water at Building TT-2453			
	7/28/1982	[1]76	—	—
	7/28/1982	[1]82	—	—
	2/5/1985	[1]**80**	[1]**8.1**	[1]**12**
	Above sample from tap water at Tarawa Terrace, address unknown			
	2/13/1985	[2]ND	[2]ND	[2]ND
	2/19/1985	[3]ND	[3]ND	[3]ND
	2/22/1985	[2]ND	[2]ND	[2]ND
	3/11/1985	[3]ND	[3]ND	[3]ND
	3/12/1985	[2]**6.6**	[2]**ND**	[2]**ND**
	3/12/1985	[3]**8.9**	[3]**ND**	[3]**ND**
	Above samples collected downstream of TTWTP reservoir after well TT-23 operated for 24 hours.			
	3/12/1985	[3]**20**	[3]**1.1**	[3]**1.2**
	3/12/1985	[2]**21.3**	[2]**ND**	[2]**ND**
	Above samples collected upstream of TTWTP reservoir after well TT-23 operated for 24 hours.			
	4/22/1985	[2]1	[2]4.1	[2]ND
	4/23/1985	[2]ND	[2]1.4	[2]ND
	4/29/1985	[2]3.7	[2]ND	—
	5/15/1985	[2]ND	[2]ND	[2]ND
	7/1/1985	[2]ND	[2]ND	[2]ND
	7/8/1985	[2]ND	[2]ND	[2]ND
	7/23/1985	[2]ND	[2]ND	[2]ND
	7/31/1985	[2]ND	[2]ND	[2]ND
	8/19/1985	[2]ND	[2]ND	[2]ND
	9/11/1985	[2]ND	[2]ND	[2]ND
	9/17/1985	[2]ND	[2]ND	[2]ND
	9/24/1985	[2]ND	[2]ND	[2]ND
	10/29/1985	[2]ND	[2]ND	[2]ND
TTWTP Tank STT-39	2/11/1985	[2]215	[2]8	[2]12

[1]Detection limit is unknown

[2]Detection limit = 10 µg/L

[3]Detection limit = 2 µg/L

communication, March 8, 1985). An analysis of finished water at the WTP obtained 2 days later on February 13, 1985, indicated that PCE concentrations were not detected. Such contrasts in PCE concentrations possibly were caused by the removal from service of contaminated wells but also may represent a range of PCE concentrations delivered in finished water by the WTP during much of its period of operation.

Concentrations of benzene and toluene ranging from 1 to 4 µg/L were reported infrequently in finished water from the Tarawa Terrace WTP during March, September, and December 1985 (Table E13) (Camp Lejeune water document CLW 1355, date unknown).

The WTP was officially closed on April 1, 1988 (Elizabeth A. Betz, written communication, April 11, 1989; Camp Lejeune water documents CLW 1818–1823).

Table E13. Summary of analyses for benzene and toluene in water samples collected at the Tarawa Terrace water treatment plant, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, micrograms per liter; TTWTP, Tarawa Terrace water treatment plant; ND, not detected; —, constituent not determined; detection limit for all analyses = 10 µg/L]

Site name	Date	Benzene concentration, in µg/L	Toluene concentration, in µg/L
TTWTP Building TT-38	2/13/1985	ND	ND
	2/22/1985	ND	ND
	3/11/1985	1.6	—
	4/22/1985	ND	ND
	4/23/1985	ND	ND
	5/15/1985	ND	ND
	7/1/1985	ND	ND
	7/8/1985	ND	ND
	7/23/1985	ND	ND
	7/31/1985	ND	ND
	8/19/1985	ND	ND
	9/11/1985	ND	4
	9/17/1985	ND	ND
	9/24/1985	ND	ND
	10/29/1985	ND	ND
	12/2/1985	2	—
	12/18/1985	1	—
TTWTP Tank STT-39A	2/11/1985	ND	ND

Discussion

Results and interpretations described in this report are substantially dependent on the accuracy of water-quality and site-location data. Substantial differences, if not outright contradictions, characterize many analyses of duplicate samples collected during various investigations of groundwater and supply well water quality. During Operable Unit 1, duplicate groundwater samples collected at hydrocone penetration sites were analyzed using a field mobile laboratory and by a CLP laboratory (Roy F. Weston, Inc. 1992). Results of these analyses are listed in Table E7. Duplicate samples are indicated by the sequential repetition of site names. The mobile laboratory result is listed first in a sequence followed by the CLP laboratory result. Probably the best example of analytical confusion occurs at site HC-20-34 where the CLP laboratory reported a PCE concentration of 30,000 µg/L, and the corresponding mobile laboratory result was 500 µg/L. Similar differences obtained to corresponding analyses of TCE at this site. Large differences in PCE concentration determined by the mobile and CLP laboratories also occurred at site HC-21-22, and, to a lesser degree, at several other sites sampled. Such differences in analytical results may have been the result of different or poorly applied analytical techniques but also could be caused by extremely large, in-situ concentration gradients in the subsurface, such that sequential samples of even small quantities of water would contain significantly different quantities of constituent. Substantial vertical concentration gradients are indicated at several sites (Table E7), including sites HC-20, HC-21, and HC-44. Concentrations of PCE at these locations changed by several orders of magnitude over depth intervals ranging from about 7 to 11 ft.

At water-supply well TT-23, duplicate samples collected on February 19, 1985 (Table E2) were analyzed by JTC Environmental Consultants, Inc., for the U.S. Navy and by the North Carolina Department of Human Resources Laboratory (Camp Lejeune water document CLW 1482, April 25, 1986). The reported concentration of PCE in the sample analyzed by JTC Environmental Consultants, Inc., was 26.2 µg/L. A PCE concentration in the sample analyzed by the North Carolina laboratory was “not detected.”

Analyses of water samples collected at water-supply well TT-26 (Table E2, Figure E15) indicate changes in PCE concentration of several orders of magnitude during relatively short intervals of time. The first available analysis of PCE at well TT-26 was obtained from a sample collected on January 16, 1985. The well probably was operating in a routine manner at this time and was still supplying water to the Tarawa Terrace WTP. The reported PCE concentration was 1,580 µg/L (Shiver 1985). The PCE concentration reported for a sample obtained on February 12, 1985, at well TT-26 had decreased to an estimated 3.8 µg/L, a change of about 2.5 orders of magnitude in only 27 days (JTC Environmental Consultants Report 85-052, Report 29, written communication, February 14, 1985). Seven days later, on February 19, 1985, the reported PCE concentration had increased

to about 60 µg/L (Camp Lejeune water document CLW 1482, April 25, 1986). Although well TT-26 was removed from service some time during February 1985, such radical changes in PCE concentration during this month are difficult to explain, other than as a result of poor sampling technique or analytical error. PCE concentrations reported in samples collected at well TT-26 during April, June, and September 1985 ranged from 630 to 1,160 µg/L and were apparently all determined from analyses at the North Carolina Department of Human Resources Laboratory, as was the sample collected on January 16, 1985. For this study, these analyses are considered the most accurate and representative of PCE concentrations at well TT-26 during 1985.

The accuracy of various analytical methods and technologies used by different laboratories at this time may have contributed significantly to conflicting analytical results. Most, if not all, water-quality analyses cited herein were accomplished using GC/MS methodologies. The accuracy of such methods in the 1980s was about ±20 percent (AH Environmental Consultants, Inc., written communication, June 18, 2004), which possibly explains a number of the conflicting results indicated in Tables E2 and E7. Detection or quantitation limits are noted on appropriate tables.

Sampling methods and techniques also affect water-quality results. Little or no information is available regarding sampling methods utilized at Tarawa Terrace and other Camp Lejeune water-supply wells from 1982 to 1985; however, sampling methods used at water-supply wells and monitor wells during ABC One-Hour Cleaners Operable Units 1 and 2 are described in detail by Roy F. Weston, Inc. (1992, 1994). These methods included purging water-supply wells of several casing volumes before sampling to assure that only aquifer water was sampled. Similar methods were applied to monitor wells. All purge waters were containerized onsite using 500-gal tanks and were subjected to regulated disposal. As such, purge volumes at water-supply wells were possibly limited to about 500 gal. Depending on well construction, 500 gal represents one to about three casing volumes at Tarawa Terrace water-supply wells. Although such methods are generally appropriate, sampling of discharge water from water-supply well TT-23 beginning March 11, 1985, indicates substantial additional pumping at Tarawa Terrace water-supply wells may have been necessary to obtain a truly representative sample of aquifer water (Table E2). Well TT-23 was initially pumped for about 2 hours. Capacity of this well at the time was about 250 gallons per minute. Water samples collected after 2 hours of pumping contained PCE concentrations of about 15 µg/L. The well continued pumping for another 22 hours. Water samples collected after this interval contained PCE concentrations of about 40 µg/L (Camp Lejeune water document CLW 1482, April 25, 1986). Such comparisons indicate that just purging several casing volumes at Tarawa Terrace water-supply wells prior to sampling for PCE and related constituents may not have provided samples representative of the total aquifer volume affected during routine operation of the wells.

Location coordinates of various water-supply and monitor wells listed in this report, as well as soil boring and hydrocone penetration sites, are almost entirely based on maps of various and possibly dubious scales and detail. Locations of Tarawa Terrace water-supply wells probably are highly accurate and are based, for the most part, on large-scale (small area) site maps of individual wells developed prior to well and well-house construction (written communication—NAVFAC drawings 4049523, 1244002, 4001327, and 1244061; Y & D drawing 765472; P.W. drawing 13060, various dates) and Camp Lejeune Quarters Maps (Tarawa Terrace II Quarters Map, June 30, 1961; Tarawa Terrace I Quarters Map, July 31, 1984). Accordingly, location coordinates of Tarawa Terrace water-supply wells listed in Table E3 are considered accurate to within a radius of about 50 ft.

Many reports that describe the investigation and removal of USTs within the Tarawa Terrace housing areas also contained detailed maps showing monitor well and soil boring locations as well as a single latitude and longitude site locator. For this study, the latitude and longitude location was considered the location of the number one (#1) monitor well, or the tank center, and all other site locations were georeferenced to that point using the various site plans and maps provided in the report. Monitor well locations at these sites are considered accurate to within a radius of 100 ft (Table E10). Location coordinates at monitor wells installed during ABC One-Hour Cleaners Operable Unit 1 (Table E6) were based on the mapped location of well sites (Figure E3), as well as coordinates of a local grid established during the operable unit (Roy F. Weston, Inc. 1992). Unfortunately, the origin of the local grid was not referenced to any typical map coordinate system, such as State Plane coordinates. In addition, comparison of mapped well locations to the local coordinates indicated that the north and east local coordinates may have been reversed at several sites. Not even local coordinates were provided for the several monitor wells constructed during ABC One-Hour Cleaners Operable Unit 2. Location coordinates at these sites were based only on georeferencing the mapped location to an obvious cultural feature, such as intersecting roads, that was easily recognized on USGS 1:24,000-scale maps. Operable Unit 1 site local coordinates also were cross-referenced with their mapped locations in a similar manner. Accordingly, the accuracy of location coordinates of monitor wells installed during Operable Units 1 and 2 varies by location and proximity to cultural features as well as the accuracy of the original well-location maps, which is unknown. Locations of wells constructed during Operable Unit 1 with assigned local coordinates and in the immediate vicinity of ABC One-Hour Cleaners and Tarawa Terrace supply wells are considered accurate to within a radius of about 50 ft. Other wells constructed during Operable Unit 1 and all wells and piezometers constructed during Operable Unit 2 are located within unknown accuracy limits but probably within distances ranging from several dozen to several hundred feet. The location coordinates of hydrocone penetration sites (Table E8) were determined by georeferencing

mapped locations using cultural features and topographic maps as previously described. The accuracy of these locations also is dependent on the accuracy and scale of the published well-location map as well as proximity to recognized cultural features and probably also varies within a range of several dozen to several hundred feet.

The several maps of soil boring locations in the vicinity of ABC One-Hour Cleaners are similar to Figure E2, are large scale, and refer to a small area, compared to monitor well-location maps (Figures E1, E3, and E6). Borings completed during Operable Unit 1 were assigned local coordinates and are probably located accurately to within a radius of about 25 ft. Locations of borings completed by Law Engineering and Testing Company, Inc. (1986a,b) and during ABC One-Hour Cleaners Operable Unit 2 (Roy F. Weston, Inc. 1994) were georeferenced using published boring-location maps and probably also are accurate to within a radius of about 25 ft. The locations of monitor wells installed during the investigations of petroleum product releases to the subsurface at storage tanks STT61–66 were georeferenced using the published well-location map and the estimated State Plane coordinates of the southeast corner of Building TT-47, which was included on the well-location map and also could be located on a 1:24,000-scale topographic map. Locations are considered accurate to within a radius of about 50 ft. Locations of monitor wells installed during remedial investigations at and in the vicinity of the Tarawa Terrace Shopping Center were determined using published maps and easily identified cultural features as described previously and also are considered accurate to within a radius of about 50 ft (Table E10).

Summary and Findings

Tetrachloroethylene (PCE) contaminants detected during 1985 at water-supply wells at Tarawa Terrace originated at ABC One-Hour Cleaners, located on State Route 24 within 1,600 ft or less of water-supply wells TT-23, TT-25, and TT-26. Investigations of groundwater contamination during 1985 at Tarawa Terrace water-supply wells resulted in wells TT-23 and TT-26 being removed from production and, subsequently, to the cessation of groundwater pumping at all Tarawa Terrace water-supply wells during March or April 1987. Remedial investigations of PCE contamination in groundwater at Tarawa Terrace and between Tarawa Terrace and ABC One-Hour Cleaners from 1991 to 1993 provided sufficient data to map the distribution of PCE within the Upper Castle Hayne aquifer. By 1991, the center of mass of PCE possibly had migrated along hydraulic gradients away from ABC One-Hour Cleaners a distance of about 800 ft to the southeast. This distance represents an average velocity along migration pathways of about 0.3 foot per day. In addition, several lobes of the PCE plume during 1991 extended to the south and southeast, generally orthogonal to the hydraulic gradient. These lobes are possibly the result of pumping at Tarawa Terrace water-supply wells within the Tarawa Terrace housing area.

Water-supply wells TT-25 and TT-26 are located along advective pathways from ABC One-Hour Cleaners. Concentrations of PCE at well TT-26 declined from about 1,100 to 350 micrograms per liter (µg/L) between September 1985 and July 1991. Concentrations of TCE at well TT-26 increased from 27 to 56 µg/L during the same period. Corresponding concentrations of PCE and TCE at well TT-25 increased from not detected to 23 µg/L and 5.8 µg/L, respectively. The changes in PCE and TCE concentration at well TT-26 between September 1985 and July 1991 are considered largely the result of microbial degradation combined with migration of PCE and TCE toward the well along hydraulic gradients. The observed changes in PCE concentration at well TT-26 during a known time interval when applied to a first-order relation of exponential decay indicates a degradation rate for PCE at Tarawa Terrace of about 0.0005 per day. The increases in PCE and TCE concentration at well TT-25 between September 1985 and July 1991 also probably result from the combined effects of advective migration of contaminant mass toward the well and microbial degradation.

At water-supply well TT-23, PCE concentrations decreased from 4 µg/L during September 1985 to below detection limits by July 1991. This reduction is somewhat anomalous given the concentration of PCE at this site during January 1985 (132 µg/L) and the continued pumping at downgradient water-supply well TT-54 until March or April 1987. Such pumping probably facilitated the continued migration of PCE mass toward well TT-23, following the removal of the well from routine service during February 1985. The reported concentrations of TCE at well TT-23 during September 1985 and July 1991 were below detection limits. These low and negligible PCE and TCE concentrations at well TT-23, if representative of actual conditions, can be at least partly explained by an accelerated rate of microbial degradation, possibly facilitated by the mixture of benzene, toluene, ethylene, and xylene compounds and PCE within water-bearing units of the Upper Castle Hayne aquifer.

Concentrations of PCE at monitor wells, hydrocone sample locations, and at Tarawa Terrace water-supply wells from 1991 to 1993 were sufficient to estimate the mass of PCE remaining in the Upper Castle Hayne aquifer. A mass of about 1.5×10^6 grams was computed, which equates to about 3,400 pounds, or 1.6 tons, of PCE. Similar methods were applied to compute the mass of PCE in the unsaturated zone at and in the vicinity of ABC One-Hour Cleaners using concentration-depth data determined from soil borings. The mass of PCE in the unsaturated zone was estimated to be more than 2,500 pounds. The total mass of PCE computed in groundwater and within the unsaturated zone thus equals about 6,000 pounds and equates to a volume of about 430 gallons. This volume represents an average minimum loss rate of PCE to the subsurface at ABC One-Hour Cleaners of about 13 gallons per year from 1953 to 1985.

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References

Agency for Toxic Substances and Disease Registry. Preliminary Public Health Assessment for ABC One-Hour Cleaners, Jacksonville, Onslow County, North Carolina. Atlanta, GA: U.S. Department of Health and Human Services; 1990. Report No.: NCD024644494.

Agency for Toxic Substances and Disease Registry. Public Health Assessment for U.S. Marine Corps Base at Camp Lejeune, Military Reservation, Camp Lejeune, Onslow County, North Carolina. Atlanta, GA: U.S. Department of Health and Human Services; 1997. Report No.: NC6170022580.

Aronson D, and Howard PH. Anaerobic Biodegradation of Organic Chemicals in Ground Water: A Summary of Field and Laboratory Studies. North Syracuse: Environmental Science Center, Syracuse Research Corporation; 1997.

Brady MM, and Kunkel LA. A Practical Technique for Quantifying Drainage Porosity: PTS Laboratories; date unknown.

Cardinell AP, Berg SA, and Lloyd OB Jr. Hydrogeologic Framework of U.S. Marine Corps Base at Camp Lejeune, North Carolina. U.S. Geological Survey Water-Resources Investigations Report 93-4049; 1993.

Catlin Engineers and Scientists. Leaking Underground Storage Tank (LUST) Phase I, Limited Site Assessment Report for TT-44, Marine Corps Base Camp Lejeune, North Carolina. Raleigh, North Carolina: Catlin Engineers and Scientists; 2002a. Contract No.: N62470-95-D-6009.

Catlin Engineers and Scientists. Leaking Underground Storage Tank (LUST) Phase I, Limited Site Assessment Report for TT-2634, Marine Corps Base Camp Lejeune, North Carolina. Raleigh, North Carolina: Catlin Engineers and Scientists; 2002b. Contract No.: N62470-95-D-6009.

CLW, Camp Lejeune Water documents, 0001-8761 (not consecutively available), provided on DVD 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, Georgia: Agency for Toxic Substances and Disease Registry; 2007.

DiGiano FA, Miller CT, Roche AC, and Wallingford ED. Methodology for Assessment of Contamination of the Unsaturated Zone by Leaking Underground Storage Tanks: Water Resources Research Institute of the University of North Carolina; 1988.

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 B: Geohydrologic Framework of the Castle Hayne Aquifer System. Atlanta, Georgia: Agency for Toxic Substances and Disease Registry; 2007a.

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; 2007b.

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.

Haliburton NUS Environmental Corporation. Draft Site Inspection Report, Site 07: Tarawa Terrace Dumps; 1992. Contract No.: N62470-90-B-7629.

Harned DA, Lloyd OB Jr, and Treece MW Jr. Assessment of Hydrologic and Hydrogeologic Data at Camp Lejeune Marine Corps Base, North Carolina. U.S. Geological Survey Water-Resources Investigations Report 89-4096; 1989.

Industrial Marine Services, Inc. Delineation and Proposed Recovery of a Subsurface Fuel Plume, Camp Lejeune. Norfolk, Virginia: Industrial Marine Services, Inc.; 1985.

Law Engineering and Environmental Services, Inc. Corrective Action Plan for the Recovery of Free Product and the Restoration of Petroleum Contaminated Soil and Groundwater, Building TT-2477/2478, Marine Corps Base, Camp Lejeune, Onslow County, North Carolina; 1996. Contract No.: 7176.

Law Engineering and Environmental Services, Inc. Leaking Underground Storage Tank Limited Site Assessment Addendum, UST TT-48-2, Tarawa Terrace II Elementary School, Marine Corps Base Camp Lejeune, North Carolina; 1998. Contract No.: 30740-6-06009.

Law Engineering, Inc. Leaking Underground Storage Tank Site Assessment Report, Building TT-2478, Marine Corps Base, Camp Lejeune, North Carolina, vol. I & II; 1994a, b.

Law Engineering, Inc. Leaking Underground Storage Tank Site Assessment Report, Building TT-2477, Marine Corps Base, Camp Lejeune, North Carolina, vol. I & II; 1995a, b.

Law Engineering and Testing Company, Inc. On-Site Sampling—Septic Tank and Outlying Area, ABC One-Hour Cleaners, Jacksonville, North Carolina, LETCO Job No. J-473-86-1623, 1986a.

Law Engineering and Testing Company, Inc. On-Site Sampling ABC One-Hour Cleaners, Jacksonville, North Carolina; 1986b.

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.

Lucius JE, Olhoeft GR, Hill PL, and Duke SK. Properties and Hazards of 108 Selected Substances: U.S. Geological Survey Open-File Report 90-408; 1990.

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, Georgia: Agency for Toxic Substances and Disease Registry; 2007.

McMorris CA. Site Inspection Report—ABC One-Hour Cleaners, NC DO24644494, 2127 Lejeune Boulevard, Jacksonville, NC, 28340: North Carolina Solid and Hazardous Waste Branch, Environmental Health Section; 1987.

Mid-Atlantic Associates, Inc. Leaking Underground Storage Tank, Phase I Limited Site Assessment, UST TT-2302/2304, Tarawa Terrace II Housing Area, Marine Corps Base Camp Lejeune, North Carolina: Mid-Atlantic Associates, Inc.; 2003a. Contract No.: N62470-90-R-7626.

Mid-Atlantic Associates, Inc. Leaking Underground Storage Tank, Phase I Limited Site Assessment, UST TT-3546/3548 Site, Tarawa Terrace II Housing Area, Marine Corps Base Camp Lejeune, North Carolina: Mid-Atlantic Associates P.A.; 2003b. Contract No.: N62740-95-D-6009.

Mid-Atlantic Associates P.A. Leaking Underground Storage Tank (LUST), Phase I Limited Site Assessment Report for UST TT-779 Site, Tarawa Terrace I Housing Area, Marine Corps Base Camp Lejeune, North Carolina: Mid-Atlantic Associates P.A.; 2002a. Contract No.: N62470-01-D-3009.

Mid-Atlantic Associates P.A. Leaking Underground Storage Tank (LUST), Phase I Limited Site Assessment Report for UST TT-2254/2256 Site, Tarawa Terrace II Housing Area, Marine Corps Base Camp Lejeune, North Carolina: Mid-Atlantic Associates P.A.; 2002b. Contract No.: N62470-01-D-3009.

Mid-Atlantic Associates P.A. Leaking Underground Storage Tank (LUST), Phase I Limited Site Assessment Report for UST TT-2258/2260 Site, Tarawa Terrace II Housing Area, Marine Corps Base Camp Lejeune, North Carolina: Mid-Atlantic Associates P.A.; 2002c. Contract No.: N62470-01-D-3009.

Mid-Atlantic Associates P.A. Leaking Underground Storage Tank (LUST), Phase I Limited Site Assessment Report for UST TT-3140/3142 Site, Tarawa Terrace II Housing Area, Marine Corps Base Camp Lejeune, North Carolina: Mid-Atlantic Associates P.A.; 2002d. Contract No.: N62470-01-D-3009.

Mid-Atlantic Associates P.A. Leaking Underground Storage Tank, Phase I Limited Site Assessment, UST TT-3165/3167, Marine Corps Base Camp Lejeune, North Carolina: Mid-Atlantic Associates, Inc.; 2002e. Contract No.: N62470-01-D-3009.

Mid-Atlantic Associates P.A. Leaking Underground Storage Tank, Phase I Limited Site Assessment, UST TT-3233/3235, Marine Corps Base Camp Lejeune, North Carolina: Mid-Atlantic Associates, Inc.; 2002f. Contract No.: N62470-01-D-3009.

Mid-Atlantic Associates P.A. Leaking Underground Storage Tank (LUST), Phase I Limited Site Assessment Report for UST TT-3524/3526 Site, Tarawa Terrace II Housing Area, Marine Corps Base Camp Lejeune, North Carolina: Mid-Atlantic Associates P.A.; 2002g. Contract No.: N62470-01-D-3009.

Morris DA, and Johnson AI. Summary of Hydrologic and Physical Properties of Rock and Soil Materials, as Analyzed by the Hydrologic Laboratory of the U.S. Geological Survey, 1948–60: U.S. Geological Survey Water-Supply Paper 1839-D; 1967.

O'Brien & Gere Engineers, Inc. Site Assessment, Tanks STT61–STT66, Tarawa Terrace, Marine Corps Base, Camp Lejeune, North Carolina; 1992.

O'Brien & Gere Engineers, Inc. Addendum Site Assessment, Tanks STT61–STT66, Tarawa Terrace, Marine Corps Base Camp Lejeune; 1993.

OHM Remediation Services Corp. Final Additional Investigation Report, Buildings TT-2477/78, Marine Corps Base Camp Lejeune, North Carolina: OHM Remediation Services Corp.; 2001. Contract No.: N62470-97-D-9000.

Pankow JF, and Cherry JA. Dense Chlorinated Solvents and Other DNAPLs in Groundwater: History, Behavior, and Remediation; Waterloo Press; 1996.

Richard Catlin & Associates, Inc. Leaking Underground Storage Tank Comprehensive Site Assessment, Building TT-2455, Marine Corps Air Station New River, Jacksonville, North Carolina, Volume I: Richard Catlin & Associates, Inc.; 1994a. Contract No.: N62470-93-D-4020.

Richard Catlin & Associates, Inc. Leaking Underground Storage Tank Comprehensive Site Assessment, Building TT-2455, Marine Corps Air Station New River, Jacksonville, North Carolina, Volume II: Richard Catlin & Associates, Inc.; 1994b. Contract No.: N62470-93-D-4020.

Richard Catlin & Associates, Inc. Leaking Underground Storage Tank Comprehensive Site Assessment, Buildings TT-2465, TT-2465, TT-2467 and TT-2471, Marine Corps Base, Camp Lejeune, North Carolina, Volume I: Richard Catlin & Associates, Inc.; 1995a. Contract No.: N62470-93-D-4020.

Richard Catlin & Associates, Inc. Leaking Underground Storage Tank Comprehensive Site Assessment, Buildings TT-2463, TT-2465, TT-2467 and TT-2471, Marine Corps Base Camp Lejeune, North Carolina. Volume II: Richard Catlin & Associates, Inc.; 1995b. Contract No.: N62470-93-D-4020.

Richard Catlin & Associates, Inc. Leaking Underground Storage Tanks Corrective Action Plan, UST TT-2463-2473, Marine Corps Base, Camp Lejeune, North Carolina: Richard Catlin & Associates, Inc.; 1996. Contract No.: N62470-93-D-4020.

Richard Catlin & Associates, Inc. Leaking Underground Storage Tanks Corrective Action Plan Building TT-2455, Marine Corps Base Camp Lejeune, North Carolina: Richard Catlin & Associates, Inc.; 1998. Contract No.: N62470-93-D-4020.

Roy F. Weston, Inc. Remedial Investigation Report, ABC One-Hour Cleaners, Jacksonville, North Carolina: Roy F. Weston, Inc.; 1992.

Roy F. Weston, Inc. Remedial Investigation Report, ABC One-Hour Cleaners, Operable Unit 2, Jacksonville, North Carolina: Roy F. Weston, Inc.; 1994.

Shiver R. A Groundwater Investigation to Define the Source(s) of Tetrachloroethylene that Have Contaminated Three Community Water Supply Wells at Tarawa Terrace I, Camp Lejeune Marine Corps Base, Onslow County: North Carolina Department of Natural Resources and Community Development; 1985.

Wiedemeier TH, Swanson MA, Moutoux DE, Gordon EK, Wilson JT, Wilson BH, et al. Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Ground Water. Cincinnati: National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency; 1998. Report No.: EPA/600/R-98/128.

Zheng C, and Wang PP. MT3DMS, A Modular Three-Dimensional Multispecies Transport Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems: Department of Geology and Mathematics, University of Alabama; 1998.

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