Prepared in cooperation with the Naval Facilities Engineering Command Southeast

Groundwater Hydrology and Chemistry in and near an Emulsified Vegetable-Oil Injection Zone, Solid Waste Management Unit 17, Naval Weapons Station Charleston, North Charleston, South Carolina, 2004–2009

Scientific Investigations Report 2009–5239

U.S. Department of the Interior
U.S. Geological Survey

Cover. **Solid Waste Management Unit 17, Naval Weapons Station Charleston, North Charleston, South Carolina, looking northeastward along the utility easement. Well 17MW-07S is on the left** *(photograph by Don A. Vroblesky, November 27, 2009)*.

Groundwater Hydrology and Chemistry in and near an Emulsified Vegetable-Oil Injection Zone, Solid Waste Management Unit 17, Naval Weapons Station Charleston, North Charleston, South Carolina, 2004–2009

By Don A. Vroblesky, Matthew D. Petkewich, Mark A. Lowery, Kevin J. Conlon, and Clifton C. Casey

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KEN SALAZAR, Secretary

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot per foot (ft/ft)	0.3048	meter per meter (m/m)
mile (mi)	1.609	kilometer (km)
	Volume	
gallon (gal)	3.785	liter (L)
	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)
	Mass	
pound, avoirdupois (oz)	0.4536	kilogram (kg)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Volume	
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound, avoirdupois (lb)
	Flow rate	
meter per day (m/d)	3.281	foot per day (ft/d)
meter per year (m/yr)	3.281	foot per year ft/yr)
	Hydraulic conductivity	
meter per day (m/d)	3.281	foot per day (ft/d)
	Hydraulic gradient	
meter per kilometer (m/km)	5.27983	foot per mile (ft/mi)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

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.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Abbreviations and acronyms used in this report

1CV	sampled from the screened interval after purging one casing volume of water (2.2 gallons) from the top of the water column
3CV	sampled from the screened interval after purging three casing volumes of water (6.6 gallons) from the top of the water column
16SrRNA	16S ribosomal RNA
1,1-DCE	1,1-dichloroethene
BLS	below land surface
BT	biotrap obtained from Microseeps, Inc.
BVC	vinyl chloride reductase associated with *Dehalococcoides* sp. strain BAV1
c/b	cells per bead
c/g	cells per gram
c/mL	cells per milliliter
*c*DCE	*cis*-1,2-dichloroethene
DNA	deoxyribonucleic acid
DSR	sulfate-reducing bacteria
ESTCP	Environmental Security Technology Certification Program
Fe^{2+}	dissolved ferrous iron
gc/b	gene copies per bead
gc/g	gene copies per gram
gc/mL	gene copies per milliliter
J or (J)	estimated value
LF	sampled by low-flow methodology
LF.5CV	sampled after purging one-half casing volume (1.1 gallons) of water from the screened interval
LF1CV	sampled after purging one casing volume (2.2 gallons) of water from the screened interval
LF2CV	sampled after purging two casing volumes (4.4 gallons) of water from the screened interval
LF3CV	sampled after purging three casing volumes (6.6 gallons) of water from the screened interval
MgO	magnesium oxide
mL	milliliter
mL/min	milliliters per minute
mRNA	messenger RNA
NAVFACSE	Naval Facilities Engineering Command Southeast
ND	not detected
NWS	Naval Weapons Station
PDB	passive diffusion bag
PCE	tetrachloroethene
qDHB	DNA or 16SrRNA associated with *Dehalobacter* sp.
qDHC	DNA or 16SrRNA associated with *Dehalococcoides* sp.
qDSM	DNA or 16SrRNA associated with *Desulfuromonas* sp.
qEBAC	DNA or 16SrRNA associated with Eubacteria
qMGN	DNA or 16SrRNA associated with methanogenic bacteria
qMOB	DNA or 16SrRNA associated with methanotrophic bacteria
qMOB1	DNA or 16SrRNA associated with type 1 methanotrophic bacteria
qMOB2	DNA or 16SrRNA associated with type 2 methanotrophic bacteria
RNA	ribonucleic acid
Sed	sediment obtained from the well sump by pumping
sMMO	methane monooxygenase

SP1	sampled after a slow purge with substantial drawdown
SWMU	Solid Waste Management Unit
sp.	species
TCE	trichloroethene
TCE R-Dase	trichloroethene reductase
TEAP	terminal electron-accepting process
TOC	total organic carbon
USGS	U.S. Geological Survey
VC	vinyl chloride
VC R-Dase	vinyl chloride reductase
VOC	volatile organic compound

Groundwater Hydrology and Chemistry in and near an Emulsified Vegetable-Oil Injection Zone, Solid Waste Management Unit 17, Naval Weapons Station Charleston, North Charleston, South Carolina, 2004–2009

By Don A. Vroblesky,[1] Matthew D. Petkewich,[1] Mark A. Lowery,[1] Kevin J. Conlon,[1] and Clifton C. Casey[2]

Abstract

The U.S. Geological Survey and the Naval Facilities Engineering Command Southeast investigated the hydrology and groundwater chemistry in the vicinity of an emulsified vegetable-oil injection zone at Solid Waste Management Unit (SWMU) 17, Naval Weapons Station Charleston, North Charleston, South Carolina. In May 2004, Solutions-IES initiated a Phase-I pilot-scale treatability study at SWMU17 involving the injection of an edible oil emulsion into the aquifer near wells 17PS-01, 17PS-02, and 17PS-03 to treat chlorinated solvents. The Phase-I injection of emulsified vegetable oil resulted in dechlorination of trichloroethene (TCE) to *cis*-1,2-dichloroethene (*c*DCE), but the dechlorination activity appeared to stall at *c*DCE, with little further dechlorination of *c*DCE to vinyl chloride (VC) or to ethene. The purpose of the present investigation was to examine the groundwater hydrology and chemistry in and near the injection zone to gain a better understanding of the apparent remediation stall. It is unlikely that the remediation stall was due to the lack of an appropriate microbial community because groundwater samples showed the presence of *Dehalococcoides* species (sp.) and suitable enyzmes. The probable causes of the stall were heterogeneous distribution of the injectate and development of low-pH conditions in the injection area. Because groundwater pH values in the injection area were below the range considered optimum for dechlorination activity, a series of tests was done to examine the effect on dechlorination of increasing the pH within well 17PS-02. During and following the in-well pH-adjustment tests, VC concentrations gradually increased in some wells in the injection zone that were not part of the in-well pH-adjustment tests. These data possibly reflect a gradual microbial acclimation to the low-pH conditions produced by the injection. In contrast, a distinct increase in VC concentration was observed in well 17PS-02 following the in-well pH increase. Adjustment of the pH to near-neutral values in well 17PS-02 may have made that well relatively favorable to VC production compared with much of the rest of the injection zone, possibly accounting for acceleration of VC production at that well. Following a Phase-II injection in which Solutions-IES, Inc., injected pH-buffered emulsified vegetable oil with an improved-efficiency injection approach, 1,1-dichloroethene, TCE, and *c*DCE rapidly decreased in concentration and are now (2009) undetectable in the injection zone, with the exception of a low concentration (43 micrograms per liter, August 2009) of *c*DCE in well 17PS-01. In August 2009, VC was still present in groundwater at the test wells in concentrations ranging from 150 to 640 micrograms per liter. The Phase-II injection, however, appears to have locally decreased aquifer permeability, possibly resulting in movement of contamination around, rather than through, the treatment area.

Introduction

Groundwater contamination by volatile organic compounds (VOCs) is present at Solid Waste Management Unit (SWMU) 17 at the Naval Weapons Station (NWS) Charleston, North Charleston, South Carolina (fig. 1) and across a street from SWMU16, a former landfill (fig. 2). Although SWMU17 was used primarily for surface disposal of solid waste between 1950 and 1978 and disposal of engine oil between 1965 and 1966 (TetraTech NUS, Inc., 2006), the primary VOCs of concern in groundwater at the site are chlorinated solvents. A tree-coring investigation in 2002 by the U.S. Geological Survey (USGS) provided a reconnaissance-level initial delineation of the contaminant plumes (Vroblesky and Casey, 2008). A study by Tetra Tech NUS, Inc. (2004), involving installation and sampling of temporary wells, confirmed the tree-core delineations and further defined the contaminant distribution and described the general hydrogeology. The studies found that groundwater contamination at SWMU17 was present in two areas: a southern plume consisting primarily of trichloroethene (TCE) (fig. 3*A*) and *cis*-1,2-dichloroethene (*c*DCE) that appeared to emanate from

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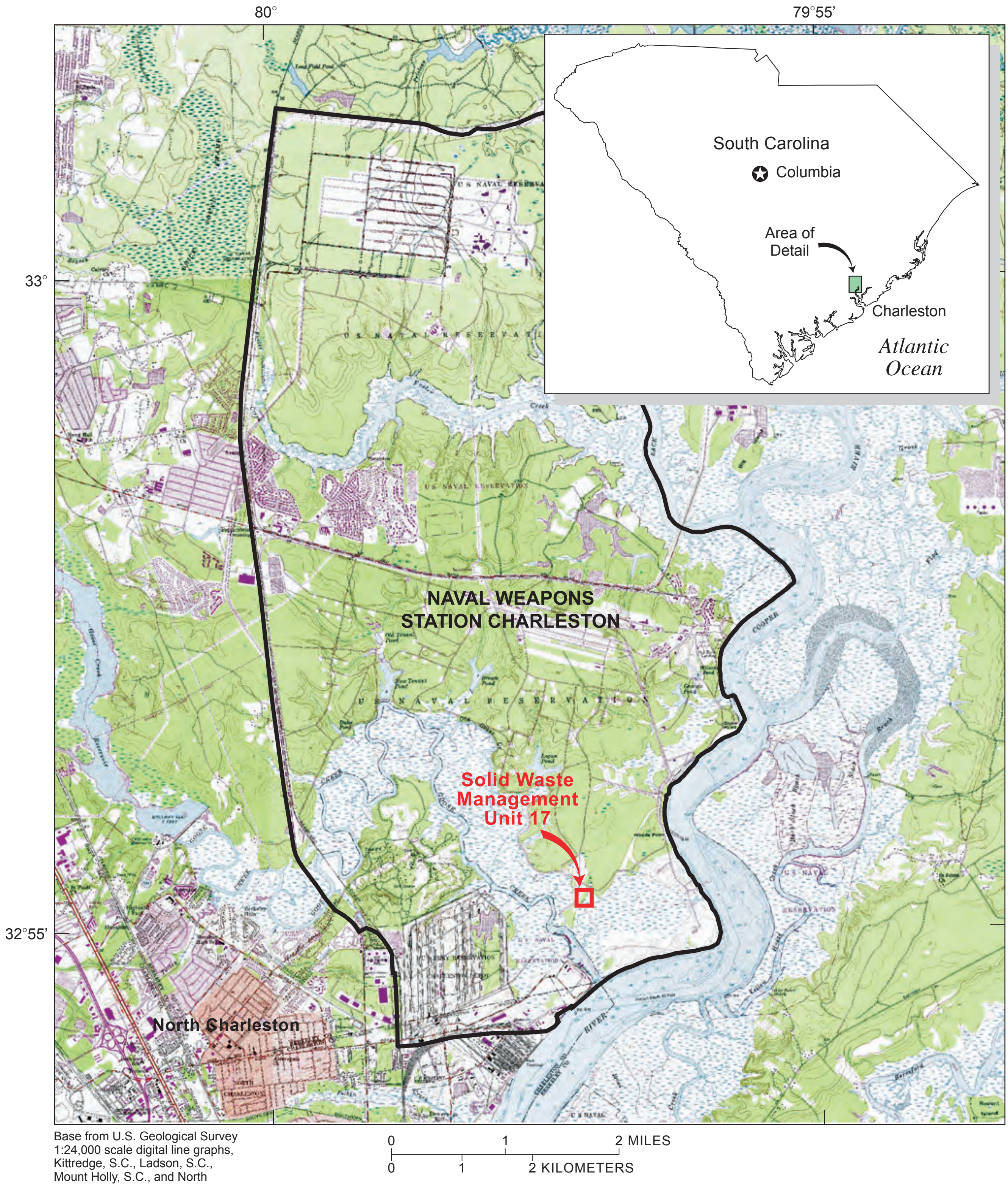
[1] U.S. Geological Survey, South Carolina Water Science Center

[2] Formerly with the Naval Facilities Engineering Command Southeast



Base from U.S. Geological Survey
1:24,000 scale digital line graphs,
Kittredge, S.C., Ladson, S.C.,
Mount Holly, S.C., and North
Charleston, S.C., 1979

Figure 1. Location of Solid Waste Management Unit 17, Naval Weapons Station Charleston, North Charleston, South Carolina.

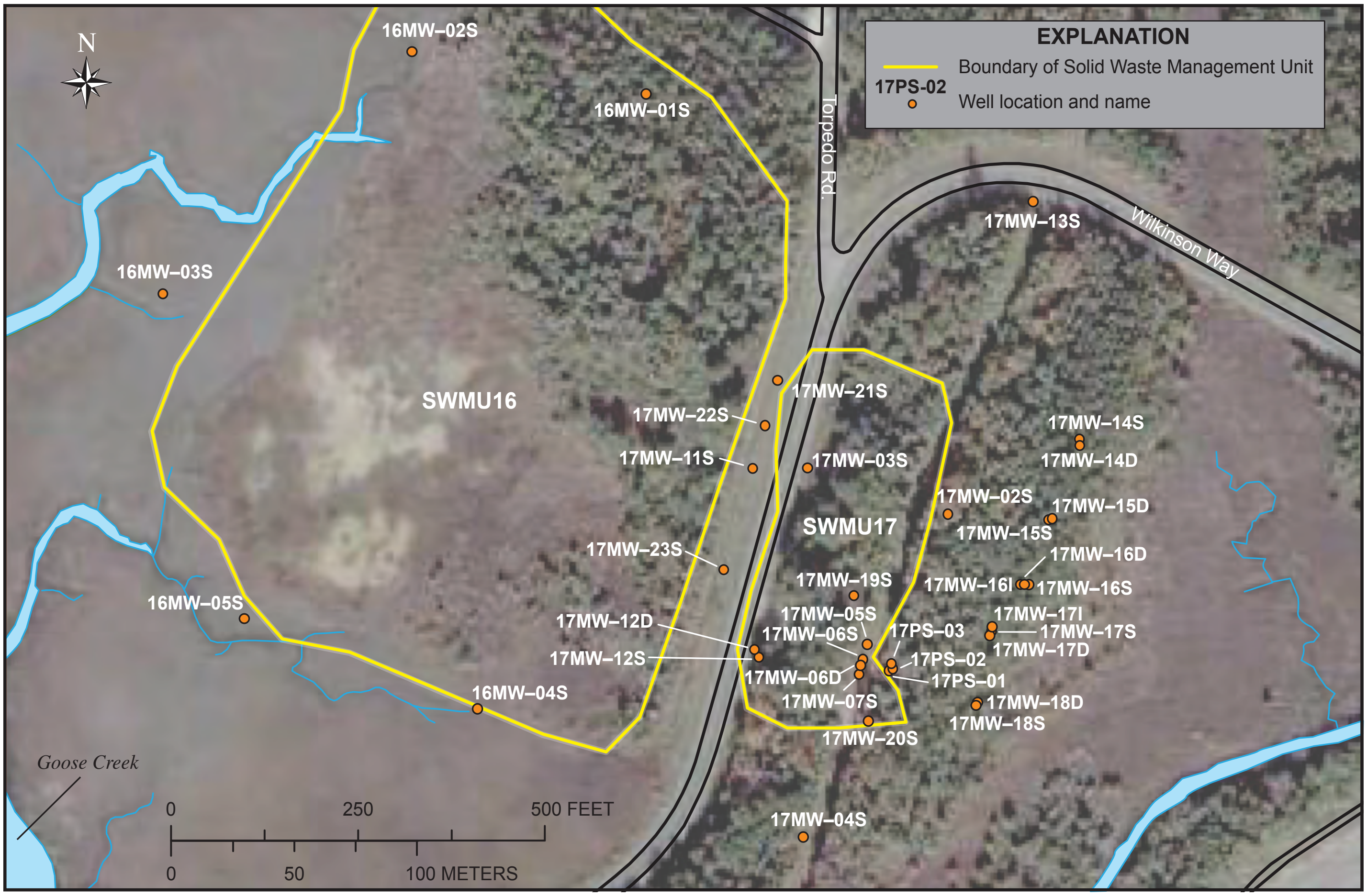


Figure 2. Locations of monitoring wells at Solid Waste Management Unit (SWMU) 16 and SWMU17, Naval Weapons Station Charleston, North Charleston, South Carolina.

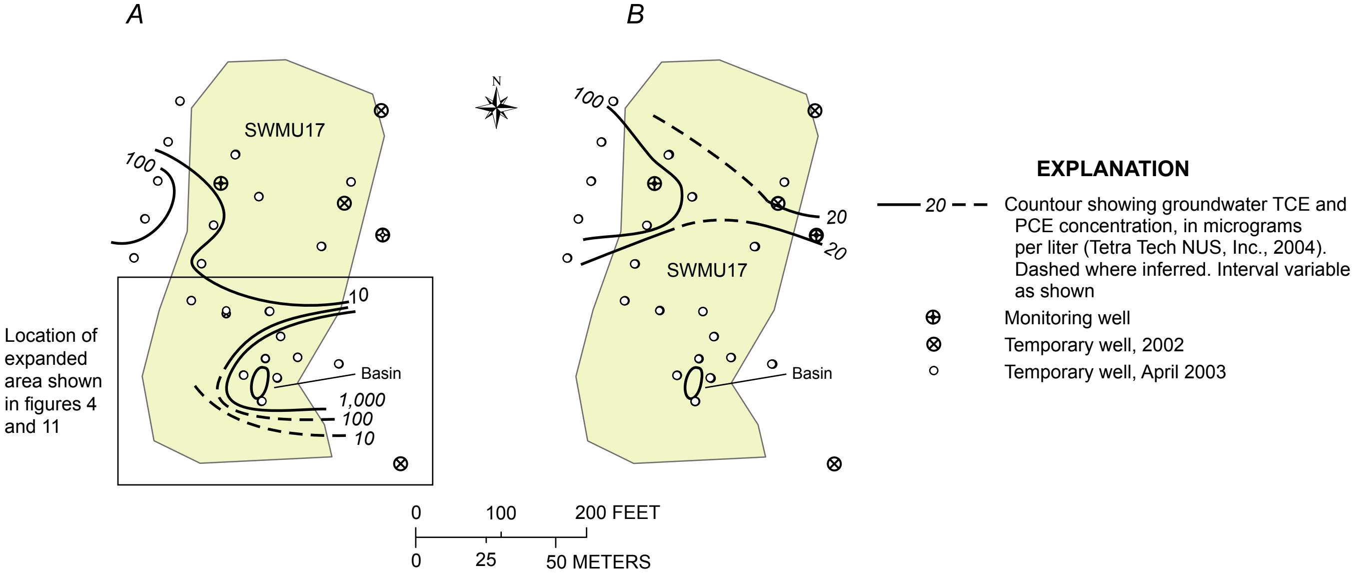


Figure 3. (*A*) Trichloroethene (TCE) and (*B*) tetrachloroethene (PCE) in groundwater at Solid Waste Management Unit (SWMU) 17, Naval Weapons Station Charleston, North Charleston, South Carolina, 2002–2004 (data from Tetra Tech NUS, Inc., 2004).

a shallow basin and a northern plume consisting primarily of tetrachloroethene (PCE) of unknown origin. Additional groundwater contaminants in the southern plume include vinyl chloride (VC) and 1,1-dichloroethene. Although the present investigation includes measurements of groundwater levels in both SWMU16 and SWMU17, the primary area of focus for this investigation is the groundwater contamination in the southern part of SWMU17 (fig. 3*A*).

A consulting firm, Solutions-IES, initiated an Environmental Security Technology Certification Program (ESTCP) project at SWMU17 in 2004 to evaluate the effectiveness of injecting emulsified-oil technology as a remediation alternative for subsurface VOC contamination (Project Number ER-0221). During Phase I of the investigation in May 2004, Solutions-IES injected about 1,260 pounds of emulsified-oil substrate into the shallow aquifer in the southern part of SWMU17 in a test plot about 20 feet (ft) by 20 ft at wells 17PS-01, 17PS-02, and 17PS-03 (Lieberman and Borden, in press; fig. 4). Solutions-IES found that the injection resulted in an initial rapid dechlorination of TCE to *c*DCE (Borden and others, 2008). The remediation appeared to stall, however, at *c*DCE, with little or no further reduction of the *c*DCE to VC or to ethene (Borden and others, 2008).

The USGS and the Naval Facilities Engineering Command Southeast (NAVFACSE) began a groundwater investigation of SWMU17 in 2005 to obtain information on the groundwater chemistry in and near the injection zone and to gain a better understanding of the nature of the remediation stall. Initial field tests during the investigation indicated that the pH in the injection area was below 6.0 and below the range typically considered optimum for dechlorination activity (near neutral). Solutions-IES modified the injectate to produce a pH-buffered emulsified-oil substrate, based partly on information obtained during the present investigation and partly on confirmatory laboratory tests conducted in their own laboratory. During September 26–28, 2006, and October 16–18, 2006, Solutions-IES injected 3,030 pounds of pH-buffered emulsified vegetable oil into the test zone as Phase-II of the field test. This second injection was done by a direct-push method, which resulted in a more efficient injection and distribution than the recirculation method of the May 2004 injection. Following this second injection, Solutions-IES reported rapid dechlorination of the solvents to VC and ethene, with a decrease in total chlorinated solvent concentration of more than 95 percent (Borden and others, 2008; Lieberman and Borden, in press). In addition, Solutions-IES reported a large increase in the *Dehalococcoides* sp. population and in TCE reductase levels, with VC reductase levels remaining low (Borden and others, 2008).

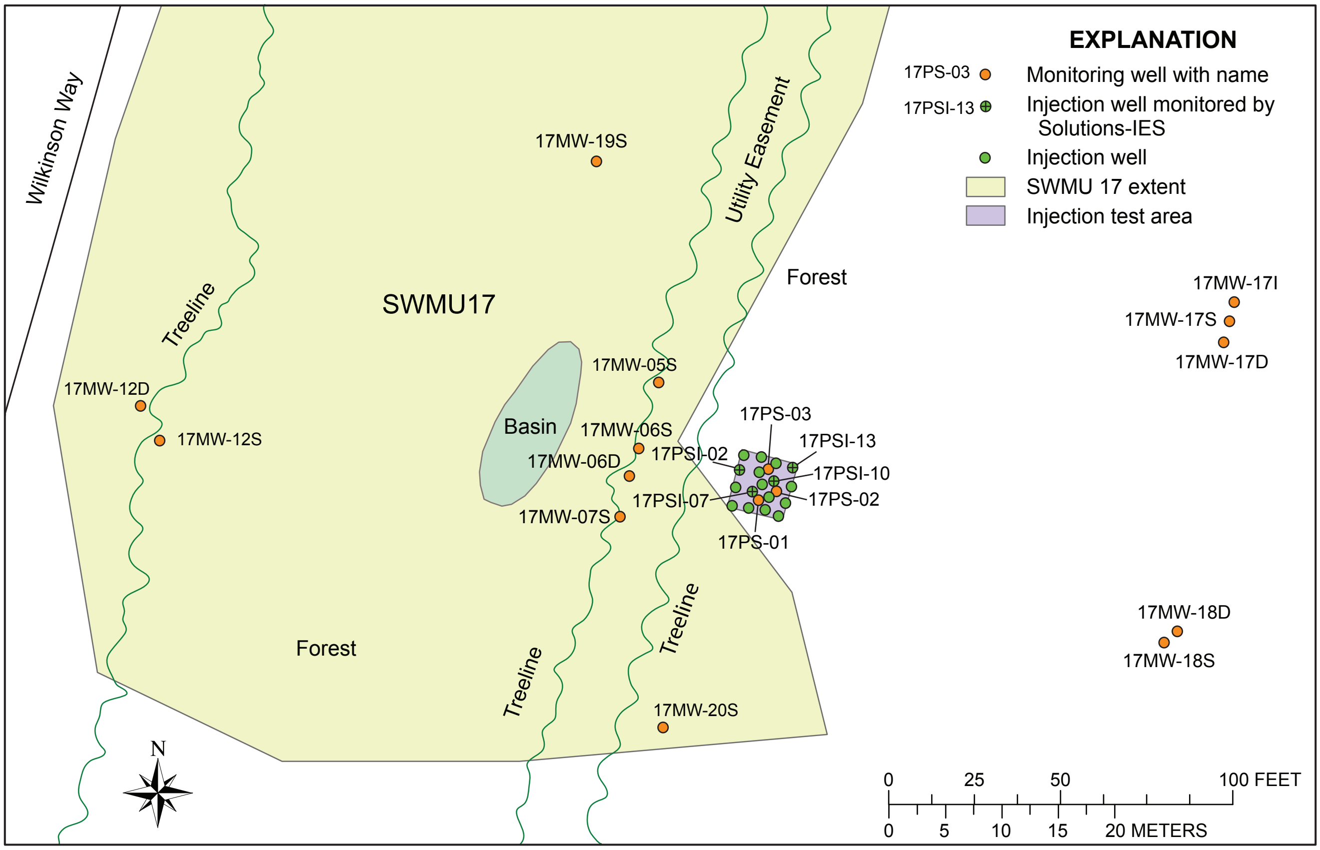


Figure 4. Locations of monitoring wells in the vicinity of the vegetable-oil injection area, Solid Waste Management Unit 17 (SWMU17), Naval Weapons Station, Charleston, North Charleston, South Carolina.

Purpose and Scope

The purposes of this report are to (1) discuss the groundwater hydrology and chemistry in and near the vegetable-oil injection zone with the goal of gaining a better understanding of the nature of the remediation stall following the Phase-I injection of emulsified vegetable oil at SWMU17 and (2) present recent data on VOC concentrations in and near the injection zone. Evaluation of the effectiveness of the vegetable-oil injection at SWMU17 as a VOC-remediation approach has been addressed by Solutions-IES in a conference proceedings (Borden and others, 2008) and is the subject of an in-depth separate document (Lieberman and Borden, in press) as part of the ESTCP investigation. Groundwater chemical and microbiological data collected from three wells in the vegetable-oil injection area and two wells in the contaminated aquifer upgradient from the injection area as part of the present investigation provide the primary supporting information for the present report; however, a substantial amount of data collected by Solutions-IES from injection wells as part of the ESTCP investigation (Lieberman and Borden, in press) also are referred to in this report. This report also refers to selected water-quality data from the ESTCP investigation for monitoring wells that were sampled on dates other than during the present investigation.

This report also discusses results of on-site jar studies and passive in-well tests to examine the effect of increasing the pH in monitoring wells on dechlorination activity at SWMU17. Water-level data are presented as appendixes to this report.

Methodology

A series of jar and in-well tests were conducted by the USGS and NAVFACSE to raise the pH of water in target wells. The jar studies were done using glass jars containing 1 liter of tap or well water amended with pH-adjustment media. From September 2005 to June 2006, permeable devices containing alkaline material were deployed at four to five depths across the screened interval of well 17PS-02. For a deployment, the alkaline material consisted of one of the following: granular calcite, magnesium oxide (MgO), sodium bicarbonate, Portland-cement grout cylinders, or a mixture of calcite and MgO. In general, the permeable bags consisted of nylon mesh. When sodium bicarbonate was used, it was deployed in a closed cylinder of porous polyethylene. In most cases, one or more data loggers for pH were deployed along with the string of permeable devices.

Because the in-well tests in well 17PS-02 were expected to alter the water in the well casing but not necessarily in the aquifer beyond the casing, sampling methodology was used to allow collection of water within the well. The in-well sampling methodology included collection and analysis of water from passive diffusion bag (PDB) samplers that were deployed at the same time as deployment of the pH-adjusting media (table 1).

Groundwater levels were collected by multiple approaches. Primarily, groundwater levels were collected by tape-down measurements using a Solinst™ electric tape and correcting the measurements to feet above North American Vertical Datum of 1988 (NAVD 88) by subtracting the measurements from the measuring-point elevations. Measurements were made at wells in the vicinity of the SWMU17 vegetable-oil injection during most sampling events. Synoptic water-level measurements were made during a high and low tide on September 10, 2008, and during a low tide on April 21, 2009, at all wells in SWMU16 and SWMU17 except for well 17MW-01S, which was not accessible. Water-level loggers in seven wells recorded data at 15-minute intervals in 2009. To ensure consistency of measurement to a common datum, all of the measurement datums for the wells were resurveyed on September 8, 2009 (table 2).

The USGS groundwater sampling at SWMU17 concentrated on a relatively small subset of the wells. The wells were 17MW-06S, 17MW-07S, 17PS-01, 17PS-02, and 17PS-03 (fig. 4). Wells 17MW-06S and 17MW-07S were in a contaminated part of the aquifer upgradient from the edible vegetable-oil injection. Wells 17PS-01, 17PS-02, and 17PS-03 were in the immediate vicinity of the injection (fig. 4). In addition, this investigation refers to monitoring data collected from injection wells 17PSI-02, 17PSI-07, 17PSI-10, and 17PSI-13 by Solutions-IES for a separate investigation (fig. 4; Lieberman and Borden, in press). The monitoring wells and the injection wells were screened 8–18 ft below land surface (BLS).

Low-flow sampling methodology (Barcelona and others, 1994; Shanklin and others, 1995; Sevee and others, 2000) was used to collect groundwater samples from all of the wells on most sampling dates. Exceptions were May 10, 2004, and July 21, 2005, when the wells were sampled following a three-casing volume purge. In addition, wells 17PS-01, 17PS-02, and 17PS-03 developed a severe permeability loss caused by vegetable-oil injections in September 2006. In an attempt to obtain samples from these wells, these wells were purged and then sampled the day following the purging to allow them to recover. Because of the potential vapor loss associated with this method of sampling, VOC concentrations from 2007 should be regarded with some level of uncertainty.

During low-flow sampling, the wells were purged at a rate of approximately 100–200 milliliters per minute (mL/min), until the water temperature, pH, dissolved oxygen concentration, and specific conductance values stabilized and no additional water-level drawdowns were observed. Stabilization of temperature, pH, dissolved oxygen, and specific conductance were observed by passing the water through a flow-through cell containing sensors. The pumpage was considered to be stabilized when the observed changes over three 3-minute intervals were within ±3 percent for water temperature and specific conductance, within ±0.1 unit for pH, and within ±10 percent for dissolved oxygen. Final dissolved oxygen measurements were determined using a Chemetrics™ colorimetric field kit.

Table 1. Chronology of pH-adjustment tests in well 17PS-02, Naval Weapons Station Charleston, North Charleston, South Carolina.

Date	Deployment or removal of in-well pH-adjusting media	Effect
9/6/2005	Added granular calcite to well 17PS-02	No substantial change; pH was 5.9 on August 23, 2005, and 6.0 on September 12, 2005
9/28/2005	Added additional granular calcite to well 17PS-02	No data
10/13/2005	Removed granulated calcite from well 17PS-02	Low-flow sample pH was 5.8
10/20/2005	Added calcite-magnesium oxide (50/50) in well 17PS-02	The pH at the top of the well screen increased from 5.9 on October 19, 2005, to 6.2 on October 25, 2005
11/3/2005	Checked pH in well 17PS-02 and found it to be 6.7; replaced two of the calcite-magnesium oxide bags with new bags of the same mix because the bags had a black coating	The pH was 6.7. Black precipitate indicates a pH increase
11/4/2005	Removed the (50/50) mix bags from well 17PS-02 and replaced them with calcite bags	No data
12/12/2005	Removed calcite from well 17PS-02 and added porous polyethylene sleeves of sodium bicarbonate	No data
1/20/2006–2/16/2006	Removed the sodium bicarbonate containers from well 17PS-02 and replaced them with grout cylinders; three grout cylinders were deployed; removed the grout cylinders on February 16, 2006	No data, but the sodium bicarbonate was nearly gone. Although approximately 1 kilogram of sodium bicarbonate was deployed, less than a gram remained
6/1/2006–6/21/2006	Added magnesium oxide to wells 17PS-02 and 17PS-03; removed the magnesium oxide on June 21, 2006	The pH in the top and bottom of the screened interval in well 17PS-02 increased from about 5.7 prior to deployment to about 6.8 after deployment. Water obtained from the well by collecting the first water to discharge from peristaltic-pump tubing in the screened interval in well 17PS-03 had a pH of 7.2

Water samples were collected from wells for VOC analysis by using PDB samplers during this investigation. A comparison of PDB-sample results from different depths in the screened intervals with low-flow sampling shows that the results generally were within or near the range of concentrations detected by at least one of the PDB samplers (figs. 5*A*–*D*, *F*, *G*). Well 17PS-02 was unusual in that the low-flow VOC concentrations were within or near the concentration range detected by at least one of the PDB samplers for the respective VOC in February 2006 (fig. 5*D*), but the TCE concentration from low-flow sampling was substantially higher than that from the PDB samplers in May 2006 (fig. 5*E*). The variability in the comparison may be due to temporal variability in the contaminant distribution in the aquifer or in the well or to changing groundwater-flow directions. Substantial fluctuations in VOC concentrations at well 17PS-03 also were detected in samples collected as part of the ESTCP investigation (Lieberman and Borden, in press).

Samples collected for microbial analysis using molecular biological tools were obtained by using a variety of methods. The methods included low-flow sampling and collecting samples after purging multiple casing volumes. On some sampling dates, sediment samples were obtained by using a peristaltic pump to collect a slurry of water and sediment from the sumps of selected wells. Samples were collected by passing well water through 0.45-micron filters and sending the filtrate to a commercial laboratory (Microbial Insights, Inc.) for analysis. Samples were collected for both deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). Because RNA sample analysis was a relatively new tool, various approaches for field preservation of the samples prior to shipment to the laboratory were tested at SWMU17. Comparisons were made among storing the samples at 4 degrees Celsius (°C) using water ice, storing them frozen using dry ice, and storing them at 4 °C after adding the preservative RNAlater® to the samples. Although the results were highly variable, usually more gene copies per milliliter of water were reported from samples preserved with RNAlater® (fig. 6). Therefore, the RNA samples typically were preserved with RNAlater® and shipped on ice to the laboratory for analysis. DNA samples were preserved by storing the samples at 4 °C.

Table 2. Locations, data, and screened intervals of wells used in the investigation at Solid Waste Mangement Units 16 and 17, Naval Weapons Station Charleston, North Charleston, South Carolina.

[ft NAVD 88, feet above the North American Vertical Datum of 1988; ft BLS, feet below land surface]

Well name	Northing	Easting	Ground elevation (ft NAVD 88)	Top of riser elevation (ft NAVD 88)	Total depth (ft BLS)	Screen interval (ft BLS)
16MW-01S	397987.2661	2320919.034	4.89	7.78	14	4–14
16MW-02S	398042.1787	2320606.301	0.65	4.77	13	3–13
16MW-03S	397728.0346	2320274.067	2.08	4.74	13	3–13
16MW-04S	397189.5322	2320693.892	1.51	4.28	13	3–13
16MW-05S	397306.6424	2320382.639	1.63	4.40	13	3–13
17MW-02S	397442.5013	2321322.98	4.56	7.66	15	5–15
17MW-03S	397501.9857	2321135.31	5.95	8.74	15	5–15
17MW-04S	397023.706	2321129.466	4.39	7.15	15	5–15
17MW-05S	397272.7887	2321215.29	5.31	7.77	19	8–18
17MW-06D	397246.08	2321206.63	5.37	7.62	23.5	18–23
17MW-06S	397253.9852	2321209.39	5.49	7.88	19	8–18
17MW-07S	397234.3491	2321203.959	5.44	7.92	19	8–18
17MW-11S	397501.23	2321062.28	7.36	9.67	20	10–20
17MW-12D	397266.21	2321064.86	5.38	7.17	29	18–28
17MW-12S	397256.37	2321070.34	5.41	7.37	14	4–14
17MW-13S	397847.74	2321436.38	5.39	7.49	14	4–14
17MW-14D	397530.54	2321499.6	4.05	6.63	25.5	15–25
17MW-14S	397539.42	2321498.64	3.95	6.27	14.5	4–14
17MW-15D	397436.19	2321462.83	3.45	5.90	40	29–39
17MW-15S	397434.77	2321457.71	3.76	6.00	20	10–20
17MW-16D	397350.51	2321425.29	3.48	5.89	42.5	32–42
17MW-16I	397350.2	2321420.68	3.66	6.02	25	15–25
17MW-16S	397351.01	2321430.67	3.52	5.80	15	5–15
17MW-17D	397284.48	2321379.32	3.52	5.97	37.5	27–37
17MW-17I	397295.98	2321382.43	3.42	6.03	23.5	13–23
17MW-17S	397290.49	2321381.1	3.37	6.15	14.5	4–14
17MW-18D	397201.33	2321365.9	3.59	5.42	22.5	15–22
17MW-18S	397198.18	2321362.01	3.76	5.36	14.5	4–14
17MW-19S	397336.43	2321197.09	5.5	7.72	18	8–18
17MW-20S	397173.63	2321216.51	4.89	7.32	14	4–14
17MW-21S	397615.39	2321095.35	7.99	10.37	18	8–18
17MW-22S	397557.42	2321078.76	7.77	10.18	20	10–20
17MW-23S	397369.78	2321023.35	4.76	7.06	20	9–19
17PS-01	397239.0561	2321244.25	6.29	7.96	20.9	8.0–18
17PS-02	397241.5962	2321249.443	6.35	7.90	20.9	8.0–18
17PS-03	397248.0191	2321247.222	6.19	7.80	20.9	8.0–18

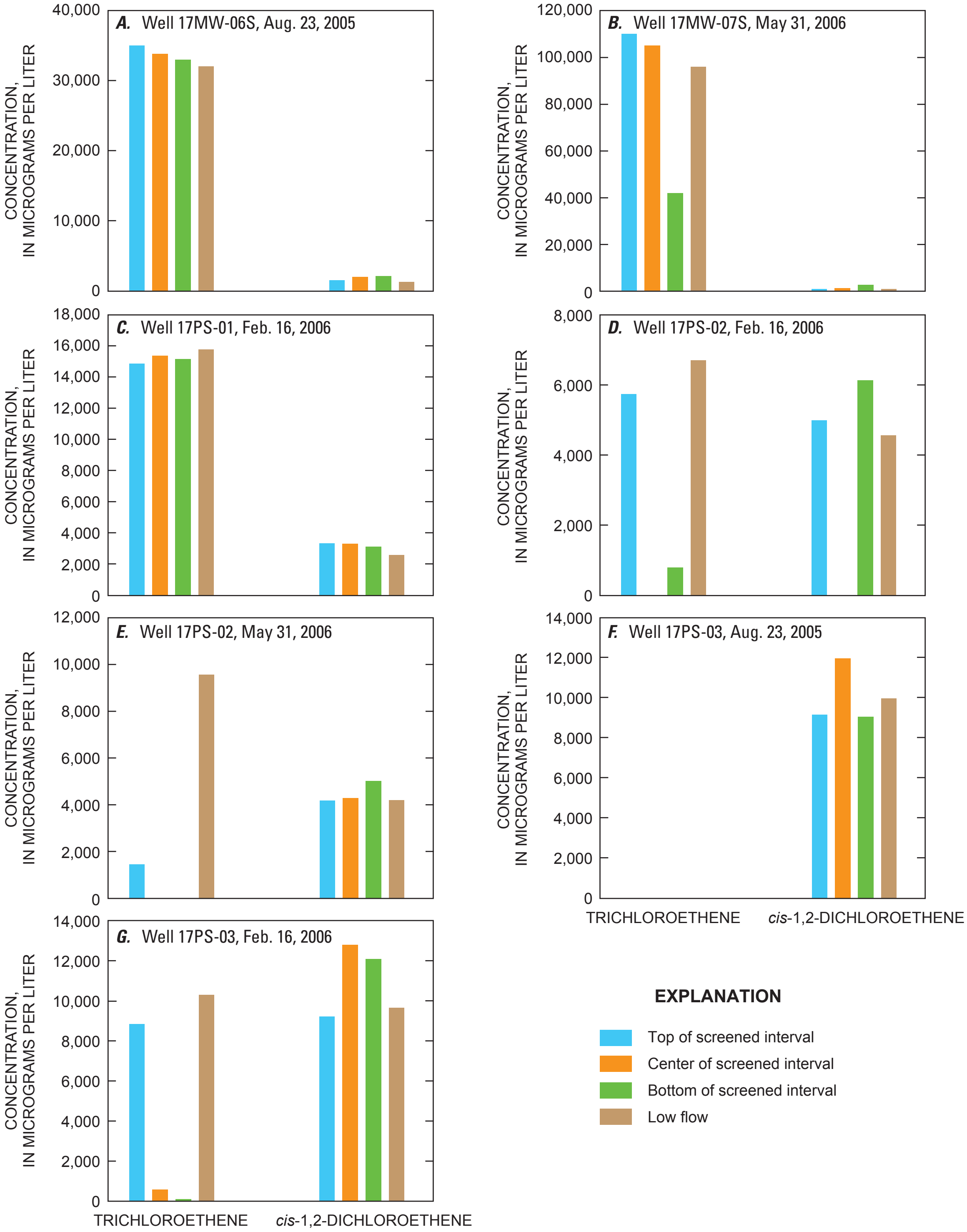


Figure 5. Trichloroethene and *cis*-1,2-dichloroethene concentrations in passive diffusion bag samplers from various depths in the screened interval during low-flow testing, Solid Waste Management Unit 17, Naval Weapons Station Charleston, North Charleston, South Carolina.

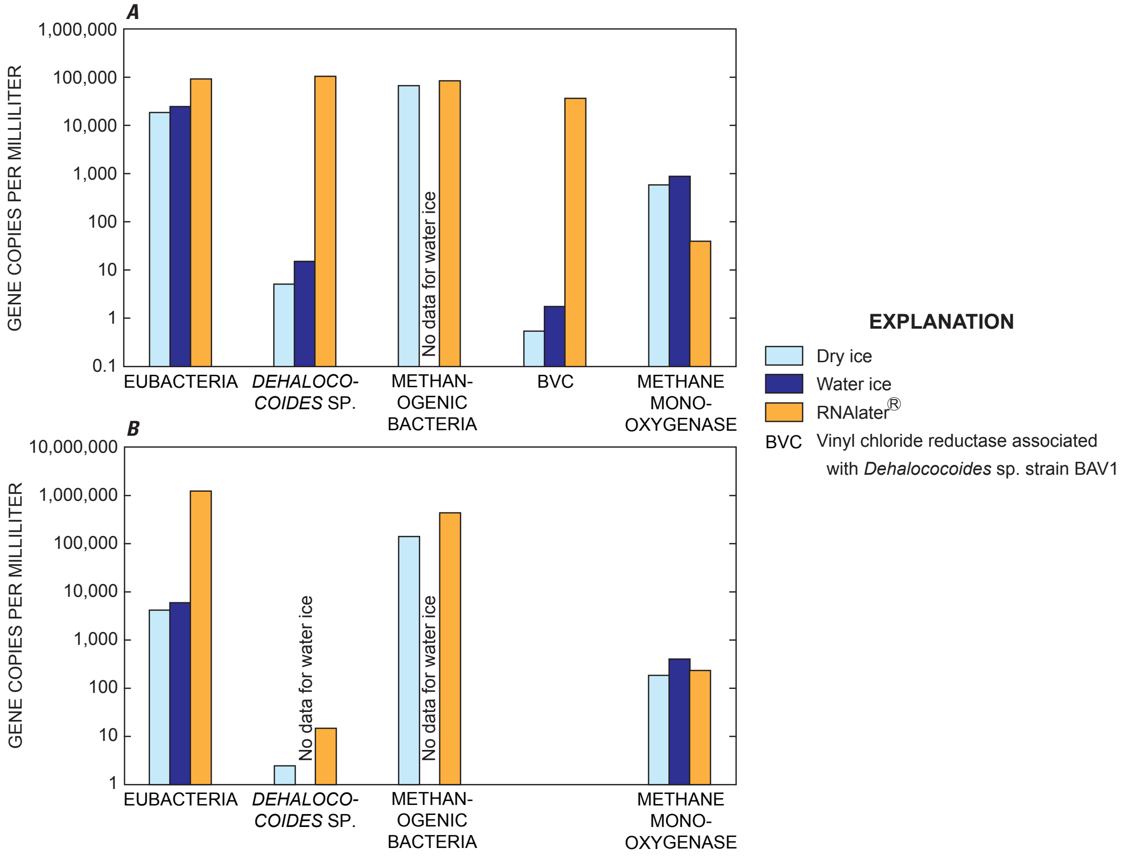


Figure 6. Ribionucleic acid (RNA) sample-preservation field methods for groundwater at wells (*A*) 17MW-07S and (*B*) 17PS-01, Solid Waste Management Unit 17, Naval Weapons Station Charleston, North Charleston, South Carolina, July 21, 2005.

Groundwater Hydrology

The study area, SWMU17, is located in a low-lying forest and is nearly surrounded by local surface-water features (fig. 2). The site geology, as described by TetraTech NUS, Inc. (2006), consists of a sandy-clay or sandy-silt unit that extends from land surface to a depth of about 5 to 11 ft BLS. The most hydraulically conductive material is a silty-sand zone about 8 to 10 ft thick, coarsening downward (Tetra Tech NUS, Inc., 2006). The silty-sand zone is underlain by silty clay with shell fragments. A clay zone is present at a depth of 16 ft in the vegetable-oil injection zone (Borden and others, 2008). Slug-test data indicate that the mean hydraulic conductivity was about 1.24 feet per day (ft/d) in wells screened above 20 ft BLS (Tetra Tech NUS, Inc., 2006). The calculated seepage velocity in the upper surficial aquifer was about 5 to 11.3 feet per year (ft/yr; Tetra Tech NUS, Inc., 2006; Borden and others, 2008).

Groundwater-flow directions near the treatment area vary at SWMU17. A previous investigation reported that water-level measurements taken in and near the injection zone on seven different occasions showed seven widely different groundwater-flow directions, some of them in opposite directions (Lieberman and Borden, in press). The present investigation found that the variations in groundwater-flow directions are related to localized ponding, recharge, evapotranspiration, tides, and possibly to differences in hydraulic conductivity.

A groundwater mound is present at SWMU17, which results in radial flow from SWMU17 toward SWMU16 to the west and toward a surface-water feature to the east (figs. 7, 8, 9). The location of the groundwater mound shifts laterally within SWMU17, resulting in localized shifts in groundwater-flow directions. The shift in location of the groundwater mound is partly caused by localized recharge from ponds that form from poor drainage following rainfall events. The highest water level measured at SWMU16 and SWMU17 on April 21, 2009, was 4.07 ft above NAVD 88 at well 17MW-03S (fig. 9), although that well did not have the highest water level on other dates (figs. 7, 8). At the time of measurement on April 21, 2009, substantial ponding was

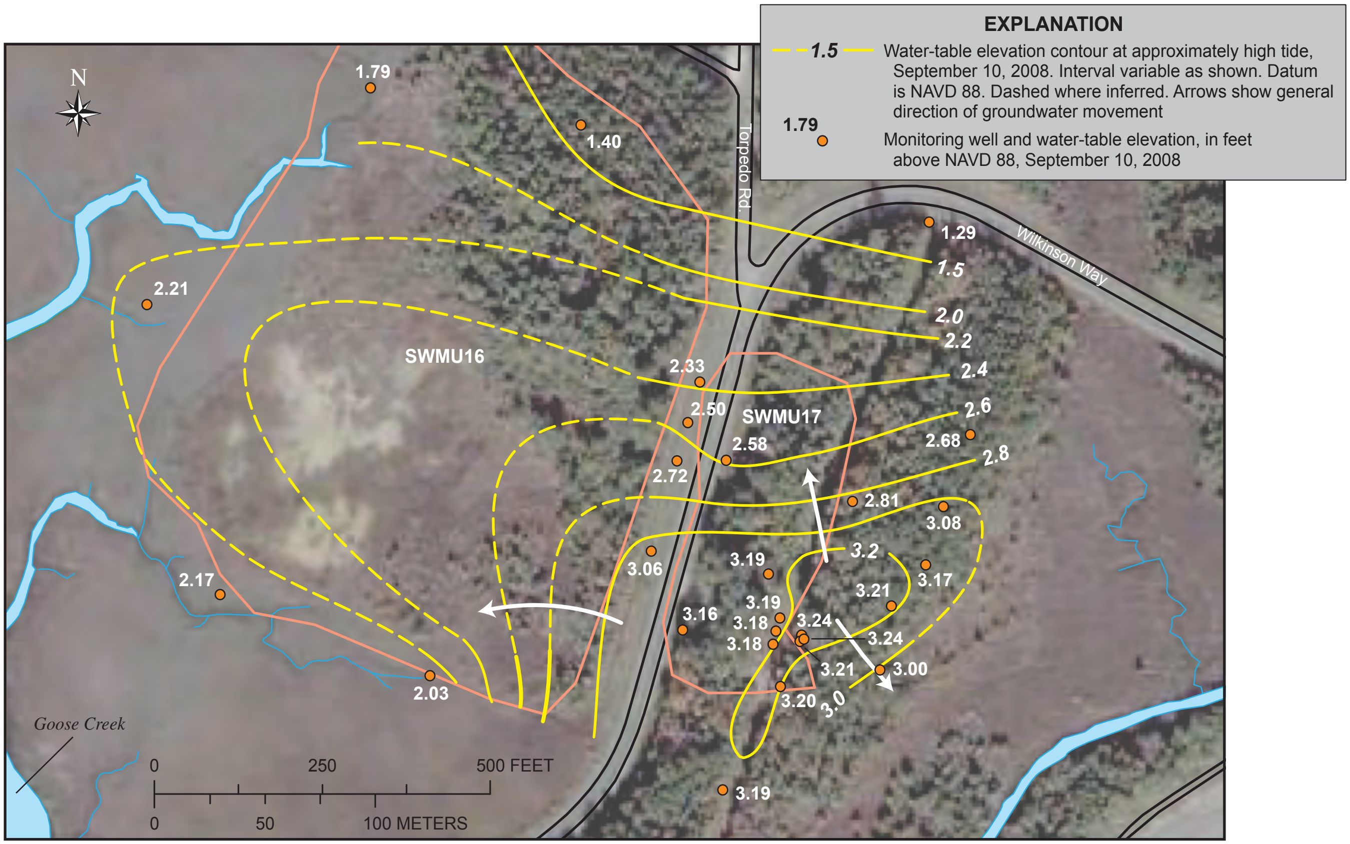


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Figure 7. Water table at Solid Waste Management Unit (SWMU) 16 and SWMU17 at approximately high tide, Naval Weapons Station Charleston, North Charleston, South Carolina, September 10, 2008.

present near well 17MW-03S because of runoff collection in the topographically low area at that well. The ponding likely resulted in localized recharge, making the groundwater levels at well 17MW-03S higher than in surrounding wells.

An additional important influence on groundwater levels at SWMU17 is evapotranspiration. Hydrographs of monitoring wells in April 2009 showed a diurnal water-level change and an overall declining trend (fig. 10). The water levels declined about 0.1 to 0.2 ft during the late morning through the afternoon and evening and rose during the night and early morning. Although a substantial tidal influence was seen during this and previous investigations on groundwater levels in nearby SWMU16 (Tetra Tech NUS, Inc., 2004, 2006), the consistent single daily cycle rather than a twice per day cycle coincident with tides indicates that evapotranspiration is a substantially more dominant influence on groundwater levels than tidal fluctuations at SWMU17.

Water levels in some of the wells change more sharply than in other wells, perhaps related in part to differences in evapotranspirative intensity. For example, water levels at well 17MW19S, in the middle of the forest, decreased by about 0.35 ft between 3:30 a.m. and 8:00 p.m. on April 23, 2009. During that same time period, the water levels in wells 17MW-17S and 17MW-18S, on the edge of the forest, decreased by only 0.18 and 0.19 ft, respectively. The difference in magnitude of change results in changes in the apparent direction of the hydraulic gradient throughout the day. On some days, the water levels in well 17MW-17S were higher or lower than the water levels in well 17MW-05S, depending on the time of day (fig. 10). In addition, water levels in well 17MW-17S were as high or higher than water levels in inland well 17MW-20S for days before declining below water levels in well 17MW-20S.

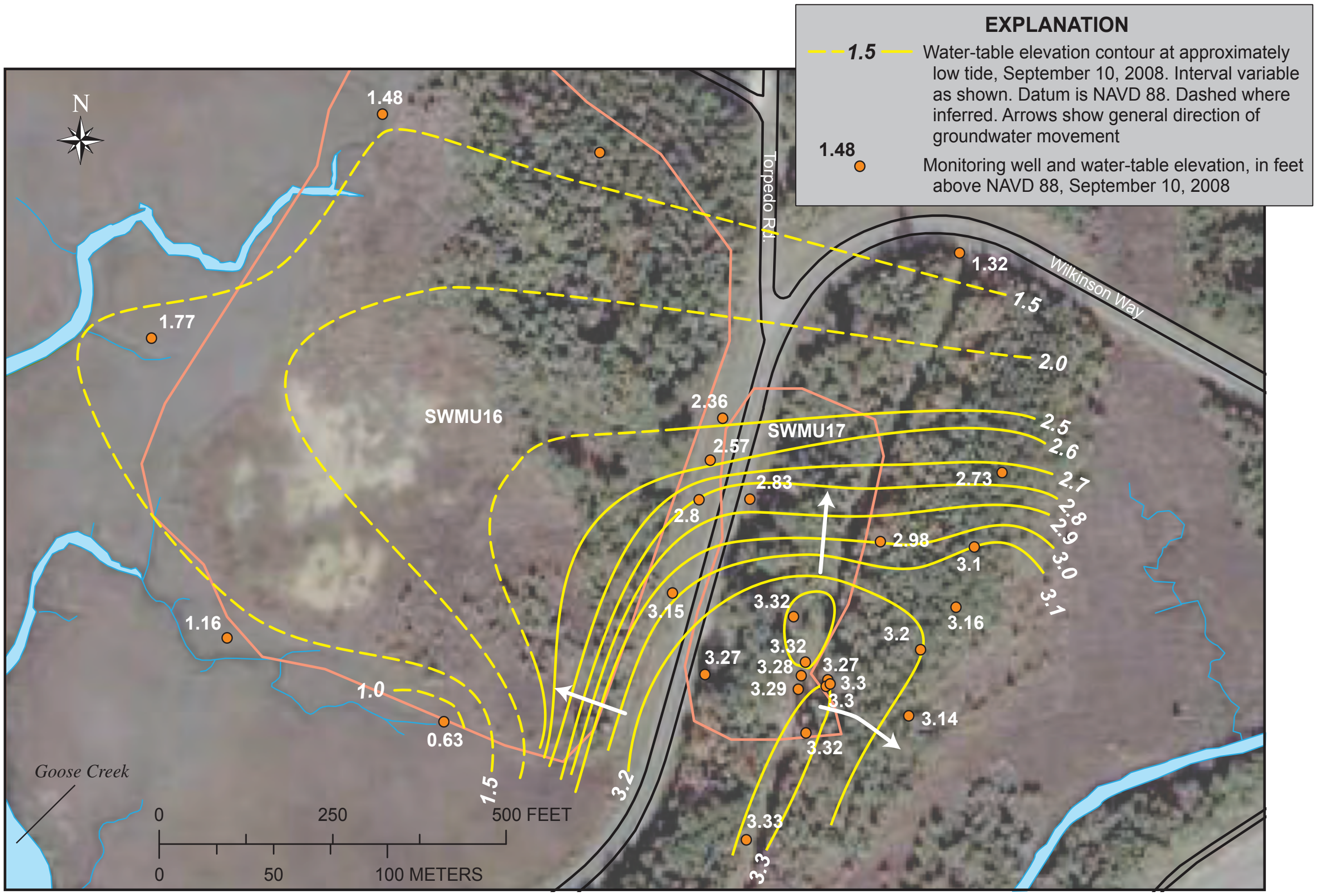

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Figure 8. Water table at Solid Waste Management Unit (SWMU) 16 and SWMU17 at approximately low tide, Naval Weapons Station Charleston, North Charleston, South Carolina, September 10, 2008.

The water level in well 17PS-02, in the vegetable-oil injection zone, changed more slowly in comparison to nearby wells. This is particularly noticeable during the part of the day when evapotranspiration is most active (fig. 10). Thus, part of the reason for the subdued water-level changes in well 17PS-02 may be the fact that no large trees are immediately adjacent to the injection zone, resulting in a relatively lower influence from evapotranspiration. An additional reason for the relatively subdued response of the well 17PS-02 is that the hydraulic conductivity at well 17PS-02 may be lower than at nearby wells outside of the injection zone because of the vegetable-oil injection. The importance of recognizing the subdued nature of well 17PS-02 is that if that well is used to obtain synoptic water levels, then substantially varying hydraulic gradients and directions can be obtained, depending on the time of day.

No direct tidal influence on water levels in wells at SWMU17 was seen during this investigation; however, a substantial tidal influence on groundwater levels at SWMU16 was observed during this and previous studies (Tetra Tech NUS, Inc., 2004, 2006). Some of the nearshore wells at SWMU16 are submerged at high tide. Overland flow during high tide allows infiltration of river water downward into the aquifer. As can be seen in figures 7 and 8, high-tide groundwater levels in some near-shore wells can be more than 1 ft higher than at low tide. The result is that the nearshore parts of SWMU16 sometimes can have higher water levels than the more inland parts (fig. 7). Because of the strong tidal influence and the lack of a well in the middle of SWMU16, the actual groundwater-flow directions beneath SWMU16 can only be approximated. Because groundwater from the southwestern side of SWMU17 generally flows to SWMU16, however, it is

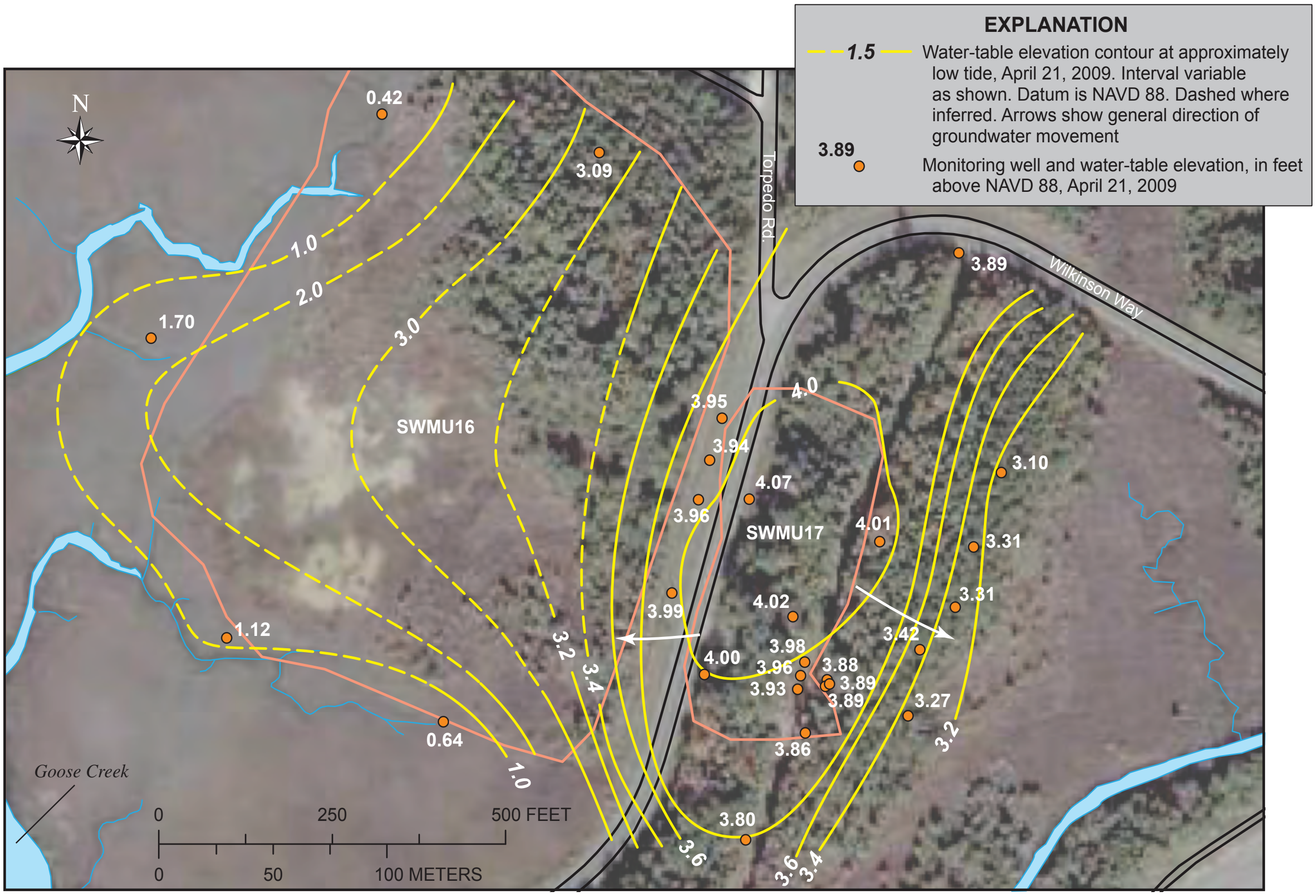

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Figure 9. Water table at Solid Waste Management Unit (SWMU) 16 and SWMU17 at approximately low tide, Naval Weapons Station Charleston, North Charleston, South Carolina, April 21, 2009.

likely that tidal changes at SWMU16 have some level of influence on groundwater-flow directions beneath the southwestern part of SWMU17.

The complex hydrology of SWMU17 and the frequent changes in hydraulic gradient make it difficult to determine flow directions based simply on synoptic water-level measurements. The average water levels at selected wells near the vegetable-oil injection zone are based on 15-minute-interval measurements for the period April 21 to May 13, 2009 (fig. 11). The resulting water-table configuration indicates a groundwater hydraulic gradient of about 0.001 foot per foot (ft/ft) in a southeastern direction. This hydraulic gradient is consistent with previous investigations using 0.001 ft/ft to calculate groundwater-flow rates of 1 to 11 ft/yr (Tetra Tech NUS, Inc., 2004; Lieberman and Borden, in press).

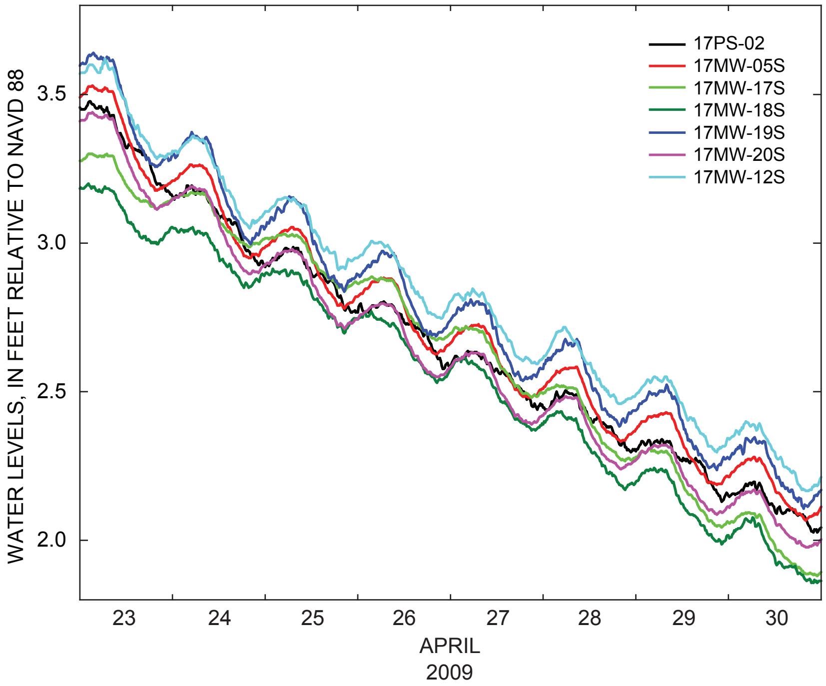
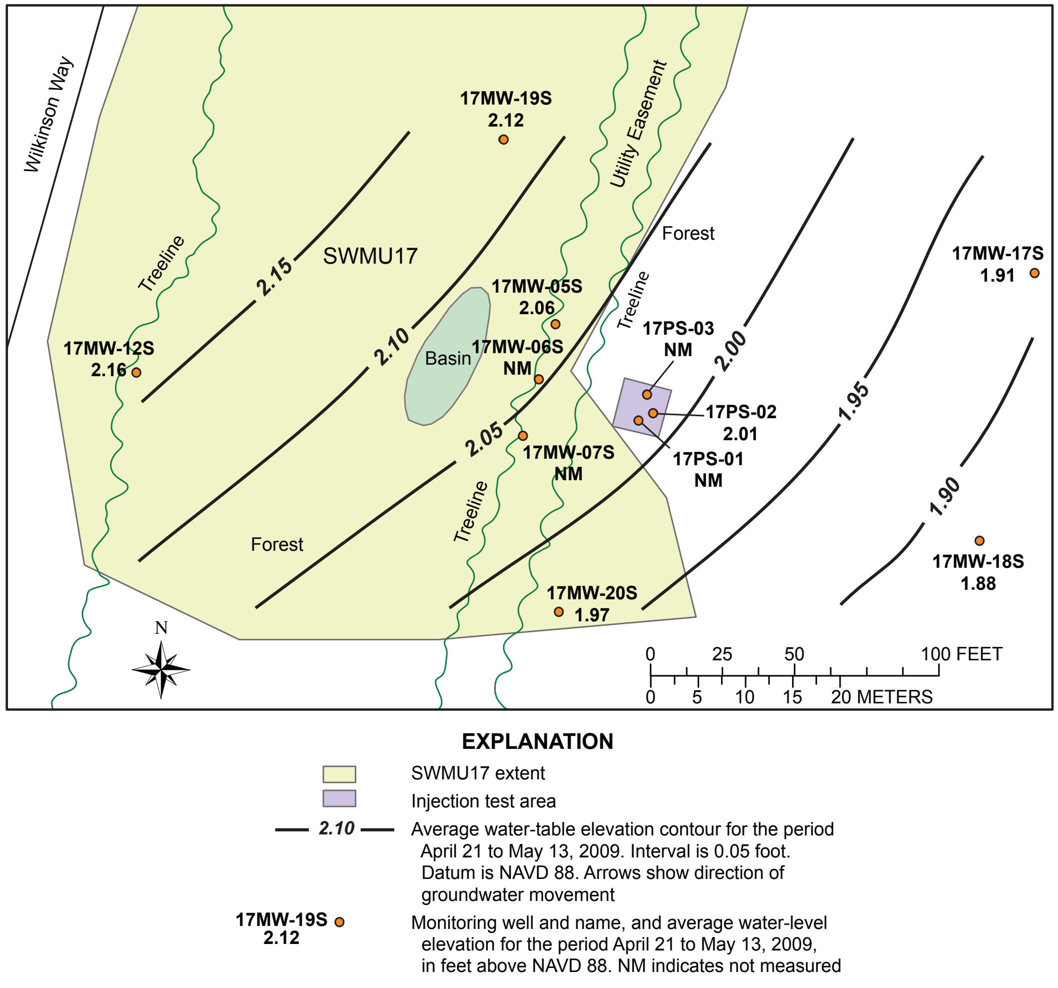


Figure 10. Hydrographs of monitoring wells in the vicinity of the vegetable-oil injection zone, Solid Waste Management Unit 17, Naval Weapons Station Charleston, North Charleston, South Carolina, April 23–30, 2009



EXPLANATION

🟩	SWMU17 extent
🟪	Injection test area
— 2.10 —	Average water-table elevation contour for the period April 21 to May 13, 2009. Interval is 0.05 foot. Datum is NAVD 88. Arrows show direction of groundwater movement
17MW-19S ● 2.12	Monitoring well and name, and average water-level elevation for the period April 21 to May 13, 2009, in feet above NAVD 88. NM indicates not measured

Figure 11. Average water table based on 15-minute-interval data in the vicinity of the vegetable-oil injection area, Solid Waste Management Unit 17, Naval Weapons Station Charleston, North Charleston, South Carolina, April 21 to May 13, 2009.

Groundwater Chemistry

Groundwater contamination in the southern part of SWMU17 (fig. 3) consists of chlorinated VOCs. Measured concentrations in groundwater at wells 17MW-06S and 17MW-07S, upgradient from the vegetable-oil injection zone, ranged from about 13,000 to 130,000 micrograms per liter (µg/L) for TCE and from 295 to 8,040 µg/L for *c*DCE (table 3). Vinyl chloride was not detected in groundwater at these upgradient wells; however, the laboratory detection limit often was 44 to 250 µg/L or higher due to the dilution factors needed to measure the high concentrations of TCE and *c*DCE.

Higher TCE concentrations were detected in PDB samplers at the top of the well screen relative to the bottom of the well screen in wells 17MW-07S, 17PS-02, and 17PS-03 (figs. 5*B*, *D*, *E*, *G*). Thus, it is likely that the groundwater contamination is more concentrated at depths shallower than about 13 ft BLS than in deeper sediment. Some degree of lateral heterogeneity of TCE concentrations also may be present in the treatment area. During a test of low-flow sampling methodology, TCE concentrations in well 17PS-03 gradually increased from 900 µg/L, after field-property stabilization (water level, temperature, pH, and specific conductance) and purging one-half of a casing volume, to 10,000 µg/L after purging three casing volumes (table 3). These data likely indicate that well 17PS-03 was screened near an interface between relatively low TCE concentrations (less than 1,000 µg/L) and relatively high concentrations (greater than 9,000 µg/L).

Aquifer Terminal Electron-Accepting Processes

The aquifer was anaerobic during this investigation, based on dissolved oxygen concentrations, usually ranging from less than 0.025 milligram per liter (mg/L) to about 0.6 mg/L (table 4). Iron reduction is a likely terminal electron-accepting process (TEAP) in the aquifer outside of the injection zone. Data from Solutions-IES show that dissolved iron in water from the injection wells increased from about 24 to 44 mg/L prior to injecting the vegetable oil to greater than 200 mg/L following injection (Lieberman and Borden, in press), indicating that the aquifer had a large amount of bioavailable iron. Because of the strongly competitive nature of iron-reducing bacteria relative to sulfate-reducing or methanogenic bacteria, the presence of bioavailable iron in this anaerobic aquifer where more efficient electron acceptors are absent indicates that iron reduction is an active TEAP in the shallow aquifer outside of the injection zone.

In addition to iron reduction, it is likely that groundwater from the wells upgradient from the injection zone represents an integration of multiple redox zones. The presence of methane (usually greater than 50 µg/L) in groundwater from wells 17MW-06S and 17MW-07S indicates that some amount of methanogenesis was taking place in or upgradient from the wells (table 3).

Data from the ESTCP investigation showed a substantial increase in dissolved iron and a decrease in dissolved sulfate concentrations in water from the monitored injection wells during the months following the injection (Lieberman and Borden, in press). Dissolved sulfate concentrations in water from the injection wells prior to the injection ranged from tens of milligrams per liter to greater than 100 mg/L. In the months following the Phase-I injection, dissolved sulfate concentrations decreased to less than 0.5 mg/L in water from the injection wells (Lieberman and Borden, in press). The decrease in sulfate indicates that enough ferrous iron was removed from the aquifer sediment to allow sulfate reduction to proceed or that enough electron acceptor was added so that competition between iron and sulfate reducers was diminished. These data indicate that the TEAP near the injection wells immediately following the Phase-I injection probably was iron reduction followed by sulfate reduction.

Depletion of dissolved sulfate to undetectable concentrations by sulfate reduction removes the electron acceptor needed to support sulfate reduction; therefore, methanogenesis likely became an active TEAP near the injection wells. The shift to methanogenesis can be seen in the data collected by Solutions-IES, which indicated that by November 2004, methane concentrations in groundwater from the monitored injection wells increased by factors of about 5.5 to 14 (Lieberman and Borden, in press). At most of the sampled injection wells, methane concentrations again showed an increase in the February 2005 sampling. By May 2005, Solutions-IES data showed that the methane concentrations in the tested injection wells had increased by factors ranging from about 24 to 197 (Lieberman and Borden, in press). Thus, the TEAP in the aquifer adjacent to the injection wells gradually shifted from iron or sulfate reduction to methanogenesis.

The progress to more reducing groundwater conditions was not as intense at monitoring wells 17PS-01 and 17PS-02, which are in the injection zone, as it was at injection wells 17PSI-02, 17PSI-07, 17PSI-10, and 17PSI-13 (fig. 4). Data from the present investigation indicated that sulfate concentrations remained between 26 and 50 mg/L in monitoring wells 17PS-01 and 17PS-02 in the injection zone through May 2006 (table 4). Data from the ESTCP investigation indicate that sulfate concentrations were between 2.7 and 20.8 mg/L at well 17PS-03 during the same period (Lieberman and Borden, in press). These concentrations are sufficient to maintain sulfate reduction as a predominant TEAP under conditions of relatively low available electron donor (Vroblesky and others, 1996). The data from both investigations collectively indicate that redox conditions in the aquifer near wells 17PS-01 and 17PS-02 in the injection zone were more oxidizing than near the injection wells. Support for the hypothesis of redox heterogeneity in the injection zone can be seen in the fact that the total organic carbon (TOC) concentrations in groundwater at the injection wells (usually in the hundreds to thousands of milligrams per liter; Lieberman and Borden, in press) were substantially greater than at wells 17PS-01 and 17PS-02 (about 6 to 27 mg/L between July 2005 and

Table 3. Concentrations of volatile organic compounds in water from wells at Solid Waste Management Unit 17, Naval Weapons Station Charleston, North Charleston, South Carolina, 2004–2007.

[LF, sampled by low-flow methodology; ---, data not collected; #, sample analyzed at a different laboratory than the other samples from the same well on the same date; LF.5CV, sampled after purging one-half casing volume (1.1 gallons) of water from the screened interval; LF1CV, sampled after purging one casing volume (2.2 gallons) of water from the screened interval; LF2CV, sampled after purging two casing volumes (4.4 gallons) of water from the screened interval; LF3CV, sampled after purging three casing volumes (6.6 gallons) of water from the screened interval; 3CV, sampled from the screened interval after purging three casing volumes of water (6.6 gallons) from the top of the water column; 1CV, sampled from the screened interval after purging one casing volume of water (2.2 gallons) from the top of the water column; PDB, passive diffusion bag sample; J, estimated value; <, less than; H, analyte holding time exceeded; B, target analyte was detected in the sample as well as the associated blank; dup, duplicate sample; SP1, possibly unreliable data because the well was sampled after a slow purge with substantial drawdown]

Well name	Date	Type of sample	Sampler location in the well casing	1,1-Dichloro-ethene	Trichloro-ethene	*cis*-1,2-Dichloro-ethene	Vinyl chloride	Chloroform	Methane	Ethane	Ethene
				micrograms per liter							
17MS-05S	8/14/2008	LF	Middle of screened interval	<75	13,400	295	<125	<62.5	457	<20	<20
17MW-06S	3/9/2005	LF.5CV	Top of the water column	<66	39,000	990	<44	250	---	---	---
17MW-06S	3/9/2005	LF1CV	Top of the water column	<66	48,000	950	<44	280	---	---	---
17MW-06S	3/9/2005	LF2CV	Top of the water column	<66	45,000	750	<44	290	---	---	---
17MW-06S	3/9/2005	LF3CV	Top of the water column	<66	46,000	660	<44	250	---	---	---
17MW-06S	8/23/2005	LF	Middle of screened interval	<430	32,000	1,300J	<360	<500	85	<0.5	1.7
17MW-06S	8/23/2005	PDB	Top of screened interval	<430	35,000	1,500J	<360	<500	95	<0.5	2.1
17MW-06S	8/23/2005	PDB	Middle of screened interval #	10	33,800H	1,990H	10.7	202H	110	<0.5	3.1
17MW-06S	8/23/2005	PDB	Bottom of screened interval	<430	33,000	2,100	<360	<500	93	<0.5	2.4
17MW-06S	2/15/2006	PDB	Top of screened interval	<150	34,600	656	<250	318J	---	---	---
17MW-06S	2/15/2006	PDB	Middle of screened interval	<150	37,800	655	<250	330J	110	0.25	2.4
17MW-06S	2/15/2006	PDB	Bottom of screened interval	<150	33,600	585	<250	308J	---	---	---
17MW-06S	5/23/2007	LF	Bottom of screened interval	<150	32,100	646	<250	271J	<6	<2	<2
17MW-06S	7/17/2007	LF	Middle of screened interval	<150	34,400	538	<250	266J	185	<2	<2
17MW-06S	8/22/2007	3CV	Top of water column, then lowered to middle of screen interval	<150	36,200	728	<250	300J	179	<2	2.51J
17MW-06S	5/5/2008	LF	Top of screened interval	<60	22,200	2,440	<250	190J	324	<2	2.62J
17MW-06S	8/14/2008	LF	Middle of screened interval	<75	17,300	2,430	<125	83.8J	377	<10	<10
17MW-06S	10/9/2008	PDB	Middle of screened interval	<75	15,700	7,260	<125	109J	---	---	---
17MW-06S	10/9/2008	PDB	Middle of screened interval	<75	15,700	7,260	<158	109J	---	---	---
17MW-06S	1/14/2009	PDB	Middle of screened interval	11.3	13,000	3,580	29.8	<250	---	---	---
17MW-06S	7/21/2009	LF	Middle of screened interval	<100	18,000	3,400	430	<100	920	<10	<10
17MW-07S	7/21/2005	1CV	Top of water column	<150	119,000	955	<250	540	---	---	---
17MW-07S	7/21/2005	3CV	Top of water column	<150	118,000	760	<250	557	---	---	---
17MW-07S	8/23/2005	LF	Middle of screened interval	<430	96,000	930J	<360	<500	83	<0.5	1.3J
17MW-07S	8/23/2005	PDB	Top of screened interval	<430	110,000	850J	<360	<500	95	<0.5	1.6
17MW-07S	8/23/2005	PDB	Middle of screened interval #	9.84	105,000H	1,180H	16.3	511H	95	<0.5	2.3
17MW-07S	8/23/2005	PDB	Bottom of screened interval	<430	42,000	2,700	<360	<500	140	<0.5	3
17MW-07S	2/15/2006	PDB	Top of screened interval	<300	83,000	826J	<500	599J	---	---	---
17MW-07S	2/15/2006	PDB	Middle of screened interval	<300	76,900	723J	<500	551J	59	0.25	1.4
17MW-07S	2/15/2006	PDB	Bottom of screened interval	<300	82,200	826J	<500	666J	---	---	---
17MW-07S	2/16/2006	LF	Bottom of screened interval	<600	104,000	871J	<1,000	765J	110	0.2	1.6
17MW-07S	5/31/2006	LF	Middle of screened interval	<30	110,000	934	<50	542	78	<0.4	1.2J
17MW-07S	5/31/2006	PDB	Bottom of screened interval	<600	73,200	2,010	<1,000	551J	---	---	---
17MW-07S	5/31/2006	PDB	Top of screened interval	<1,500	130,000	<1,500	<2,500	1470J	---	---	---
17MW-07S	5/23/2007	LF	Bottom of screened interval	<600	87,000	764J	<1,000	746J	181	<2	2.59J
17MW-07S	8/22/2007	3CV	Top of water column, then lowered to middle of screen interval	<150	49,500	1,020	<250	371J	158	<2	<2
17MW-07S	5/5/2008	LF	Top of screened interval	<150	57,900	1,750	<250	457J	162	<2	<2
17MW-07S	8/14/2008	LF	Middle of screened interval	<150	25,800	6,570	<250	<125	243	<10	<10
17MW-07S dup	8/14/2008	LF	Middle of screened interval	<150	24,300	6,470	<250	<125	220	<10	<10
17MW-07S	10/9/2008	PDB	Middle of screened interval	<75	18,100	8,040	<125	62.5J	---	---	---
17MW-07S	1/14/2009	PDB	Middle of screened interval	14.6	250B	300	0.5	250J	---	---	---
17MW-07S	7/21/2009	LF	Middle of screened interval	<500	37,000	2,200	<500	<500	110	<10	<10
17PS-01	7/21/2005	1CV	Top of water column	<30	11,400	2,110	<50	63.7J	206	2.59J	2.05J
17PS-01	7/21/2005	3CV	Top of water column	<30	11,700	2,230	<50	110	157	<2	2.08J
17PS-01	8/23/2005	LF	Middle of screened interval	<210	14,000	2,300	<180	<250	110	1.9	3
17PS-01	2/16/2006	LF	Bottom of screened interval	<60	15,800	2,630	<100	146J	330	1.7	1.9
17PS-01	2/16/2006	PDB	Top of screened interval#	<60	14,900	3,380	<100	119J	---	---	---
17PS-01	2/16/2006	PDB	Middle of screened interval	<60	15,400	3,340	<100	130J	290	1.8	2.1
17PS-01	2/16/2006	PDB	Bottom of screened interval	<60	15,200	3,160	<100	138J	---	---	---
17PS-01	5/31/2006	LF	2 feet from bottom of screened interval	<30	3,550	9,440	<50	40.1J	350	1.9	2.7
17PS-01	8/10/2006	LF	Middle of screened interval	<30	4,150	6,900	431	62.7J	2,650	<2	<2
17PS-01	5/23/2007	SP1	Top of the water column	<15	<12.5	<15.0	3,470	<12.5	9,130	<20	196J
17PS-01	8/22/2007	SP1	Top of the water column	<7.50	<6.25	28	1,770	<6.25	11,700	<200	<200
17PS-01	8/14/2008	PDB	Middle of screened interval	<0.3	<1	5	442	<0.25	22,800	<1,000	<1,000
17PS-01	8/21/2009	LF	Middle of screened interval	<10	<10	43	640	<10	1,000	<20	<20
17PS-01	8/21/2009	PDB	Middle of screened interval	<10	<10	<10	570	<10	---	---	---

Table 3. Concentrations of volatile organic compounds in water from wells at Solid Waste Management Unit 17, Naval Weapons Station Charleston, North Charleston, South Carolina., 2004–2007.—Continued

[LF, sampled by low-flow methodology; ---, data not collected; #, sample analyzed at a different labortory then the other samples from the same well on the same date; LF.5CV, sampled after purging one-half casing volume (1.1 gallons) of water from the screened interval; LF1CV, sampled after purging one casing volume (2.2 gallons) of water from the screened interval; LF2CV, sampled after purging two casing volumes (4.4 gallons) of water from the screened interval; LF3CV, sampled after purging three casing volumes (6.6 gallons) of water from the screened interval; 3CV, sampled from the screened interval after purging three casing volumes of water (6.6 gallons) from the top of the water column; 1CV, sampled from the screened interval after purging one casing volume of water (2.2 gallons) from the top of the water column; PDB, passive diffusion bag sample; J, estimated value; <, less than; H, analyte holding time exceeded; B, target analyte was detected in the sample as well as the associated blank; dup, duplicate sample; SP1, possibly unreliable data because the well was sampled after a slow purge with substantial drawdown]

Well name	Date	Type of sample	Sampler location in the well casing	1,1-Dichloro-ethene	Trichloro-ethene	*cis*-1,2-Dichloro-ethene	Vinyl chloride	Chloroform	Methane	Ethane	Ethene
				micrograms per liter							
17PS-02	5/10/2004	3CV	Top of water column, then lowered to middle of screen interval	<230	13,000	<180	<190	<280	---	---	---
17PS-02	7/21/2005	3CV	Top of water column, then lowered to middle of screen interval	<60	10,300	2,900	<100	77.4J	1,860	2.55J	2.15J
17PS-02	8/23/2005	LF	Middle of screened interval	<85	4,400	5,900	<73	<99	1,600	0.72J	1.1J
17PS-02	8/23/2005	PDB	Top of screened interval	18J	690	4,500	5.8J	8.6J	1,300	0.68J	1J
17PS-02	8/23/2005	PDB	Middle of screened interval #	28.7	2,090BH	8,230H	7.46	8.73	2,300	0.85J	1.5J
17PS-02	8/23/2005	PDB	Bottom of screened interval	<140	2,300	7,400	<120	<160	2,300	0.85J	1.5J
17PS-02	10/13/2005	LF	Middle of screened interval	25.2	9,620	6,630	<10	61.1	---	---	---
17PS-02	2/16/2006	LF	Middle of screened interval	<30	6,720	4,570	422	60.5J	4,300	1	3.1
17PS-02	2/16/2006	PDB	Top of screened interval	<30	5,750	5,010	427	60.7J	---	---	---
17PS-02	2/16/2006	PDB	Bottom of screened interval	<30	802	6,150	1,470	43.1J	4,700	0.97	4.6
17PS-02	5/31/2006	LF	2 feet from bottom of screened interval	<30	9,590	4,230	1,430	84.4J	3,200	<0.4	16
17PS-02	5/31/2006	LF	2 feet from bottom of screened interval	<30	9,710	4,370	1,470	84J	3,000	<0.4	17
17PS-02	5/31/2006	PDB	Top of screened interval	<30	1,480	4,200	3,570	<25	---	---	---
17PS-02	5/31/2006	PDB	Middle of screened interval	<30	31.4J	4,310	3,470	<25	---	---	---
17PS-02	5/31/2006	PDB	Bottom of screened interval	<30	<25	5,040	3,830	<25	---	---	---
17PS-02	6/8/2006	LF	2 feet from bottom of screened interval	<150	705	3,640	3,080	<125	---	---	---
17PS-02	06/21/2006	PDB	Top of screened interval	<15	1,330	3,920	3,590	19.4J	---	---	---
17PS-02	06/21/2006	PDB	Middle of screened interval	<15	454	4,450	4,500	15.6J	---	---	---
17PS-02	06/21/2006	PDB	Bottom of screened interval	<15	330	4,770	4,370	13.3J	---	---	---
17PS-02	08/10/2006	LF	Middle of screened interval	<15	5,980	2,580	2,170	53.2	4,140	<2	54.7
17PS-02	5/23/2007	SP1	Top of water column	<6	6.28J	34.3	1,180	<5.00	10,700	<20	181J
17PS-02 dup	5/23/2007	SP1	Top of water column	<6	6.44J	36.9	1,370	<5.00	9,130	24.6J	232J
17PS-02	8/22/2007	SP1	Top of water column	<3	<0.25	9.4J	793	<2.50	31,800	<200	<200
17PS-02	5/5/2008	LF	Middle of screened interval	<0.3	<0.25	2.11	323	<0.250	9,840	<2.00	36.2
17PS-02R	5/5/2008	LF	Middle of screened interval	<0.3	<0.25	<0.3	276	<0.250	9,520	<2.00	23.7J
17PS-02	8/14/2008	PDB	Middle of screened interval	<0.3	0.42J	<10.8	244	<0.25	23,400	<1,000	<1,000
17PS-02	8/21/2009	LF	Middle of screened interval	3	<5	<5	200	<5	6,800	<30	<30
17PS-02 dup	8/21/2009	LF	Middle of screened interval	<5	<5	<5	240	<5	5,800	<10	<10
17PS-02	8/21/2009	PDB	Middle of screened interval	<5	<5	<5	150	<5	---	---	---
17PS-03	3/9/2005	LF.5CV	Top of the water column	<53	900	18,000	<35	60J	---	---	---
17PS-03	3/9/2005	LF1CV	Top of the water column	<53	3,900	19,000	37J	94J	---	---	---
17PS-03	3/9/2005	LF2CV	Top of the water column	<33	9,100	14,000	34J	110	---	---	---
17PS-03	3/9/2005	LF3CV	Top of the water column	<26	10,000	11,000	33J	110	---	---	---
17PS-03	8/23/2005	LF	Middle of screened interval	19J	32J	10,000	21J	<16	3,500	<0.5	<0.5
17PS-03	8/23/2005	PDB	Middle of screened interval #	21.4	<25H	9,670H	17.2	<0.25	3,400	<0.5	<0.5
17PS-03 dup	8/23/2005	PDB	Middle of screened interval #	29.1	<0.25	12,000H	25.7	<0.25	5,100	<0.5	<0.5
17PS-03	8/23/2005	PDB	Bottom of screened interval	<170	<280	9,100	<150	<200	5,900	<0.5	<0.5
17PS-03	8/23/2005	PDB	Top of screened interval	16J	<23	9,200	22J	<16	5,200	<0.5	<0.5
17PS-03	2/16/2006	LF	Middle of screened interval	<60	10,600	9,920	<100	132J	6,500	0.68	1.1
17PS-03 dup	2/16/2006	LF	Middle of screened interval	<60	10,300	9,650	<100	113J	6,000	0.61	1
17PS-03	2/16/2006	PDB	Middle of screened interval #	<60	589	12,500	<100	78.2J	---	---	---
17PS-03	2/16/2006	PDB	Bottom of screened interval	<60	99.7J	12,100	<100	65.9J	---	---	---
17PS-03 dup	2/16/2006	PDB	Middle of screened interval #	<60	583	12,800	<100	60.6J	---	---	---
17PS-03	2/16/2006	PDB	Top of screened interval	<30	8,850	9,220	<50	104	6,500	0.48	0.96
17PS-03	5/31/2006	LF	2 feet from bottom of screened interval	<30	<25	7,590	1,860	<25	1,000	<0.4	<0.5
17PS-03	6/8/2006	LF	2 feet from bottom of screened interval	<300	<250	6,700	2,720	<250	---	---	---
17PS-03	5/23/2007	SP1	Top of the water column	<6	10.2J	105	1,270	<5.00	6,980	<20	58.1J
17PS-03	8/22/2007	SP1	Top of the water column	<0.6	3.86	25.3	125	<0.500	1,490	<20.0	<20.0
17PS-03	8/14/2008	PDB	Middle of screened interval	<0.3	0.6J	9.44	618	<0.25	24,800	<1,000	<1,000
17PS-03	8/21/2009	LF	Middle of screened interval	<5	<5	<5	270	<5	---	---	---
17PS-03	8/21/2009	PDB	Middle of screened interval	<5	<5	<5	250	<5	---	---	---

Table 4. Selected water-quality parameters in water from wells at Solid Waste Management Unit 17, Naval Weapons Station Charleston, North Charleston, South Carolina, 2004–2007.

[NTU, nephelometric turbidity units; °C, degrees Celsius; SU, standard units; µS/cm, microsiemens per centimeter; LF, sampled by low-flow methodology; ---, data not collected; LF.5CV, sampled after purging one-half casing volumes (1.1 gallons) of water from the screened interval; <, less than; >, greater than; LF1CV, sampled after purging one casing volume (2.2 gallons) of water from the screened interval; LF2CV, sampled after purging two casing volumes (4.4 gallons) of water from the screened interval; LF3CV, sampled after purging three casing volumes (6.6 gallons) of water from the screened interval; 3CV, sampled from the screened interval after purging three casing volumes of water (6.6 gallons) from the top of the water column; 1CV, sampled from the screened interval after purging one casing volume of water (2.2 gallons) from the top of the water column; SP1, sampled after a slow purge with substantial drawdown; DHP, data collected by using a downhole probe]

Well name	Date	Type of sample	Alkalinity	Biochemical oxygen demand	Calcium	Carbon dioxide	Chemical oxygen demand	Chloride	Hydrogen sulfide	Iron, ferrous	Magnesium	Manganese	Oxygen, dissolved	Potassium	Sodium	Sulfate	Acetic acid	Total organic carbon	Turbidity	Temperature	pH	Specific conductance
			milligrams per liter																NTU	°C	SU	µS/cm
17MW-06S	3/9/2005	LF.5CV	---	<2	---	---	48.2	---	---	4.7	---	---	0.3	---	---	---	---	---	---	15.34	5.6	1,232
17MW-06S	3/9/2005	LF1CV	---	<2	---	---	46.2	---	---	6.7	---	---	0.27	---	---	---	---	---	---	15.51	5.6	1,241
17MW-06S	3/9/2005	LF2CV	---	<2	---	400	40	---	---	7.6	---	---	0.29	---	---	---	---	---	---	15.58	6.2	---
17MW-06S	3/9/2005	LF3CV	---	<2	---	---	48.2	---	---	7.5	---	---	0.21	---	---	---	---	---	---	15.56	6.2	---
17MW-06S	8/23/2005	LF	---	---	67	---	---	270	---	---	10	0.16	---	2.9	120	33	<0.7	17	---	24.6	7.3	1,156
17MW-06S	5/23/2007	LF	---	---	0	---	---	373	---	---	---	---	---	---	---	61.8	---	<5.0	---	20.9	5.8	1,520
17MW-06S	7/17/2007	LF	---	---	0	---	---	606	---	---	---	---	---	---	---	34.8	0.38	29	---	23.4	5.5	2,176
17MW-06S	8/22/2007	3CV	---	---	---	---	---	593	---	---	---	---	---	---	---	44.9	0.19	<5	---	---	---	---
17MW-06S	5/5/2008	LF	<15	---	---	275	---	868	0.2	38	---	---	0.025	---	---	39.5	---	---	---	19.85	5.6	3,220
17MW-06S	7/21/2009	LF	<10	---	---	255	---	1,100	0.1	46	46	0.59	<0.025	---	---	80	---	2.7	---	21.9	5.3	3614
17MW-07S	5/10/2004	3CV	40	---	---	120	---	---	0.1	12	---	---	---	---	---	---	---	---	---	---	---	---
17MW-07S	7/21/2005	1CV	---	---	---	---	---	---	---	---	---	---	<0.05	---	---	---	---	---	---	24.48	5.4	850
17MW-07S	7/21/2005	3CV	---	---	---	---	---	---	---	---	---	---	<0.05	---	---	31.4	<0.7	<5	---	22.41	5.4	861
17MW-07S	8/23/2005	LF	115	---	40	---	---	150	<0.05	36	6.4	0.09	---	2.7	100	32	<0.7	11	---	21.53	5.8	883
17MW-07S	2/16/2006	LF	---	---	---	---	---	---	<0.05	6.5	---	---	0.15	---	---	34	---	---	49.1	---	5.6	765
17MW-07S	5/31/2006	LF	22	---	36	140	---	160	<0.05	10	7	68	0.4	1.4	92	34	<0.07	5.6	---	20.7	5.5	826
17MW-07S	5/23/2007	LF	---	---	---	---	---	338	---	---	---	---	---	---	---	29.6	---	<5	---	20.87	5.5	1,413
17MW-07S	7/17/2007	LF	---	---	---	---	---	356	---	---	---	---	---	---	---	44.1	0.24	<5	---	22.0	6.0	4,675
17MW-07S	8/22/2007	3CV	---	---	---	---	---	537	---	---	---	---	---	---	---	71.8	0.26	<5	---	---	---	---
17MW-07S	5/5/2008	LF	<15	---	---	200	---	871	0.3	63	---	---	<0.025	---	---	39.7	---	---	---	19.76	5.7	3,262
17MW-07S	7/21/2009	LF	<10	---	---	80	---	1,400	0.16	>50	62	0.61	<0.025	---	---	180	---	2.2	---	22.38	5.7	4,458
17PS-01	5/10/2004	3CV	20	---	---	255	---	---	<0.2	100	---	---	<0.05	---	---	---	---	---	---	---	---	---
17PS-01	7/21/2005	1CV	---	---	---	---	---	---	---	---	---	---	<0.05	---	---	---	---	---	---	22.43	5.3	4,530
17PS-01	7/21/2005	3CV	---	---	---	---	---	---	---	---	---	---	<0.05	---	---	33.5	0.378	12	---	22.44	5.2	4,500
17PS-01	8/23/2005	LF	78	---	200	450	---	1,300	0.2	367	51	0.56	---	3.8	420	35	<0.7	6	---	24.17	5.6	4,470
17PS-01	2/16/2006	LF	---	---	---	---	---	---	1	>250	---	---	0.04	---	---	50	---	---	21.7	---	5.4	4,403
17PS-01	5/31/2006	LF	125.0	---	230	600	---	1,300	0.5	225	50	0.61	<0.025	3.1	420	37	0.77	6.6	1.7	19.3	5.8	4,618
17PS-01	8/10/2006	LF	170	---	---	550	---	---	0.6	---	---	---	0.05	---	---	---	---	<5	---	27.82	5.7	4,458
17PS-01	5/23/2007	SP1	1,000	---	---	180	---	1,430	<0.05	>50	---	---	0.16	---	---	<0.1	---	1,100	---	23.2	6.7	6,839
17PS-01	7/18/2007	SP1	---	---	---	---	---	---	---	---	---	---	---	---	---	---	830	600	---	---	---	---
17PS-01	8/22/2007	SP2	---	---	---	---	---	1,500	---	---	---	---	---	---	---	0.906	630	570	---	---	---	---
17PS-01	7/21/2009	LF	1,000	---	---	300.0	---	2,200	0.2	>125	420	0.25	0.1	---	---	3.4	---	81	---	21.7	7.1	8,537

Table 4. Selected water-quality parameters in water from wells at Solid Waste Management Unit 17, Naval Weapons Station Charleston, North Charleston, South Carolina, 2004–2007.—Continued

[NTU, nephelometric turbidity units; ºC, degrees Celsius; SU, standard units; µS/cm, microsiemens per centimeter; LF, sampled by low-flow methodology; ---, data not collected; LF.5CV, sampled after purging one-half casing volumes (1.1 gallons) of water from the screened interval; <, less than; >, greater than; LF1CV, sampled after purging one casing volume (2.2 gallons) of water from the screened interval; LF2CV, sampled after purging two casing volumes (4.4 gallons) of water from the screened interval; LF3CV, sampled after purging three casing volumes (6.6 gallons) of water from the screened interval; 3CV, sampled from the screened interval after purging three casing volumes of water (6.6 gallons) from the top of the water column; 1CV, sampled from the screened interval after purging one casing volume of water (2.2 gallons) from the top of the water column; SP1, sampled after a slow purge with substantial drawdown; DHP, data collected by using a downhole probe]

Well name	Date	Type of sample	Alkalinity	Biochemical oxygen demand	Calcium	Carbon dioxide	Chemical oxygen demand	Chloride	Hydrogen sulfide	Iron, ferrous	Magnesium	Manganese	Oxygen, dissolved	Potassium	Sodium	Sulfate	Acetic acid	Total organic carbon	Turbidity	Temperature	pH	Specific conductance
			milligrams per liter																NTU	°C	SU	µS/cm
17PS-02	5/10/2004	3CV	30	---	---	225	---	---	0.1	100	---	---	<0.05	---	---	---	---	---	---	---	---	---
17PS-02	7/21/2005	3CV	---	---	---	---	---	---	---	---	---	---	<0.05	---	---	34.5	0.478	11	---	21.02	5.1	4,450
17PS-02	8/23/2005	LF	80	---	260	470	---	1,300	0.3	360	50	0.67	<0.05	3.7	390	26	<0.7	8.7	---	23.08	5.9	4,280
17PS-02	9/12/2005	DHP	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	6.0	---
17PS-02	10/13/2005	LF	---	---	---	---	---	---	---	---	---	---	0.64	---	---	---	---	---	---	21.2	5.8	4,181
17PS-02	2/16/2006	LF	---	---	---	---	---	---	0.4	>250	---	---	<0.025	---	---	49	---	---	27.3	---	5.7	4,695
17PS-02	5/31/2006	LF	115	---	220	550	---	1,200	0.7	175	50	0.55	0.05	3.1	390	26	3.8	27	57.9	20.4	5.7	4,345
17PS-02	6/8/2006	LF	---	---	---	---	---	0	---	---	---	---	---	---	---	---	---	---	---	23.1	5.9	4,280
17PS-02	08/10/2006	LF	225	---	---	450	---	0	0.5	---	---	---	<0.05	---	---	---	---	---	---	23.68	6.1	4,495
17PS-02	5/23/2007	SP1	500	---	---	230	---	758	<0.05	---	---	---	0.05	---	---	0.454	---	1,900	---	---	---	---
17PS-02 Dup	5/23/2007	SP1	---	---	---	---	---	788	---	---	---	---	---	---	---	0.413	---	1,700	---	---	---	---
17PS-02	7/18/2007	SP1	---	---	---	---	---	0	---	---	---	---	---	---	---	---	3,300	910	---	---	---	---
17PS-02	8/22/2007	SP1	---	---	---	---	---	544	---	---	---	---	---	---	---	0.535	880	690	---	---	---	---
17PS-02	5/5/2008	LF	>1,000	---	---	325	---	762	0.3	87	---	---	0.15	---	---	0.34J	---	---	---	22.07	6.9	5,185
17PS-02 Dup	5/5/2008	LF	---	---	---	---	---	749	---	---	---	---	---	---	---	0.32J	---	---	---	---	---	---
17PS-02	7/21/2009	LF	500	---	---	200	---	1,100	0.61	21.62	740	0.18	0.2	---	---	<1	---	120	---	21.52	7.1	7,227
17PS-03	5/10/2004	3CV	20	---	---	70	---	---	0.3	75	---	---	<0.05	---	---	---	---	---	---	---	---	---
17PS-03	3/9/2005	LF.5CV	---	46.3	---	---	144	---	---	---	---	---	0.31	---	---	---	---	---	---	14.56	5.6	4,550
17PS-03	3/9/2005	LF1CV	---	35.4	---	---	140	---	---	---	---	---	0.24	---	---	---	---	---	---	14.91	5.6	4,290
17PS-03	3/9/2005	LF2CV	---	51.1	---	---	128	---	---	---	---	---	0.25	---	---	---	---	---	---	15.17	5.5	4,170
17PS-03	3/9/2005	LF3CV	110	29.2	---	400	132	---	0.25	---	---	---	0.16	---	---	---	---	---	---	15.31	5.5	4,210
17PS-03	8/23/2005	LF	170	---	270	500	---	1,300	0.1	192	49	0.65	0.12	3.6	400	<2.5	92	36	0.8	23.68	5.8	4,750
17PS-03	2/16/2006	LF	---	---	---	---	---	---	1.5	175	---	---	<0.025	---	---	9.5	---	---	17	15.98	5.6	3,103
17PS-03	5/31/2006	LF	260	---	270	550	---	1,300	0.1	250	49	0.65	0.5	3.3	420	<2.5	11	15	14.9	20.15	5.9	4,665
17PS-03	6/8/2008	LF	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	24.56	7.4	4,290
17PS-03	5/23/2007	SP1	>1,000	---	---	<10	---	1,110	<0.05	2	---	---	0.6	---	---	0.864	---	6,500	---	---	---	---
17PS-03	7/18/2007	SP1	---	---	---	---	---	---	---	---	---	---	---	---	---	---	5,200	19,000	---	---	---	---
17PS-03	7/21/2009	LF	950	---	---	400	---	1,100	0.25	18	860	0.2	0.1	---	---	<1	---	310	---	22.8	7.2	8,298

May 2006; table 4). The redox heterogeneity probably is the result of irregular distribution of the injectate, which was most concentrated near the injection wells and apparently much less concentrated near wells 17PS-01 and 17PS-02.

Unlike in wells 17PS-01 and 17PS-02, the sulfate concentrations in well 17PS-03 rapidly declined following the Phase-I injection. Pre-injection sampling by Solutions-IES detected 77.5 mg/L of sulfate in groundwater at well 17PS-03 (Lieberman and Borden, in press). Subsequent sampling during the present and the ESTCP investigation show that sulfate concentrations in water from well 17PS-03 declined to less than 2.5 mg/L. This is probably caused by heterogeneous distribution of injectate, resulting in more substrate and more rapid depletion of efficient electron acceptors at well 17PS-03 than at wells 17PS-01 and 17PS-02. The TOC concentration a few months after the Phase-I injection was somewhat higher at well 17PS-03 (84.5 mg/L) than at wells 17PS-01 (62.7 mg/L) and 17PS-02 (62.9 mg/L; Lieberman and Borden, in press). Thus, TEAP conditions at well 17PS-03 probably became more reducing than at wells 17PS-01 and 17PS-02 within months after the injection.

A marked difference in redox was apparent following the Phase-II injection relative to the Phase-I injection. During the Phase-II injection, the injectate was more efficiently distributed and injected in larger quantity than during the Phase-I injection (Lieberman and Borden, in press). Following the Phase-II injection in September and October 2006, sulfate concentrations declined to less than 1 mg/L in wells 17PS-01 and 17PS-02. The data indicate a probable shift to methanogenesis in the aquifer at wells 17PS-01 and 17PS-02.

Groundwater and In-Well pH

The pH of the groundwater can be an important influence on microbial reduction of chlorinated solvents. Although reductive dechlorination of chlorinated solvents in a low-pH environment (2–4 range) has been reported in a Fenton's reagent treatment area (Bradley and others, 2007), the more common observation is that microbial reductive dechlorination substantially decreases with decreasing pH below neutral and with maximum chlorinated-solvent dechlorination rates between pH values of about 6.8 to 7.6 (Holliger and others, 1993; Zhuang and Pavlostathis, 1995; Wiedemeier and others, 1996; Cirpka and others, 1999; Fennell and Gossett, 2003). One study showed that although *Dehalococcoides* sp. were inhibited from dechlorination activity in an aquifer having a pH of about 4.0, they were not killed by the low pH and could reactivate after a suitable pH was established (Dennis and others, 2008).

Ambient pH

Data from multiple depths in monitoring wells 17MW-06S and 17MW-07S indicate that the pH in the wells outside the injection area show a seasonal variation in vertical gradient. A strong vertical gradient was present in well 17NW-06S in May 2006, with lower pH values near the top of the well than at the bottom of the well. The pH in well 17MW-06S was 5.2 to 5.6 near the top of the 10-ft well screen and about 6.3 at the bottom of the well screen in May 2006 (fig. 12*A*). Data loggers in the top and bottom parts of the screened intervals of well 17MW-07S detected a similar pH gradient, with a pH of 5.76 near the top part of the 10-ft screened interval and 6.34 near the bottom part of the screened interval in October 2005 (data not shown). The warm water at the top of the well relative to the bottom of the well during the summer limited the amount of thermally induced mixing in the well (fig. 12*B*). Thus, the data indicate a downward increase in pH in the aquifer outside of the injection area.

In the winter, however, cooler water at the top of the well relative to the bottom of the well initiates in-well convection. At the Naval Weapons Station Charleston, thermal convection continues through mid-March (Vroblesky and others, 2007) and sometimes extends into April or May (unpublished data available at the USGS South Carolina Water Science Center). Wells 17MW-06S and 17MW-07S are screened across the same interval and are approximately 20 ft apart, indicating that they are subject to the same temperature-induced effects. A vertical profile of well 17MW-07S in the winter shows that the shallow water in the well was more than 2 °C cooler at the top of the well than at the bottom of the well, indicating that convection was occurring in the wells. The convection eliminated the pH gradient and produced uniform pH values of approximately 5.6 standard units in well 17MW-07S (fig. 12*A*). Continuous data loggers in the top and bottom of the screened interval of well 17MW-07S showed that during 2005, the pH gradient in the well disappeared in early December after the shallow water became cooler than the deeper water. It is likely that the convection is an in-well process rather than an aquifer process. Thus, during winter months, static measurements of pH in wells at the site with no flow-limiting devices probably do not represent pH stratification in the adjacent aquifer.

The pH of groundwater in the injection area was less variable with depth. Data loggers deployed in well 17PS-02 showed that in the thermally stable part of late May 2006, the pH was about 5.9 in the bottom part of the 10-ft screened interval and about 6.0 in the top part of the screened interval (fig. 13). In early June 2006, the pH in well 17PS-02 ranged from about 6.0 near the bottom of the screened interval to about 5.9 at the top of the screened interval. Data collected by the Solutions-IES showed that the pH at the injection wells from September 2004 to May 2005 ranged from about 4.0 to 5.2 (Robert Borden, North Carolina State University, written commun., 2006).

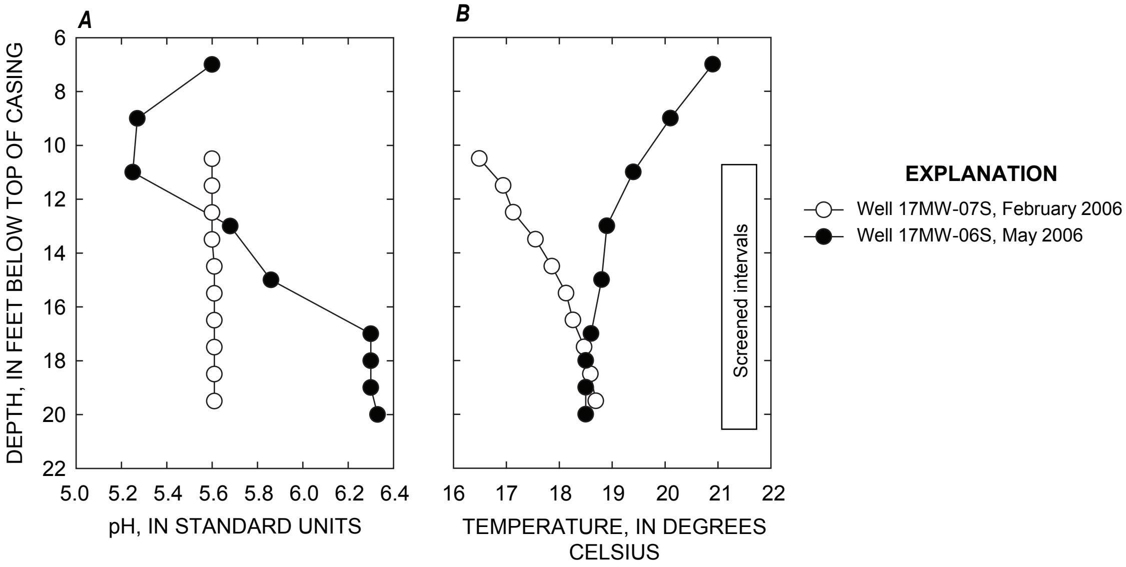


Figure 12. Seasonal differences in the (*A*) pH and (*B*) temperature profiles in monitoring wells at Solid Waste Management Unit 17, Naval Weapons Station Charleston, North Charleston, South Carolina, February and May 2006.

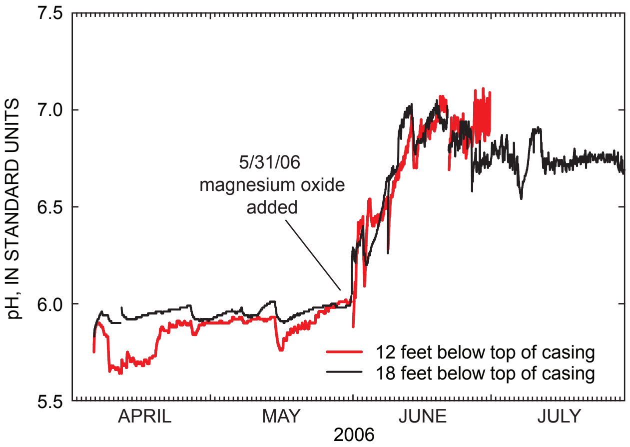


Figure 13. Changes in pH in the screened interval of well 17PS-02 following deployment of magnesium oxide, Solid Waste Management Unit 17, Naval Weapons Station Charleston, North Charleston, South Carolina, April through July 2006.

Results of pH-Adjustment Tests

The pH-adjustment tests at SWMU17 showed that a variety of media were capable of raising the pH in jars of pH-adjusted tap water and well water. Sodium hydroxide (41grams in a liter of water) raised the pH of tap water from 4.9 to 6.5 in an hour. A solidified cylinder of well grout (type 1 Portland cement) raised the pH of tap water from 5.0 to 11.7 after about 8 hours. A container of commercial pH-adjustment media for swimming pools (Poolife™) raised the pH of tap water from 4.6 to 11.3 and raised the pH of well water from well 17PS-01 from 5.6 to 10.6 in 30 minutes. The pH of groundwater from well 17PS-02 showed a slight increase from 5.6 to 5.9 during the 2.5 hours of observation when a bag of granular magnesium oxide was added. When granular calcite was added to the test jar containing groundwater, little or no change in pH (5.6 to 5.8) was observed relative to the control test jar (5.6 to 5.8) during the 2.5-hour test, presumably because of the comparatively low dissolution rate.

Jar studies showed that the pH of well water from well 17PS-01 in a jar containing a bag of commercial pH-adjustment media for swimming pools increased from 5.8 in the unamended control jar to 10.9 in the test jar. Despite the effectiveness of the pH adjustment, the commercial pH-adjustment media were not deployed in wells at SWMU17 because of concern that the rapid dissolution of the media and the rapid pH shift could produce a short-lived pH extreme that would be harmful to the native microbial populations and would not last long enough to allow the microbial community to acclimate. It is interesting, however, that the substantial pH increase from the commercial pH-adjustment media resulted in production of black precipitate from the well water in the jar with the commercial pH-adjustment media. The black precipitate was not observed in jars containing well water in which the pH was not adjusted or in which the pH adjustment was more subdued than in the jar with the commercial pH-adjustment media.

In-well experiments involving deployment of pH-adjustment media began in September 2005, with calcite-magnesium oxide deployment beginning in October 2005 (table 1). Down-hole pH data are not available during the initial deployment of calcite-magnesium oxide because of problems with the data logger. It is clear, however, that the deployment substantially increased in-well pH values because the black precipitate that was observed as a result of the substantial pH increase in jar studies also was observed on the calcite-magnesium oxide bags deployed in well 17PS-02 and recovered on November 3, 2008. Furthermore, down-hole pH values from a later deployment of magnesium oxide in the same well showed a substantial pH increase in June 2006 (fig. 13). Comparison of the sharp pH increase in June 2006 in well 17PS-02 after deployment of magnesium oxide further indicates that the October to November 2005 deployment of calcite-magnesium oxide increased the in-well pH to near neutral values.

The data indicate that the pH in well 17PS-02 increased during a series of in-well deployments of alkaline material. The increases probably began in late October 2005. Because these in-well tests did not involve injection of substrate into the aquifer, the direct influence of the pH adjustment probably did not extend far beyond the immediate vicinity of the screened interval.

Contributing Factors Affecting the Stall in Dechlorination Activity Following the Phase-I Emulsified Vegetable-Oil Injection

The Phase-I injection of emulsified vegetable oil resulted in dechlorination of TCE to *c*DCE, but the dechlorination activity appeared to stall at *c*DCE, with little further dechlorination of *c*DCE to VC or to ethene (Borden and others, 2008; Lieberman and Borden, in press). The initial dechlorination activity is consistent with other studies that found reductive dechlorination of TCE to *c*DCE to be common at sites where conditions are at least sulfate-reducing (Bradley, 2003). A variety of factors can contribute to the lack of continued dechlorination to VC and ethene. The primary factors are the lack of bacteria capable of efficient dechlorination of *c*DCE to ethene and insufficient electron donors to achieve strongly reducing conditions. In addition, conditions need to be within an acceptable range for pH, temperature, and moisture, and sufficient nutrients need to be present (Looney and Vangelas, 2004). In some cases, the lack of apparent VC and ethene accumulation may be due to anaerobic oxidation of VC and ethene (Bradley and Chapelle, 1996).

The cause of the stall in reductive dechlorination following the Phase-I injection at SWMU17 does not appear to be a lack of bacteria capable of efficient dechlorination. Molecular analysis as part of this investigation showed the presence of *Dehalococcoides* sp. and BVC, which is VC reductase associated with *Dehalococcoides* sp. strain BAV1 (table 5). The presence of members of the *Dehalococcoides* group is related to completed dechlorination (Hendrickson and others, 2002; Cupples and others, 2003; He and others, 2003a, b). Strain BAV1 grows using all DCE isomers and VC as electron acceptors and cometabolizes PCE and TCE, efficiently converting these compounds to ethene and inorganic chloride (He and others, 2003b).

One major factor likely affecting the dechlorination stall in the months following the Phase-I injection was the low pH values in the aquifer. Following the 2004 injection, the groundwater pH in parts of the injection zone declined to about 5.0 (Borden and others, 2008). The groundwater pH was below the optimum range for microbial dehalogenation of chlorinated ethenes, which is 6.8 to 7.6 (Holliger and others, 1993; Zhuang and Pavlostathis, 1995; Wiedemeier and others, 1996; Cirpka and others, 1999; Fennell and Gossett, 2003). Loading an aquifer with readily degradable organic substrate, such as vegetable oil, can result in a buildup of low molecular-weight organic acids, such as acetate, which can lower the pH in a poorly buffered aquifer. Acetic acid concentrations greater than 1 mg/L were detected in water from the injection-zone monitoring wells on some occasions during 2005–2006, but not in water from nearby wells outside of the injection zone (table 4). The accumulation of organic acids may be related to acid production by fermenting bacteria at a rate faster than the acids can be consumed by methanogens, or to methanogens using the carbon dioxide reduction pathway instead of the acetotrophic pathway (Bradley and others, 1993; McMahon and others, 1995).

A second major factor likely affecting the dechlorination stall in the months following the Phase-I injection was the heterogeneous distribution of injected substrate. The heterogeneous distribution can be seen in the substantially higher TOC concentrations in groundwater from the injection wells (usually greater than 500 mg/L; Lieberman and Borden, in press) relative to concentrations in groundwater from the monitoring wells 17PS-01 and 17PS-02 in the injection zone. Data from Lieberman and Borden (in press) found that TOC in wells 17PS-01 and 17PS-02 ranged from less than 5 to 62.9 mg/L. This investigation found a range of TOC concentrations for wells 17PS-01 and 17PS-02 from about 6 to 12 mg/L during July and August 2005. In areas receiving relatively low amounts of injectate, such as at wells 17PS-01 and 17PS-02, the rate of microbial activity apparently was insufficient to remove the sulfate (table 4), indicating a persistence of iron or sulfate reduction. Groundwater from the wells in the injection zone contained less than 100 µg/L of methane prior to November 2004 and increasing amounts of methane in subsequent samplings (Lieberman and Borden, in press). Thus, in areas receiving substantially more injectate, such as near the injection wells, the amount of electron donor was sufficient to allow microbial removal of ferric iron and sulfate, eventually resulting in methanogenic conditions.

In injection wells 17PSI-02, 17PSI-07, 17PSI-10, and 17PSI-13, the VC concentrations changed from less than 5 µg/L to about 10 to 40 µg/L during about November 2004 to May 2005 (Lieberman and Borden, in press). Thus, some low level of VC production was initiated at the injection wells

Table 5. Molecular analysis of phylogenic groups and functional genes in water and sediment filtrate pumped from monitoring wells, Solid Waste Management Unit 17, Naval Weapons Station Charleston, North Charleston, South Carolina, 2005–2007.

[DNA, deoxyribonucleic acid; RNA, ribonucleic acid; 16SrRNA, 16S ribosomal RNA; mRNA, messenger RNA; BVC, vinyl chloride reductase associated with *Dehalococcoides* sp. strain BAV1; DSR, sulfate-reducing bacteria; sMMO, methane monooxygenase; TCE R-Dase, trichloroethene reductase; VC R-Dase, vinyl chloride reductase; LF.5CV, sampled after purging one-half casing volume (1.1 gallons) of water from the screened interval; c/mL, cells per milliliter; <, less than; ---, data not collected; gc/mL, gene copies per milliliter; gc/b, gene copies per bead; gc/g, gene copies per gram; c/g, cells per gram; LF2CV, sampled after purging two casing volumes (4.4 gallons) of water from the screened interval; LF3CV, sampled after purging three casing volumes (6.6 gallons) of water from the screened interval; NP, sample was the first water pumped from in the screened interval of the well; LF, sampled by low-flow methodology; c/mL, cells per milliliter; BT, biotrap obtained from Microseeps, Inc.; c/b, cells per bead; 1CV, sampled from the screened interval after purging one casing volume of water (2.2 gallons) from the top of the water column; 3CV, sampled from the screened interval after purging three casing volumes of water (6.6 gallons) from the top of the water column; sed, sediment obtained from the well sump by pumping; (J), estimated value; SP1, sampled after a slow purge with substantial drawdown; LF1CV, sampled after purging one casing volume (2.2 gallons) of water from the screened interval]

						Phylogenic groups										Functional genes						
						DNA or 16SrRNA										DNA or mRNA						
Well name	Date	DNA or RNA	Type of sample	Preservation medium	Units	Eubacteria (*qEBAC*)	*Dehalobacter* sp. (*qDHB*)	*Dehalococcoides* sp. (*qDHC*)	Methanogenic bacteria (*qMGN*)	*Desulfuromonas* sp. (*qDSM*)	*Geobacter* sp.	Methanotrophic bacteria (*qMOB*)	Type 1 Methanotrophic bacteria (*qMOB1*)	Type 2 Methanotrophic bacteria (*qMOB2*)	Iron-reducing and sulfate-reducing bacteria	BVC	DSR	sMMO	TCE R-Dase	VC R-Dase	Volume filtered, in milliliters	Percent recovery
17MW-06S	3/9/2005	DNA	LF.5CV	ice	c/mL	4.94E+06	6.45E+03	<5E-01	4.74E+03	<1.00E+00	<7.5E-01	1.98E+06	1.98E+06	1.68E+04	2.39E+00	---	---	1.48E+05	<5E-01	<5E-01	---	---
17MW-06S	3/9/2005	DNA	LF2CV	ice	c/mL	3.69E+05	1.16E+04	<5E-01	2.30E+04	<1.00E+00	5.70E+01	1.85E+06	1.85E+06	1.05E+03	2.41E+01	---	---	8.03E+04	<5E-01	<5E-01	---	---
17MW-06S	3/9/2005	DNA	LF3CV	ice	c/mL	3.63E+06	1.62E+04	1.90E+01	5.69E+00	<1.00E+00	5.00E+01	2.01E+06	1.94E+06	7.40E+04	2.41E+01	---	---	6.42E+04	1.76E+01	1.09E+01	---	---
17MW-06S	8/23/2005	RNA	NP	RNAlater®	gc/mL	1.78E+06	---	1.91E+01	---	---	---	4.29E+02	---	4.29E+02	---	---	1.07E+06	1.11E+03	---	---	240	---
17MW-06S	8/23/2005	RNA	LF	RNAlater®	gc/mL	1.21E+05	---	---	---	---	---	1.47E+02	---	1.47E+02	---	---	2.23E+05	2.82E+01	---	---	1,000	---
17MW-06S	8/23/2005	RNA	BT	ice	gc/b	3.19E+06	---	1.09E+01	---	---	---	2.10E+03	1.81E+03	2.94E+02	---	---	2.93E+05	1.68E+03	---	---	90	---
17MW-07S	7/21/2005	RNA	1CV	dry ice	gc/mL	1.80E+04	---	4.96E+00	6.45E+04	---	---	---	---	---	---	5.16E-01	---	5.80E+02	---	---	2,000	---
17MW-07S	7/21/2005	RNA	1CV	ice	gc/mL	2.46E+04	---	1.53E+01	<1.00E+00	---	---	---	---	---	---	1.76E+00	---	8.82E+02	---	---	2,000	---
17MW-07S	7/21/2005	RNA	1CV	RNAlater®	gc/mL	9.18E+04	---	1.05E+05	8.29E+04	1.68E+06	---	---	---	---	1.39E+06	3.62E+04	---	4.00E+01	---	---	2,000	---
17MW-07S	7/21/2005	RNA	3CV	dry ice	gc/mL	3.12E+03	---	---	9.78E+05	---	---	---	---	---	---	---	---	3.04E+02	---	---	2,000	---
17MW-07S	7/21/2005	RNA	3CV	ice	gc/mL	1.14E+03	---	---	---	---	---	---	---	---	---	---	---	2.83E+03	---	---	2,000	---
17MW-07S	7/21/2005	RNA	3CV	RNAlater®	gc/mL	1.79E+03	---	5.02E+01	2.44E+04	1.12E+03	---	---	---	---	---	---	---	1.71E+02	---	1.52E+00	2,000	---
17MW-07S	7/21/2005	RNA	3CV	RNAlater®	gc/mL	4.42E+05	---	1.62E+00	2.37E+05	---	---	---	---	---	6.12E+02	---	---	1.54E+02	---	---	5,000	---
17MW-07S	8/23/2005	RNA	BT	RNAlater®	gc/b	2.37E+06	---	1.94E+02	---	9.81E+02	---	2.36E+03	1.67E+03	6.83E+02	---	---	---	---	---	---	80	---
17MW-07S	8/23/2005	RNA	LF	RNAlater®	gc/mL	5.73E+05	---	1.93E+03	---	3.86E+02	---	4.85E+02	---	4.85E+02	---	---	---	---	---	---	1,000	---
17MW-07S	8/23/2005	RNA	NP	RNAlater®	gc/mL	7.75E+05	---	7.52E+03	---	9.07E+02	---	5.91E+02	---	5.91E+02	---	---	---	---	---	---	240	---
17MW-07S	2/16/2006	DNA	LF	ice	c/mL	5.74E+05	2.55E+03	1.38E+00	5.53E+03	---	6.02E+00	---	---	---	2.79E+00	4.55E+00	1.57E+05	---	3.36E+00	<5E-01	1,000	79.76
17MW-07S	2/16/2006	RNA	LF	RNAlater®	gc/mL	1.47E+06	<1E+00	3.38E+02	2.17E+02	---	1.21E+02	---	---	---	7.26E+01	6.04E-01	<1E+00	---	9.55E+00	<5E-01	1,000	45.31
17MW-07S	2/16/2006	DNA	3CV	ice	c/mL	4.41E+05	1.11E+03	2.58E+00	3.17E+03	---	6.65E+00	---	---	---	7.67E+00	4.00E-02 (J)	8.39E+04	---	6.06E-01	<5E-01	1,000	77.38
17MW-07S	2/16/2006	RNA	3CV	RNAlater®	gc/mL	1.27E+04	<1E+00	1.95E+00	<1E+00	---	3.45E+01	---	---	---	6.36E+01	<5E-01	<1E+00	---	3.04E+01	<5E-01	1,000	88.1
17MW-07S	2/15/2006	DNA	BT	ice	c/b	4.67E+05	3.06E+04	1.00E+02	3.36E+05	---	1.06E+04	---	---	---	1.36E+04	1.48E+01 (J)	4.20E+06	---	2.45E+01 (J)	<2.5E+01	20	92.29
17MW-07S	2/15/2006	RNA	BT	RNAlater®	gc/b	2.69E+05	1.70E+02	3.12E+01	<2.13E+01	---	<1.6E+01	---	---	---	<1.6E+01	2.57E+01	7.53E+03	---	4.78E+02	<1.06E+01	47	51.92
17MW-07S	2/15/2006	DNA	Sed	ice	c/mL	4.41E+07	1.80E+05	2.09E+02	4.55E+05	---	6.22E+02	---	---	---	4.44E+03	<5E+01	4.79E+06	---	3.6E+01 (J)	<5E+01	10	71.9
17MW-07S	2/15/2006	RNA	Sed	RNAlater®	gc/mL	5.47E+08	3.40E+02	1.94E+02	6.11E+04	---	<7.5E+01	---	---	---	<7.5E+01	4.89E+01 (J)	3.24E+04	---	3.26E+03	<5E+01	10	98.55
17MW-07S	2/16/2006	DNA	Sed	ice	c/mL	1.28E+07	5.44E+04	1.07E+03	1.75E+04	---	8.27E+01	---	---	---	3.13E+02	4.24E+00 (J)	4.66E+05	---	8.09E+02	<5E+01	10	59.94
17MW-07S	2/16/2006	RNA	Sed	RNAlater®	gc/mL	1.21E+06	6.28E+02	1.04E+02	<1E+02	---	<7.5E+01	---	---	---	<7.5E+01	3.62E+00 (J)	4.40E+04	---	1.59E+03	<5E+01	10	46.04
17MW-07S	5/31/2006	DNA	Sed	ice	c/g	5.31E+06	<1E+03	1.67E+03	---	---	---	---	---	---	---	1.2E+02 (J)	---	---	<5E+02	<5E+02	---	---
17MW-07S	5/31/2006	RNA	Sed	RNAlater®	gc/g	1.13E+07	<1E+03	<5E+02	---	---	---	---	---	---	---	<5E+02	---	---	<5E+02	<5E+02	---	---
17MW-07S	6/21/2006	DNA	Sed	ice	c/mL	4.36E+10	4.22E+06	6.70E+05	---	---	---	---	---	---	7.79E+07	<3.33E+04	3.75E+07	---	5.64E+01 (J)	<3.33E+04	---	82.31
17MW-07S	6/21/2006	RNA	Sed	RNAlater®	gc/g	1.09E+07	2.48E+04	<4.55+03	---	---	---	---	---	---	1.80E+04	<4.55+03	6.81E+02 (J)	---	<4.55+03	<4.55+03	---	---
17MW-07S	6/21/2006	RNA	Sed	RNAlater®	gc/g	5.27E+06	1.21E+04	<2.38+03	---	---	---	---	---	---	2.31E+04	<2.38+03	2.17E+02 (J)	---	<2.38+03	<2.38+03	---	---
17MW-07S	8/10/2006	RNA	NP	RNAlater®	gc/mL	2.14E+04	3.66E+01	1.75E+00	---	---	---	---	---	---	---	5.00E-01	---	---	5.00E-01	5.00E-01	1,000	66.73
17MW-07S	8/10/2006	DNA	NP	ice	c/mL	2.54E+06	5.23E+04	1.51E+02	---	---	---	---	---	---	---	5.00E-01	---	---	4.56E+01 (J)	9.71E+00	1,000	91.84
17PS-01	7/21/2005	RNA	1CV	dry ice	gc/mL	4.28E+03	---	2.46E+00	1.38E+05	1.11E+00	---	---	---	---	---	---	---	1.80E+02	---	---	1,500	---
17PS-01	7/21/2005	RNA	1CV	ice	gc/mL	6.02E+03	---	---	---	---	---	---	---	---	---	---	---	3.99E+02	---	---	1,500	---
17PS-01	7/21/2005	RNA	1CV	RNAlater®	gc/mL	1.23E+06	---	1.45E+01	4.33E+05	---	---	---	---	---	---	---	---	2.32E+02	---	---	1,500	---
17PS-01	7/21/2005	RNA	3CV	dry ice	gc/mL	8.83E+03	---	---	9.41E+05	---	---	---	---	---	---	---	---	1.13E+03	---	---	2,000	---
17PS-01	7/21/2005	RNA	3CV	ice	gc/mL	9.40E+03	---	---	2.14E+04	---	---	---	---	---	---	---	---	4.32E+02	---	---	3,200	---
17PS-01	7/21/2005	RNA	3CV	RNAlater®	gc/mL	4.72E+06	---	9.30E+00	3.71E+07	1.36E+02	---	---	---	---	---	---	---	2.29E+02	---	2.80E+01	2,000	---
17PS-01	7/21/2005	RNA	3CV	RNAlater®	gc/mL	5.16E+06	---	2.12E+01	2.06E+06	8.14E+05	---	---	---	---	5.63E+07	8.32E+02	---	1.68E+03	---	2.95E+00	5,000	---
17PS-01	8/23/2005	RNA	LF	RNAlater®	gc/mL	3.38E+06	---	1.52E+03	---	---	---	---	---	---	---	---	---	1.75E+02	---	---	1,000	---
17PS-01	8/23/2005	RNA	NP	RNAlater®	gc/mL	1.46E+06	---	3.21E+03	---	---	---	2.01E+01	---	2.01E+01	---	---	---	---	---	---	240	---
17PS-01	2/16/2006	DNA	BT	ice	c/b	9.89E+06	<5E+01	163	<5E+01	---	<3.75E+01	---	---	---	<3.75E+01	<2.5E+01	<5E+01	---	1.1E+01 (J)	<2.5E+01	20	68.93
17PS-01	2/16/2006	RNA	BT	RNAlater®	gc/b	7.86E+06	<1.64E+01	<8.2E+00	<1.64E+01	---	<1.23E+01	---	---	---	<1.23E+01	<8.2E+00	<1.64E+01	---	<8.2E+00	<8.2E+00	61	77.5
17PS-01	5/31/2006	DNA	Sed	ice	c/g	2.03E+09	1.77E+05	8.80E+04	---	---	---	---	---	---	---	<5E+02	---	---	6.20E+02	<5E+02	---	---
17PS-01	5/31/2006	RNA	Sed	RNAlater®	gc/g	3.30E+06	3.35E+03	<5E+02	---	---	---	---	---	---	---	<5E+02	---	---	<5E+02	<5E+02	---	---
17PS-01	6/21/2006	DNA	Sed	ice	c/g	1.31E+11	2.99E+06	1.83E+07	---	---	---	---	---	---	2.49E+08	<7.46E+03	8.49E+07	---	6.51E+05	<7.46E+03	---	55.85
17PS-01	6/21/2006	RNA	Sed	RNAlater®	gc/g	5.28E+07	<1.55+04	9.06E+04	---	---	---	---	---	---	5.63E+04	<7.74+03	4.21E+03 (J)	---	5.53E+01 (J)	<7.74E+03	---	---
17PS-01	6/21/2006	RNA	Sed	RNAlater®	gc/g	1.08E+08	<1.89+04	3.13E+05	---	---	---	---	---	---	8.91E+05	<9.43+03	3.78E+03 (J)	---	<9.43E+03	<9.43E+03	---	---
17PS-01	8/10/2006	RNA	NP	RNAlater®	gc/mL	8.92E+03	<1	1.26E+02	---	---	---	---	---	---	---	<5E-01	---	---	<5E-01	1.79E+00	1,000	30.68
17PS-01	8/10/2006	RNA	LF	RNAlater®	gc/mL	1.41E+04	<1	7.12E+01	---	---	---	---	---	---	---	<5E-01	---	---	<5E-01	2.68E+00	1,000	91.94
17PS-01	8/10/2006	DNA	NP	ice	c/mL	2.15E+06	1.04E+04	2.44E+05	---	---	---	---	---	---	---	<5E-01	---	---	1.67E+05	7.82E+00	1,000	81.82
17PS-01	8/10/2006	DNA	LF	ice	c/mL	2.06E+06	2.91E+03	1.10E+05	---	---	---	---	---	---	---	<5E-01	---	---	3.34E+04	3.47E+00	1,000	85.89
17PS-01	7/18/2007	RNA	SP1	ice	gc/mL	8.55E+04	<1.31E+00	4.78E+00	---	---	---	---	---	---	---	<6.55E-01	---	---	1.36E+00	<6.55E-01	---	---
17PS-01	7/18/2007	DNA	SP1	ice	c/mL	5.37E+06	9.34E+02	7.02E+04	---	---	---	---	---	---	---	<6.6E-01	---	---	6.06E+03	<6.6E-01	---	---

Table 5. Molecular analysis of phylogenic groups and functional genes in water and sediment filtrate pumped from monitoring wells, Solid Waste Management Unit 17, Naval Weapons Station Charleston, North Charleston, South Carolina, 2005–2007.—Continued

[DNA, deoxyribonucleic acid; RNA, ribonucleic acid; 16SrRNA, 16S ribosomal RNA; mRNA, messenger RNA; BVC, vinyl chloride reductase associated with *Dehalococcoides* sp. strain BAV1; DSR, sulfate-reducing bacteria; sMMO, methane monooxygenase; TCE R-Dase, trichloroethene reductase; VC R-Dase, vinyl chloride reductase; LF.5CV, sampled after purging one-half casing volume (1.1 gallons) of water from the screened interval; c/mL, cells per milliliter; <, less than; ---, data not collected; gc/mL, gene copies per milliliter; gc/b, gene copies per bead; gc/g, gene copies per gram; c/g, cells per gram; LF2CV, sampled after purging two casing volumes (4.4 gallons) of water from the screened interval; LF3CV, sampled after purging three casing volumes (6.6 gallons) of water from the screened interval; NP, sample was the first water pumped from in the screened interval of the well; LF, sampled by low-flow methodology; c/mL, cells per milliliter; BT, biotrap obtained from Microseeps, Inc.; c/b, cells per bead; 1CV, sampled from the screened interval after purging one casing volume of water (2.2 gallons) from the top of the water column; 3CV, sampled from the screened interval after purging three casing volumes of water (6.6 gallons) from the top of the water column; sed, sediment obtained from the well sump by pumping; (J), estimated value; SP1, sampled after a slow purge with substantial drawdown; LF1CV, sampled after purging one casing volume (2.2 gallons) of water from the screened interval]

Well name	Date	DNA or RNA	Type of sample	Preservation medium	Units	Phylogenic groups										Functional genes					Volume filtered, in milliliters	Percent recovery
						DNA or 16SrRNA										DNA or mRNA						
						Eubacteria (*qEBAC*)	*Dehalobacter* sp. (*qDHB*)	*Dehalococcoides* sp. (*qDHC*)	Methanogenic bacteria (*qMGN*)	*Desulfuromonas* sp. (*qDSM*)	*Geobacter* sp.	Methanotrophic bacteria (*qMOB*)	Type 1 Methanotrophic bacteria (*MOB1*)	Type 2 Methanotrophic bacteria (*MOB2*)	Iron-reducing and sulfate-reducing bacteria	BVC	DSR	sMMO	TCE R-Dase	VC R-Dase		
17PS-02	7/21/2005	RNA	3CV	dry ice	gc/mL	1.78E+05	---	5.19E+04	2.86E+04	---	---	---	---	---	6.27E+04	3.45E+02	---	1.31E+02	1.64E-01	8.52E+04	2,000	---
17PS-02	7/21/2005	RNA	3CV	ice	gc/mL	1.10E+05	---	1.08E+00	2.53E+07	---	---	---	---	---		5.16E+03	---	1.09E+03	6.83E-01	4.91E+03	2,000	---
17PS-02	8/23/2005	RNA	BT	RNAlater®	gc/b	1.39E+06	---	4.62E+03	---	---	---	9.76E+02	---	9.76E+02	---	---	---	2.65E+03	---	6.92E+03	80	---
17PS-02	8/23/2005	RNA	LF	RNAlater®	gc/mL	1.82E+05	4.95E+01	2.31E+04	---	---	---	1.96E+02	---	1.96E+02	---	---	---	5.57E+01	---	1.14E+03	1,000	---
17PS-02	8/23/2005	RNA	NP	RNAlater®	gc/mL	1.41E+05	---	3.68E+02	---	---	---	2.25E+02	---	2.25E+02	---	---	---	8.07E+02	---	2.16E+03	240	---
17PS-02	2/16/2006	DNA	Sed	ice	c/mL	1.47E+08	5.61E+05	9.84E+05	1.72E+06	---	3.46E+03	---	---	---	8.00E+03	4.07E+00 (J)	3.13E+08	---	1.60E+05	<5E+01	10	54.71
17PS-02	2/16/2006	RNA	Sed	RNAlater®	gc/mL	2.41E+04	3.58E+02	9.80E+01	<1E+02	---	<7.5E+01	---	---	---	<7.5E+01	3.86E+00 (J)	<1E+02	---	5.49E+03	<5E+01	10	74.46
17PS-02	2/16/2006	DNA	BT	ice	c/b	2.18E+05	<5E+01	1.70E+03	<5E+01	---	<3.75E+01	---	---	---	<3.75E+01	<2.5E+01	<5E+01	---	4.92E+02	<2.5E+01	20	80.73
17PS-02	2/16/2006	RNA	BT	RNAlater®	gc/b	9.22E+05	<1.69E+01	<8.47E+00	<1.69E+01	---	<1.27E+01	---	---	---	<1.27E+01	<8.47E+00	<1.69E+01	---	<8.47E+00	<8.47E+00	59	71.53
17PS-02	2/16/2006	DNA	LF	ice	c/mL	6.00E+06	5.91E+03	5.95E+04	3.54E+04	---	1.17E+03	---	---	---	1.42E+03	1.62E+01 (J)	2.09E+05	---	8.20E+03	<5E-01	1,000	91.17
17PS-02	2/16/2006	RNA	LF	RNAlater®	gc/mL	1.19E+04	1.44E+00	2.93E+01	<1E+00	---	<7.5E-01	---	---	---	<7.5E-01	2.44E+00	<1E+00	---	1.45E+01	<5E-01	1,000	58.91
17PS-02	2/16/2006	DNA	3 cv	ice		2.84E+05	3.07E+03	3.83E+00	2.32E+04	---	2.13E+01	---	---	---	1.14E+01	3.88E-02 (J)	4.30E+05	---	8.52E-01	<5E-01	1,000	82.23
17PS-02	2/16/2006	RNA	3 cv	RNAlater®	gc/mL	1.16E+04	1.62E+00	2.00E+00	<1E+00	---	2.50E+01	---	---	---	5.05E+00	3.56E+02 (J)	5.36E+02	---	2.16E+01	<5E-01	1,000	90.97
17PS-02	5/31/2006	DNA	Sed	ice	c/g	1.39E+09	5.41E+05	1.89E+08	---	---	---	---	---	---	---	<5E+02	---	---	1.01E+08	<5E+02	---	---
17PS-02	5/31/2006	RNA	Sed	RNAlater®	gc/g	3.06E+06	<1E+03	3.89E+04	---	---	---	---	---	---	---	<5E+02	---	---	<5E+02	<5E+02	---	---
17PS-02	6/21/2006	DNA	Sed	ice	c/g	2.89E+10	4.24E+06	2.14E+09	---	---	---	---	---	---	8.19E+07	1.38E+03 (J)	3.80E+07	---	3.71E+08	<8.62E+03	---	66.01
17PS-02	6/21/2006	RNA	Sed	RNAlater®	gcg	1.44E+07	1.65E+04	1.49E+06	---	---	---	---	---	---	1.58E+04	<2.13E+03	5.59E+02 (J)	---	2.43E+02 (J)	<2.13+03	---	---
17PS-02	6/21/2006	RNA	Sed	RNAlater®	gc/g	2.47E+07	1.21E+04	3.31E+06	---	---	---	---	---	---	1.16E+06	<8.19+02	8.53E+02 (J)	---	4.73E+02 (J)	<8.19+02	---	---
17PS-02	8/10/2006	RNA	NP	RNAlater®	gc/mL	1.59E+04	8.89E+00	5.19E+02	---	---	---	---	---	---	---	<5E-01	---	---	<5E-01	<5E-01	1,000	72.88
17PS-02	8/10/2006	RNA	LF	RNAlater®	gc/mL	3.72E+04	4.17E+01	2.97E+02	---	---	---	---	---	---	---	<5E-01	---	---	<5E-01	<5E-01	1,000	94.18
17PS-02	8/10/2006	DNA	NP	ice	c/mL	1.09E+07	1.09E+04	1.74E+06	---	---	---	---	---	---	---	<5E-01	---	---	2.89E+06	6.42E+01	1,000	77.46
17PS-02	8/10/2006	DNA	LF	ice	c/mL	1.18E+07	2.84E+01	2.98E+06	---	---	---	---	---	---	---	<5E-01	---	---	<5E-01	3.95E+00	1,000	90.18
17PS-02	7/18/2007	RNA	SP1	RNAlater®	gc/mL	1.14E+03	<7.45E-01	9.89E+02	---	---	---	---	---	---	---	<3.73E-01	---	---	2.35E+00	<3.73E-01	---	---
17PS-02	7/18/2007	DNA	SP1	ice	c/mL	7.78E+06	<1.03E+00	2.54E+05	---	---	---	---	---	---	---	<5.15E-01	---	---	2.85E+04	<5.15E-01	---	---
17PS-02	7/21/2009	RNA	LF	RNAlater®	gc/mL	3.92E+05	3.50E+04	6.2J	1.90E+03	1.41E+04	---	5.52E+05	---	---	---	---	---	---	---	---	---	---
17PS-02	8/10/2006	DNA	LF	ice	c/mL	1.39E+07	1.12E+05	7.51E+02	5.14E+06	5.78E+00	---	1.65E+06	---	---	---	---	---	---	---	---	---	---
17PS-02	7/22/2009	RNA	LF	RNAlater®	gc/mL	3.92E+05	3.50E+04	6.20E+00	1.90E+03	1.41E+04	---	5.52E+05	---	---	---	---	---	---	---	---	100	---
17PS-02	7/22/2009	DNA	LF	ice	c/mL	1.39E+07	1.12E+05	7.51E+02	5.14E+06	5.78E+00	---	1.65E+06	---	---	---	2.10E+00	---	---	3.05E+02	4.40E+00	300	---
17PS-03	3/9/2005	DNA	LF.5CV	ice	c/mL	3.62E+07	2.81E+05	1.38E+03	2.48E+05	<8.33	<6.25	3.01E+07	1.58E+07	1.44E+07	1.47E+04	---	---	9.58E+05	8.42E+01	1.54E+01	---	51.86
17PS-03	3/9/2005	DNA	LF1CV	ice	c/mL	3.07E+07	1.14E+05	2.05E+00	2.15E+05	9.55E+04	<1.98	2.83E+07	1.94E+07	8.89E+06	1.80E+04	---	---	1.61E+04	2.99E+01	1.49E+01	---	66.94
17PS-03	3/9/2005	DNA	LF2CV	ice	c/mL	1.41E+07	1.84E+04	3.24E+01	7.23E+03	<1	1.24E+01	2.48E+07	1.72E+07	7.60E+06	2.63E+04	---	---	9.38E+05	9.72E+01	<50	---	96.29
17PS-03	3/9/2005	DNA	LF4CV	ice	c/mL	1.05E+07	4.45E+04	---	2.25E+05	<1	1.67E+02	7.80E+06	5.10E+06	2.70E+06	3.85E+04	---	---	9.87E+03	1.21E+01	<50	---	74.13
17PS-03	8/23/2005	RNA	BT	RNAlater®	gc/b	4.40E+06	---	2.62E+04	---	---	---	1.52E+04	1.20E+03	1.40E+04	---	---	---	---	---	---	90	---
17PS-03	8/23/2005	RNA	LF	RNAlater®	gc/mL	2.19E+05	---	1.20E+05	---	---	---	4.05E+04		4.05E+04	---	---	---	---	---	---	1,000	---
17PS-03	8/23/2005	RNA	NP	RNAlater®	gc/mL	2.04E+06	---	1.02E+06	---	---	---	1.92E+04	2.52E+02	1.89E+04	---	---	---	---	---	---	240	---
17PS-03	2/16/2006	DNA	LF	ice	c/mL	1.69E+06	1.53E+03	5.46E+00	2.34E+04	---	7.36E+02	---	---	---	9.07E+02	1.19E-01 (J)	2.03E+05	---	7.55E-01	<5E-01	1,000	84.82
17PS-03	2/16/2006	RNA	LF	RNAlater®	gc/mL	1.62E+06	<1E+00	2.07E+00	<1E+00	---	<7.5E-01	---	---	---	<7.5E-01	<5E-01	<1E+00	---	<5E-01	<5E-01	1,000	42.5
17PS-03	2/16/2006	DNA	BT	ice	c/b	1.50E+07	1.32E+04	3.80E+02	2.90E+04	---	3.25E+04	---	---	---	4.51E+04	5.80E+01	9.09E+06	---	1.97E+02	---	20	66.06
17PS-03	2/16/2006	RNA	BT	RNAlater®	gc/b	1.42E+07	<2.27E+01	<1.14E+01	<2.27E+01	---	<1.7E+01	---	---	---	<1.7E+01	<1.14E+01	<2.27E+01	---	<1.14E+01	<1.14E+01	44	81.97
17PS-03	5/31/2006	DNA	Sed	ice	c/g	1.07E+09	8.49E+05	4.17E+07	---	---	---	---	---	---	---	<5E+02	---	---	1.00E+07	<5E+02	---	---
17PS-03	5/31/2006	RNA	Sed	RNAlater®	gc/g	3.28E+06	<1E+03	1.81E+05	---	---	---	---	---	---	---	<5E+02	---	---	<5E+02	<5E+02	---	---
17PS-03	6/21/2006	DNA	Sed	ice	c/g	8.68E+10	6.76E+07	1.08E+10	---	---	---	---	---	---	1.51E+09	<6.25E+04	3.40E+08	---	1.51E+09	<6.25E+04	---	85.68
17PS-03	6/21/2006	RNA	Sed	RNAlater®	gc/g	5.38E+07	8.87E+04	6.83E+06	---	---	---	---	---	---	1.09E+05	<1.87E+04	1.94E+04 (J)	---	5.24E+01 (J)	<1.87E+04	---	---
17PS-03	6/21/2006	RNA	Sed	RNAlater®	gc/g	3.31E+07	2.69E+04	5.90E+06	---	---	---	---	---	---	5.53E+04	<3.58E+03	1.9E+02 (J)	---	7.89E+02	<3.58E+03	---	---
17PS-03	8/10/2006	RNA	NP	RNAlater®	gc/mL	1.33E+04	<1	5.00E+02	---	---	---	---	---	---	---	<5E-01	---	---	7.83E+01	<5E-01	1,000	97.25
17PS-03	8/10/2006	DNA	NP	ice	c/mL	9.39E+06	1.59E+04	4.22E+06	---	---	---	---	---	---	---	<5E-01	---	---	7.66E+06	2.25E+00	1,000	72.89

following the Phase-I injection. During October 2005, the VC concentration in the aquifer at well 17PS-02 was less than 10 µg/L (table 3). The data indicate that in the months following the Phase-I injection, aquifer conditions at the injection wells were more conducive to VC production than conditions at well 17PS-02.

The VC concentration in water from low-flow sampling at well 17PS-02 substantially increased from less than 10 µg/L in October 2005 to 422 µg/L in February 2006 (fig. 14; table 3), and the VC concentration in the adjacent monitoring wells remained less than 100 µg/L (table 3). The VC concentration at well 17PS-02 was substantially higher than in groundwater from the injection wells (less than 5 to 25 µg/L) for August 2005 and March 2006 (Lieberman and Borden, in press). The persistence of 49 mg/L of sulfate in groundwater at well 17PS-02 in February 2006 indicates that iron or sulfate reduction remained active TEAPs at some level within or near the screened interval despite a slight increase in methane concentration (tables 3, 4). Thus, even though conditions were more oxidizing at well 17PS-02 than in the injection wells, VC production at well 17PS-02 outpaced VC production in the injection wells from October 2005 to February 2006, during the time of the pH-adjustment tests in well 17PS-02.

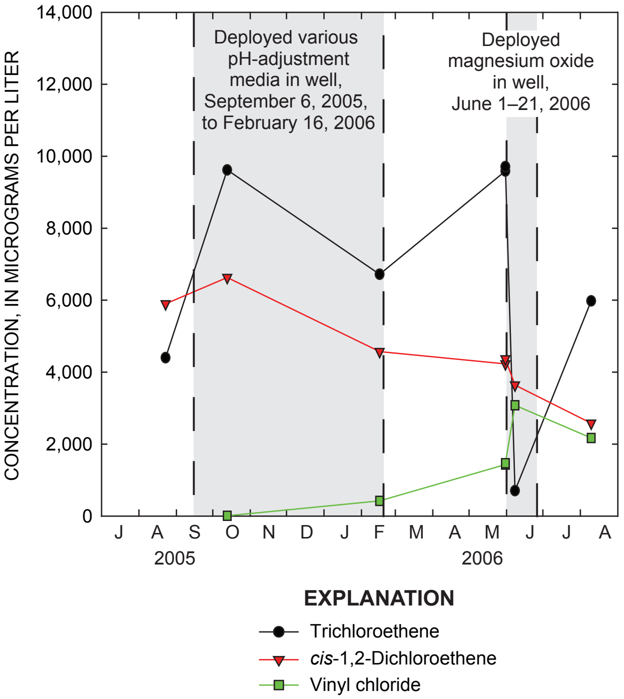


Figure 14. Changes in volatile organic compound concentrations in low-flow groundwater samples from well 17PS-02 during 2005–2006 showing initiation of vinyl chloride production following in-well pH adjustments, Solid Waste Management Unit 17, Naval Weapons Station Charleston, North Charleston, South Carolina, August 2005 through August 2006.

The VC concentration in well 17PS-02 continued to increase following cessation of the pH-adjustment tests in February 2006. By May 2006, the VC concentration in groundwater at the well had risen to 1,430 µg/L, while the VC concentration in well 17PS-01 remained at less than 50 µg/L (table 3). The VC concentrations in the injection wells remained below 100 µg/L through September 2006 (data from Lieberman and Borden, in press). The ethene concentration in water from low-flow samples at well 17PS-02 increased from 3.1 µg/L in February 2006 to 16 µg/L in May to 54.7 µg/L in August, indicating an increase in complete dechlorination activity (table 3).

The VC concentrations in water from well 17PS-03 increased from less than 100 µg/L in February 2006 to 1,860 µg/L in May 2006 (table 3). At that point, no pH-adjustment tests had been done in well 17PS-03, although there had been pH adjustments in well 17PS-02 approximately 6.5 ft away. The concentrations of VC in wells 17PS-02 and 17PS-03 on May 31, 2006, were greater than 10 to greater than 100 times higher than the VC concentrations in the monitored injection wells and in monitoring well 17PS-01 in the injection area. An injection well midway between wells 17PS-02 and 17PS-03 contained only 52 µg/L on May 25, 2006 (Lieberman and Borden, in press).

A potential explanation for the increase in VC production at wells 17PS-02 and 17PS-03 is that VC production was slowly being initiated in various parts of the injection zone after a long period of microbial acclimation. This activity would be expected to occur most readily in parts of the aquifer most favorable for VC production, such as highly reducing conditions with near-neutral pH. Adjustment of the pH to near-neutral values in well 17PS-02 may have made that area relatively favorable to VC production compared with much of the rest of the injection zone, possibly accounting for acceleration of VC production at that well. The lack of measurable sulfate (less than 2.5 mg/L) in water from well 17PS-03 in May 2006 indicated the presence of more reducing conditions than at well 17PS-02 (26 mg/L of sulfate (table 4). Although conditions probably were even more reducing at the injection wells, by virtue of proximity to the injectate, the pH values in the injection wells typically were near or less than 5 pH units (data from Lieberman and Borden, in press). Conditions at well 17PS-03 may have represented a more favorable balance of highly reducing conditions and a slightly higher pH (usually greater than about 5.5 pH units) than at the injection wells. Thus, conditions likely were more favorable for VC production at well 17PS-03 than at the injection wells.

Following an additional deployment of magnesium oxide in wells 17PS-02 and 17PS-03 on June 1, 2006, VC concentration sharply increased in well 17PS-02 (fig. 14). In addition, the pH in well 17PS-03 increased to about 7.4 (table 4), and the VC concentration increased in low-flow samples from 1,860 µg/L prior to the deployment to 2,720 µg/L 7 days after deployment (table 3). Thus, there is the potential that the pH adjustment in the wells locally invigorated VC production.

These changes in concentration of VOCs also can be seen by comparing PDB sampler results at multiple depths in the screened interval (fig. 15). The data in figure 15*A* show that within well 17PS-02, the post-injection VOCs were dominantly *c*DCE and TCE. Once pH adjustment experiments began in the well, however, VC became an important constituent (fig. 15*B*) and eventually became the dominant constituent (figs. 15*C*, *D*). The substantially lower VC concentrations in low-flow samples from well 17PS-02 relative to the in-well PDB samplers in February 2006 may be because the water represented by the PDB samplers was in closer proximity to the pH-adjustment tests than the water represented by the low-flow samples (table 3).

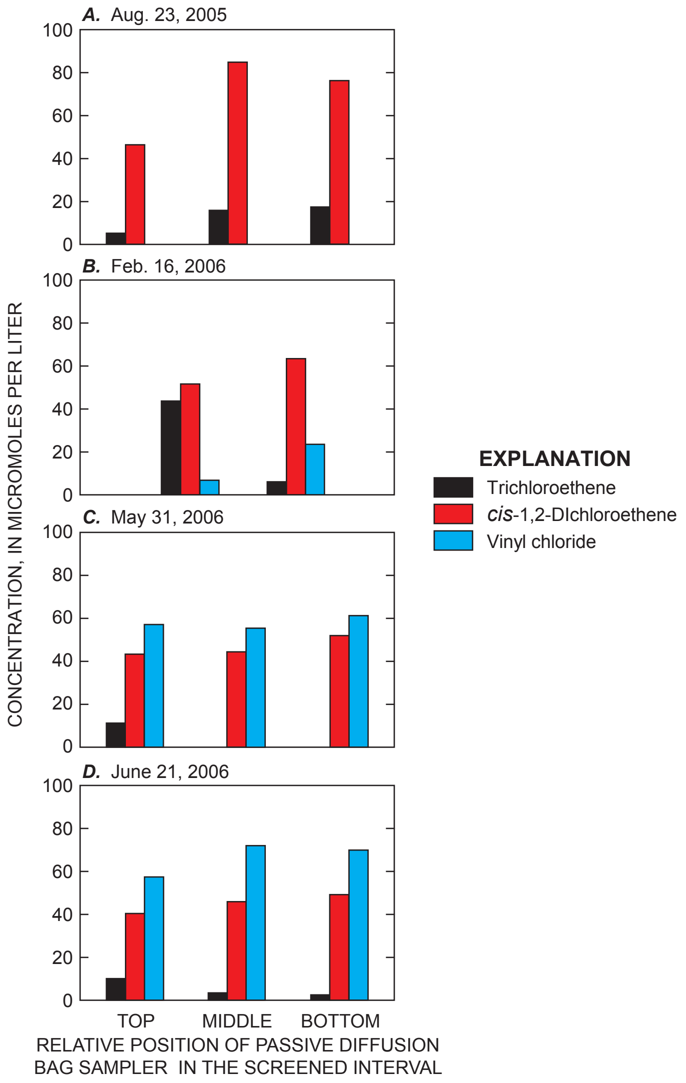


Figure 15. Concentrations of trichloroethene, *cis*-1,2-dichloroethene, and vinyl chloride in passive diffusion bag samplers at various depths in the screened interval of well 17PS-02, Solid Waste Management Unit 17, Naval Weapons Station Charleston, North Charleston, South Carolina, 2005–2006.

In response to what appeared to be low-pH-induced reduction of dechlorination activity in the injection area, Solutions-IES initiated a Phase-II injection in the fall of 2006. During this phase, pH-buffered emulsified vegetable oil was injected into the aquifer. The groundwater pH in the injection zone increased in the range of 6.4–7.7, TCE and *c*DCE rapidly dechlorinated to VC, and substantial increases were seen in *Dehalococcoides* populations and in TCE-reductase levels (Borden and others, 2008). TCE and *c*DCE concentrations have continued to decrease in the test area since injection of the pH-buffered emulsified vegetable oil. TCE declined from a pre-injection concentration of 5,980 µg/L in August 2006 to less than 2.5 µg/L in August 2007 at well 17PS-02 (table 3). The success of the Phase-II injection likely is partly related to the pH buffering, although the injection also involved an increase in the amount of substrate injected and in the efficiency of the injection.

The Phase-II injection in September 2006 substantially decreased well yield in the injection zone. In August 2006, prior to the Phase-II injection, the low-flow pumping rate from well 17PS-02 was easily maintained at 220 milliliters per minute (mL/min). Following the injection, a substantial amount of crusty material accumulated in monitoring wells 17PS-01, 17PS-02, and 17PS-03, even though these wells were not used for the injection. In August 2007, well 17PS-02 could not be sampled by low-flow methodology because pumping the well at a unacceptably low rate (less than 90 mL/min) caused water levels to draw down about 9 ft, which lowered the water level about 6 ft into the well screen. Some of the reduced well yield was the result of well clogging. Solutions-IES conducted a field effort in late 2007 to restore well yield, with some measure of success. The field effort removed most of the precipitation deposits that had been present in the monitoring wells and increased well yield. The well yield, however, still remained substantially lower than in nearby wells outside of the injection zone. Attempts by the USGS to sample wells 17PS-01, 17PS-02, and 17PS-03 in May 2008 following the injection showed that water levels in the wells drew down substantially (several feet) even when pumping only 60 mL/min, while wells outside the injection zone could be pumped at 200 mL/min with almost no drawdown. Considering that the yields of the monitoring wells remained relatively low and that the injections had been in wells other than the monitoring wells, it is likely that some level of permeability reduction is present outside of the monitoring wells in the aquifer matrix. Thus, the groundwater contamination transport pathway following the Phase-II injection likely was around the injection zone rather than through it.

Recent Data on Contaminants and Water Movement in and near the Injection Zone

Following the Phase-II injection of pH-buffered emulsified vegetable oil into the test zone by Solutions-IES in September and October 2006, concentrations of 1,1-Dichloroethene (1,1-DCE), TCE, and *c*DCE sharply declined in the injection area (table 3). The concentrations have remained low. Samples collected on July 21, 2009, showed that these constituents were undetectable in the injection zone, with the exception of a low concentration (43 µg/L) of *c*DCE in well 17PS-01. VC was still present in groundwater at the test wells in concentrations ranging from 150 to 640 µg/L. Total organic carbon, which was present in the monitoring wells in the injection zone at concentrations greater than 1,000 mg/L in May 2007, declined to concentrations ranging from 81 to 310 mg/L (table 4). These concentration levels contrast with concentration levels in water from wells outside the injection zone. In July 2009, water from wells 17MW-06S and 17MW-07S contained greater than 10,000 µg/L of TCE, less than 500 µg/L of VC, and TOC concentrations less than 3 mg/L (tables 3 and 4). It is of interest to note, however, that the July 2009 sampling of well 17PS-06 showed the presence of a higher VC concentration (430 µg/L) than had been seen in that well during any previous sampling event. In general, the distinct changes in VOC concentrations in water from wells in the injection area relative to wells outside of the injection area indicate that the pH-buffered emulsified vegetable oil substantially enhanced VOC degradation.

The yields of wells 17PS-01, 17PS-02, and 17PS-03 remain lower than nearby wells outside of the injection zone. In July 2009, the water levels during low-flow sampling in wells outside of the injection area could be maintained at less than about 1 ft of drawdown at pumping rates greater than 200 mL/min, but water levels in the monitoring wells in the injection zone drew down several feet at a pumping rate of only 100 mL/min. The continued low well yield even after well renovation and the fact that the accumulation of deposits took place in wells that were not used for the injection indicate that there is some level of permeability reduction in the aquifer outside of the monitoring wells. Permeability reduction in the injection zone could explain the sluggish and subdued response of water levels in well 17PS-02 to diurnal fluctuations, compared to nearby wells (fig. 10). These data indicate that because of the localized permeability reduction in the injection zone, contamination transport may be around, rather than through, the injection zone.

Summary and Conclusions

Groundwater contamination by VOCs is present at SWMU17 at the Naval Weapons Station Charleston, North Charleston, South Carolina. This investigation focused on the groundwater contamination in the southern part of SWMU17, where the primary contaminants are TCE and its dechlorination products. In May 2004, Solutions-IES initiated a Phase-I pilot-scale treatability study at SWMU17 involving the injection of an edible oil emulsion into the aquifer near wells 17PS-01, 17PS-02, and 17PS-03 to treat chlorinated solvents. The Phase-I injection of emulsified vegetable oil resulted in dechlorination of TCE to *c*DCE, but the dechlorination activity appeared to stall at *c*DCE, with little further dechlorination of *c*DCE to VC or to ethene. Groundwater pH values in the injection area declined to less than 6.0, which is below the range considered optimum for dechlorination activity. The USGS and NAVFACSE initiated the present investigation to examine the groundwater hydrology and chemistry in and near the injection zone and to gain a better understanding of the apparent remediation stall.

Groundwater flows radially from SWMU17 toward SWMU16 to the west and toward a surface-water feature to the east. Specific groundwater-flow paths vary temporally because of changes in evapotranspiration, tides, recharge, and localized ponding, and possibly because of differences in hydraulic conductivity. The aquifer was anaerobic during this investigation. Iron reduction is a likely TEAP in the aquifer outside of the injection zone. In addition to iron reduction, it is likely that groundwater from the wells upgradient of the injection zone represents an integration of multiple redox zones, including iron reduction, sulfate reduction, and methanogenesis. The TEAP near the injection wells immediately following the Phase-I injection probably was iron reduction followed by sulfate reduction with a gradual shift to methanogenesis.

The progress to more reducing groundwater conditions was not as intense at monitoring wells 17PS-01 and 17PS-02 in the injection zone as it was at the injection wells. The redox heterogeneity probably is the result of irregular distribution of the injectate, which was most concentrated near the injection wells and apparently much less concentrated near wells 17PS-01 and 17PS-02. Unlike wells 17PS-01 and 17PS-02, the sulfate concentrations at well 17PS-03 rapidly declined following the Phase-I injection. This is likely the result of heterogeneous distribution of injectate resulting in more substrate and more rapid depletion of efficient electron acceptors at well 17PS-03 than at wells 17PS-01 and 17PS-02. TEAP conditions at well 17PS-03 likely became more reducing relative to those at wells 17PS-01 and 17PS-02 within months after the injection. The TEAP appeared to shift to methanogenesis in the aquifer at wells 17PS-01 and 17PS-02 following the Phase-II injection.

The pH level of the groundwater in well 17MW-06S outside the injection area shows a strong vertical gradient during months when there is no thermal convection in the well, with lower pH values near the top of the 10-ft well screen (5.2 to 5.6) than at the bottom of the screen (about 6.3). The pH of groundwater in the injection area was less variable with depth (about 6.0 through the screened interval). Because the pH values in the injection area were lower than the optimum near-neutral range for bioremediation of chlorinated solvents, a series of tests were done in wells to raise the pH. Different pH-adjustment media were deployed at multiple levels in the screened interval of well 17PS-02. Deployment of calcite-magnesium oxide increased the in-well pH to near-neutral values.

The cause of the stall in reductive dechlorination following the Phase-I injection at SWMU17 does not appear to be a lack of bacteria capable of efficient dechlorination. Molecular analysis as part of this investigation indicated the presence of *Dehalococcoides* sp. and BVC, which is VC reductase associated with *Dehalococcoides* sp. strain BAV1. One major factor likely affecting the dechlorination stall in the months following the Phase-I injection was the low pH values in the aquifer in the injection zone. A second major factor likely affecting the dechlorination stall in the months following the Phase-I injection was the heterogeneous distribution of injected substrate, resulting in localized areas that remained relatively oxidizing.

Concentrations of VC slightly increased in some wells in the injection area during early 2005, indicating a gradual shift toward VC production. These data possibly reflect a gradual microbial acclimation to the low-pH conditions produced by the injection.

The VC concentrations in water from low-flow sampling at well 17PS-02 during a period of in-well pH-adjustment tests substantially increased from less than 10 µg/L in October 2005 to 422 µg/L in February 2006, while the VC concentration in the adjacent monitoring wells remained less than 100 µg/L. The VC concentration in well 17PS-02 continued to increase following cessation of the pH-adjustment tests in February 2006. Between February and May 2006, VC concentrations also substantially increased in well 17PS-03.

A potential explanation for the increase in VC production at wells 17PS-02 and 17PS-03 is that VC production was slowly being initiated in various parts of the injection zone after a long period of microbial acclimation. This activity would be expected to occur most readily in parts of the aquifer most favorable for VC production, such as highly reducing conditions with near-neutral pH. Adjustment of the pH to near-neutral values in well 17PS-02 may have made that area relatively favorable to VC production compared with much of the rest of the injection zone, possibly accounting for acceleration of VC production at that well. The lack of measurable sulfate in water from well 17PS-03 indicated the presence of more reducing conditions than at well 17PS-02. Although conditions probably were even more reducing at the injection wells, by virtue of proximity to the injectate, the pH values in the injection wells typically were near or less than 5 pH units. Conditions at well 17PS-03 may have represented a more favorable balance of highly reducing conditions and a slightly higher pH (usually greater than about 5.5 pH units) than at the injection wells for VC production. By September 2006, prior to the Phase-II injection, data collected as part of the ESTCP project indicated that all three of the monitoring wells in the injection zone contained greater than 4,000 µg/L of VC, while the injection wells contained only 70 µg/L or less of VC.

In response to a low-pH-induced reduction of dechlorination activity in the injection area, Solutions-IES initiated a Phase-II injection in the fall of 2006. During this phase, pH-buffered emulsified vegetable oil was injected into the aquifer. The groundwater pH in the injection zone increased to 6.4–7.7, TCE and *c*DCE rapidly dechlorinated to VC, and substantial increases were seen in *Dehalococcoides* populations and in TCE-reductase levels. Samples collected on July 21, 2009, indicated that 1,1-DCE, TCE, and *c*DCE were undetectable in the injection zone, with the exception of a low concentration (43 µg/L) of *c*DCE in well 17PS-01. VC was still present in groundwater at the monitoring wells in concentrations ranging from 150 to 640 µg/L. Total organic carbon, which was present in the monitoring wells in the injection zone at concentrations greater than 1,000 mg/L in May 2007, declined to concentrations ranging from 81 to 310 mg/L. Water from wells 17MW-06S and 17MW-07S outside the injection zone contained greater than 10,000 µg/L of TCE and TOC concentrations less than 3 mg/L. The distinct changes in VOC concentrations in water from wells in the injection area relative to wells outside of the injection area indicate that the pH-buffered emulsified vegetable oil enhanced VOC degradation. The Phase-II injection, however, appears to have locally decreased aquifer permeability, possibly resulting in movement of contamination around, rather than through, the treatment area.

References Cited

Barcelona, M., Wehrmann, H.A., and Varljen, M.D., 1994, Reproducible well-purging procedures and VOC stabilization criteria for groundwater sampling: Groundwater, v. 32, p. 12–22.

Borden, A.M., Lieberman, M.T., Borden, R.C., and Tillotson, Jason, 2008, Impact of pH adjustment on enhanced reductive dechlorination of TCE: The Sixth International Conference, Remediation of Chlorinated and Recalcitrant Compounds, Monterey, CA, May 19–22, 2008, session E3, poster 99.

Bradley, P.M., 2003, History and ecology of chloroethene biodegradation—A review: Bioremediation Journal, v. 7, no. 2, p. 81–109.

Bradley, P.M., and Chapelle, F.H., 1996, Anaerobic mineralization of vinyl chloride in Fe(III)-reducing, aquifer sediments: Environmental Science and Technology, v. 30, p. 2084–2086.

Bradley, P.M., Chapelle, F.H., and Vroblesky, D.A., 1993, Does lead affect microbial metabolism in aquifer sediments under different terminal electron accepting conditions?: Geomicrobiology Journal, v. 11, p. 85–94.

Bradley, P.M., Singletary, M.A., and Chapelle, F.H., 2007, Chloroethene dechlorination in acidic groundwater—Implications for combining Fenton's treatment with natural attenuation: Remediation Journal, v. 18, no. 1, p. 7–19.

Cirpka, O.A., Windfuhr, C., Bisch, B., Granzow, S., Scholz-Muramatsu, J., and Kobus, H., 1999, Microbial reductive dechlorination in a large-scale sandbox model: Journal of Environmental Engineering, v. 125, p. 861–870.

Cupples, A.M., Spromann, A.M., and McCarty, P.L., 2003, Growth of a *Dehalococcoides*-like microorganism on vinyl chloride and *cis*-dichloroethene as electron acceptors as determined by competitive PCR: Applied and Environmental Microbiology, v. 69, no. 2, p. 953–959.

Dennis, Philip, Dworatzek, Sandra, Repta, Cory, and Graves, Duane, 2008, Aquifer pH neutralization for bioremediation of chlorinated solvents: The Sixth International Conference, Remediation of Chlorinated and Recalcitrant Compounds, Monterey, CA, May 19–22, 2008, session B3, poster 49.

Fennell, D.E., and Gossett, J.M., 2003, Microcosms for site-specific evaluation of enhanced biological reductive dehalogenation, *in* Haggblom, M.M., and Bossert, I.D., eds., Dehalogenation: Boston, MA, Kluwer, p. 385–420.

He, J., Ritalahti, K.M., Aiello, M.R., and Löffler, F.E., 2003a, Complete detoxification of vinyl chloride by an anaerobic enrichment culture and identification of the reductively dechlorinating population as a *Dehalococcoides* species: Applied and Environmental Microbiology, v. 69, p. 996–1003.

He, J., Ritalahti, K.M., Yang, K., Koenigsberg, S., and Löffler, F.E., 2003b, Detoxification of vinyl chloride to ethene coupled to growth of an anaerobic bacterium: Nature, v. 424, p. 62–65.

Hendrickson, E.R., Payne, Jo Ann, Young, R.M., Starr, M.G., Perry, M.P., Fahnestock, Stephen, Ellis, D.E., and Ebersole, R.C., 2002, Molecular analysis of *Dehalococcoides* 16S ribosomal DNA from chloroethene-contaminated sites throughout North America and Europe: Applied and Environmental Microbiology, v. 68, no. 2, p. 485–495.

Holliger, C., Schraa, G., Stams, A.J., and Zehnder, AJ., 1993, A highly purified enrichment culture couples the reductive dechlorination of tetrachloroethene to growth: Applied and Environmental Microbiology, v. 59, no. 9, p. 2991–2997.

Lieberman, M.T., and Borden, R.C., in press, Edible oil emulsion for treatment of chlorinated solvent contaminated groundwater at SWMU17, Charleston Naval Weapons Station, Charleston, SC: Arlington, VA, Solutions-IES, Inc., Environmental Security Technology Certification Program (ESTCP), Project ER-0221, 136 p.

Looney, B.B., and Vangelas, K.M., 2004, Compatibility of alternative chlorinated solvent source treatment strategies with monitored natural attenuation: Aiken, SC, Westinghouse Savannah River Company, WSRC-MS-2004-00236, 21 p.

McMahon, P.B., Vroblesky, D.A., Bradley, P.M., and Chapelle, F.H., 1995, Evidence for enhanced mineral dissolution in organic-rich shallow ground water: Ground Water, v. 33, no. 2.

Sevee, J.E., White, C.A., and Maher, D.J., 2000, An analysis of low-flow groundwater sampling methodology: Groundwater Monitoring and Remediation, v. 20, no. 2, p. 87–93.

Shanklin, D.E., Sidle, W.C., and Ferguson, M.E., 1995, Micropurge low-flow sampling of uranium-contaminated groundwater at the Fernald Environmental Management Project: Groundwater Monitoring and Remediation, v. 15, no. 3, p. 168–176.

Tetra Tech NUS, Inc., 2004, RCRA facility investigation documentation and data summary 2000–2003, for Old Southside Landfill—SWMU 16 and Old Southside Missile and Waste Oil Disposal Area—SWMU 17, Naval Weapons Station Charleston, Charleston, South Carolina: Consultant's report to Southern Division Naval Facilities Engineering Command, January 2004 [variously paged].

Tetra Tech NUS, Inc., 2006, RFI report SWMU 16—Old Southside Landfill and SWMU 17—Old Southside Missile and Waste Oil Disposal Area, Naval Weapons Station Charleston, South Carolina: Consultant's report to Naval Facilities Engineering Command, March 2006 [variously paged].

Vroblesky, D.A., Bradley, P.M., and Chapelle, F.H., 1996, Influence of electron donor on the minimum sulfate concentration required for sulfate reduction in a petroleum hydrocarbon-contaminated aquifer: Environmental Science & Technology, v. 30, no. 4, p. 1377–1381.

Vroblesky, D.A., and Casey, C.C., 2008, Case study 2—Tree coring as a guide to well placement, Solid Waste Management Unit 17, Naval Weapons Station Charleston, South Carolina, 2002, *in* Vroblesky, D.A., User's guide to the collection and analysis of tree cores to assess the distribution of subsurface volatile organic compound: U.S. Geological Survey Scientific Investigations Report 2008–5088, p. 32–33.

Vroblesky, D.A., Casey, C.C., and Lowery, M.A., 2007, Influence of dissolved oxygen convection on well sampling: Ground Water Monitoring and Remediation, v. 27, no. 3, p. 49–58.

Wiedemeier, T.H., Wilson, J.T., and Kampbell, D.H., 1996, Natural attenuation of chlorinated aliphatic hydrocarbons at Plattsburg Air Force Base, New York, *in* Proceedings of the Symposium on Natural Attenuation of Chlorinated Organics in Groundwater: U.S. Environmental Protection Agency, EPA/540/R-96/509, p. 74–82.

Zhuang, Ping, and Pavlostathis, S.G., 1995, Effect of temperature, pH, and electron donor on the microbial reductive dechlorination of chloroalkenes: Chemosphere, v. 31, no. 6, p. 3537–3548.

Appendix 1. Groundwater levels not associated with synoptical tidal water-level measurements, Solid Waste Management Units 16 and 17, Naval Weapons Station Charleston, North Charleston, South Carolina, 2006–2009.

[NAVD 88, North American Vertical Datum of 1988]

Well	Date and time	Datum (feet above NAVD 88)	Depth to water (feet below top of casing)	Water level (feet above NAVD 88)
16MW-01S	9/11/08 11:52	7.78	6.41	1.37
17MW-05S	6/1/06 11:18	7.77	6.84	0.93
17MW-05S	6/28/06 10:09	7.77	6.19	1.58
17MW-05S	8/10/06 12:43	7.77	7.27	0.50
17MW-05S	8/1/07 8:29	7.77	4.25	3.52
17MW-05S	8/22/07 9:41	7.77	7.08	0.69
17MW-05S	5/13/09 10:00	7.77	6.83	0.94
17MW-06D	6/28/06 10:11	7.62	5.94	1.68
17MW-06D	8/10/06 12:40	7.62	6.92	0.70
17MW-06S	3/8/05 14:14	7.88	3.91	3.97
17MW-06S	6/1/06 11:15	7.88	6.94	0.94
17MW-06S	6/28/06 10:10	7.88	6.31	1.57
17MW-06S	8/10/06 12:41	7.88	7.37	0.51
17MW-06S	8/22/07 9:39	7.88	7.14	0.74
17MW-06S	8/14/08 11:10	7.88	7.9	-0.02
17MW-07S	7/21/05 10:41	7.92	5.93	1.99
17MW-07S	2/16/06 12:08	7.92	3.96	3.96
17MW-07S	6/1/06 11:12	7.92	6.97	0.95
17MW-07S	6/28/06 10:12	7.92	6.34	1.58
17MW-07S	8/10/06 12:37	7.92	7.4	0.52
17MW-07S	8/1/07 8:28	7.92	4.43	3.49
17MW-07S	8/1/07 8:28	7.92	4.43	3.49
17MW-07S	5/13/09 10:01	7.92	7	0.92
17MW-12S	5/13/09 9:45	7.37	6.32	1.05
17MW-17S	5/13/09 10:14	6.15	5.26	0.89
17MW-18S	5/13/09 10:16	5.36	4.46	0.90
17MW-19S	5/13/09 9:59	7.72	6.76	0.96
17MW-20S	5/13/09 9:48	7.32	6.43	0.89
17MW-6D	3/8/05 16:19	7.62	3.86	3.76
17PS-01	7/21/05 (time not recorded)	7.96	6.15	1.81
17PS-01	2/16/06 9:46	7.96	4.12	3.84
17PS-01	5/31/06 10:10	7.96	6.9	1.06
17PS-01	6/1/06 11:20	7.96	6.99	0.97
17PS-01	6/28/06 10:05	7.96	6.29	1.67
17PS-01	8/10/06 10:51	7.96	7.37	0.59
17PS-01	8/14/06 10:51	7.96	7.37	0.59
17PS-01	8/22/07 9:46	7.96	7.21	0.75
17PS-02	7/21/05 10:56	7.90	6.09	1.81
17PS-02	2/16/06 10:37	7.90	4.09	3.81
17PS-02	5/31/06 10:11	7.90	6.84	1.06
17PS-02	6/1/06 11:22	7.90	6.92	0.98
17PS-02	6/28/06 10:07	7.90	6.22	1.68
17PS-02	8/10/06 10:57	7.90	7.31	0.59
17PS-02	7/17/07 14:59	7.90	6.1	1.80
17PS-02	8/1/07 8:43	7.90	4.38	3.52
17PS-02	5/5/08 11:16	7.90	6.29	1.61
17PS-02	5/13/09 9:48	7.90	7.01	0.89
17PS-03	6/29/05 15:14	7.80	3.77	4.03
17PS-03	2/16/06 10:40	7.80	3.98	3.82
17PS-03	5/31/06 10:37	7.80	6.76	1.04
17PS-03	5/31/06 10:37	7.80	6.76	1.04
17PS-03	6/1/06 11:23	7.80	6.85	0.95
17PS-03	6/28/06 10:08	7.80	6.15	1.65
17PS-03	8/10/06 10:59	7.80	7.24	0.56
17PS-03	8/22/07 9:49	7.80	6.54	1.26
17PS-03	8/22/07 9:51	7.80	6.54	1.26

Appendix 2. Synoptic water-level measurements in wells during high and low tides, Solid Waste Management Unit 17, Naval Weapons Station Charleston, North Charleston, South Carolina, 2008–2009.

[NAVD 88, North American Vertical Datum of 1988; ---, data not collected]

Synoptic water levels near high tide (17:54), September 10, 2008					Synoptic water levels near low tide (11:01), September 10, 2008				
Well	Date and time	Datum (feet above NAVD 88)	Depth to water (feet below top of casing)	Water level (feet above NAVD 88)	Well	Date and time	Datum (feet above NAVD 88)	Depth to water (feet below top of casing)	Water level (feet above NAVD 88)
16MW-01S	9/10/08 16:46	7.78	6.38	1.40	16MW-01S	---	---	---	---
16MW-02S	9/10/08 16:51	4.77	2.98	1.79	16MW-02S	9/10/08 11:16	4.77	3.29	1.48
16MW-03S	9/10/08 17:00	4.74	2.53	2.21	16MW-03S	9/10/08 11:38	4.74	2.97	1.77
16MW-04S	9/10/08 17:15	4.28	2.25	2.03	16MW-04S	9/10/08 11:50	4.28	3.65	0.63
16MW-05S	9/10/08 17:10	4.40	2.23	2.17	16MW-05S	9/10/08 11:46	4.40	3.24	1.16
17MW-02S	9/10/08 16:45	7.66	4.85	2.81	17MW-02S	9/10/08 12:39	7.66	4.68	2.98
17MW-03S	9/10/08 17:43	8.74	6.16	2.58	17MW-03S	9/10/08 12:16	8.74	5.91	2.83
17MW-04S	9/10/08 16:20	7.15	3.96	3.19	17MW-04S	9/10/08 12:25	7.15	3.82	3.33
17MW-05S	9/10/08 16:32	7.77	4.58	3.19	17MW-05S	9/10/08 12:31	7.77	4.45	3.32
17MW-06D	9/10/08 16:28	7.62	4.57	3.05	17MW-06D	9/10/08 12:29	7.62	4.49	3.13
17MW-06S	9/10/08 16:30	7.88	4.7	3.18	17MW-06S	9/10/08 12:30	7.88	4.60	3.28
17MW-07S	9/10/08 16:26	7.92	4.74	3.18	17MW-07S	9/10/08 12:27	7.92	4.63	3.29
17MW-11S	9/10/08 17:34	9.67	6.95	2.72	17MW-11S	9/10/08 12:15	9.67	6.87	2.80
17MW-12D	9/10/08 17:26	7.17	5.45	1.72	17MW-12D	9/10/08 12:20	7.17	4.46	2.71
17MW-12S	9/10/08 17:24	7.37	4.21	3.16	17MW-12S	9/10/08 12:21	7.37	4.10	3.27
17MW-13S	9/10/08 17:40	7.49	6.2	1.29	17MW-13S	9/10/08 12:06	7.49	6.17	1.32
17MW-14D	9/10/08 16:52	6.63	4.51	2.12	17MW-14D	9/10/08 12:50	6.63	4.51	2.12
17MW-14S	9/10/08 16:50	6.27	3.59	2.68	17MW-14S	9/10/08 12:48	6.27	3.54	2.73
17MW-15D	9/10/08 16:56	5.90	3.74	2.16	17MW-15D	9/10/08 12:54	5.90	3.80	2.10
17MW-15S	9/10/08 16:58	6.00	2.92	3.08	17MW-15S	9/10/08 12:57	6.00	2.90	3.10
17MW-16D	9/10/08 17:02	5.89	3.71	2.18	17MW-16D	9/10/08 13:02	5.89	3.73	2.16
17MW-16I	9/10/08 17:00	6.02	3.36	2.66	17MW-16I	9/10/08 12:59	6.02	3.35	2.67
17MW-16S	9/10/08 17:05	5.80	2.63	3.17	17MW-16S	9/10/08 13:04	5.80	2.64	3.16
17MW-17D	9/10/08 17:14	5.97	3.75	2.22	17MW-17D	9/10/08 13:11	5.97	3.77	2.20
17MW-17I	9/10/08 17:08	6.03	3.54	2.49	17MW-17I	9/10/08 13:07	6.03	3.57	2.46
17MW-17S	9/10/08 17:11	6.15	2.94	3.21	17MW-17S	9/10/08 13:10	6.15	2.95	3.20
17MW-18D	9/10/08 17:19	5.42	3.16	2.26	17MW-18D	9/10/08 13:16	5.42	3.18	2.24
17MW-18S	9/10/08 17:17	5.36	2.36	3.00	17MW-18S	9/10/08 13:18	5.36	2.22	3.14
17MW19S	9/10/08 17:55	7.72	4.53	3.19	17MW19S	9/10/08 13:24	7.72	4.40	3.32
17MW-20S	9/10/08 16:24	7.32	4.12	3.20	17MW-20S	9/10/08 12:26	7.32	4.00	3.32
17MW-21S	9/10/08 17:40	10.37	8.04	2.33	17MW-21S	9/10/08 12:11	10.37	8.01	2.36
17MW-22S	9/10/08 17:37	10.18	7.68	2.50	17MW-22S	9/10/08 12:13	10.18	7.61	2.57
17MW23S	9/10/08 17:30	7.06	4	3.06	17MW23S	9/10/08 12:18	7.06	3.91	3.15
17PS-01	9/10/08 16:40	7.96	4.75	3.21	17PS-01	9/10/08 12:34	7.96	4.63	3.33
17PS-02	9/10/08 16:38	7.90	4.66	3.24	17PS-02	9/10/08 12:33	7.90	4.60	3.30
17PS-03	9/10/08 16:35	7.80	4.56	3.24	17PS-03	9/10/08 12:32	7.80	4.53	3.27

Appendix 2. Synoptic water-level measurements in wells during high and low tides, Solid Waste Management Unit 17, Naval Weapons Station Charleston, North Charleston, South Carolina, 2008–2009.—Continued

[NAVD 88, North American Vertical Datum of 1988; ---, data not collected]

Synoptic water levels near low tide (12:24), April 21, 2009				
Well	**Date and time**	**Datum (feet above NAVD 88)**	**Depth to water (feet below top of casing)**	**Water level (feet above NAVD 88)**
16MW-01S	4/21/09 13:54	7.78	4.74	3.04
16MW-02S	4/21/09 13:42	4.77	4.35	0.42
16MW-03S	4/21/09 13:36	4.74	3.04	1.70
16MW-04S	4/21/09 13:24	4.28	3.64	0.64
16MW-05S	4/21/09 13:27	4.40	3.28	1.12
17MW-02S	4/21/09 12:37	7.66	3.65	4.01
17MW-03S	4/21/09 14:15	8.74	4.67	4.07
17MW-04S	4/21/09 14:26	7.15	3.35	3.80
17MW-05S	4/21/09 12:47	7.77	3.79	3.98
17MW-06D	4/21/09 12:54	7.62	3.88	3.74
17MW-06S	4/21/09 12:48	7.88	3.92	3.96
17MW-07S	4/21/09 12:50	7.92	3.99	3.93
17MW-11S	4/21/09 14:09	9.67	5.71	3.96
17MW-12D	4/21/09 13:03	7.17	4.21	2.96
17MW-12S	4/21/09 13:04	7.37	3.37	4.00
17MW-13S	4/21/09 12:32	7.49	3.60	3.89
17MW-14D	4/21/09 12:20	6.63	4.02	2.61
17MW-14S	4/21/09 12:21	6.27	3.17	3.10
17MW-15D	4/21/09 12:18	5.90	3.25	2.65
17MW-15S	4/21/09 12:17	6.00	2.69	3.31
17MW-16D	4/21/09 12:15	5.89	3.25	2.64
17MW-16I	4/21/09 12:14	6.02	3.07	2.95
17MW-16S	4/21/09 12:15	5.80	2.49	3.31
17MW-17D	4/21/09 12:06	5.97	3.30	2.67
17MW-17I	4/21/09 12:05	6.03	3.16	2.87
17MW-17S	4/21/09 12:04	6.15	2.73	3.42
17MW-18D	4/21/09 12:02	5.42	2.75	2.67
17MW-18S	4/21/09 12:01	5.36	2.09	3.27
17MW19S	4/21/09 12:45	7.72	3.70	4.02
17MW-20S	4/21/09 11:58	7.32	3.46	3.86
17MW-21S	4/21/09 14:14	10.37	6.42	3.95
17MW-22S	4/21/09 14:10	10.18	6.24	3.94
17MW23S	4/21/09 14:06	7.06	3.07	3.99
17PS-01	4/21/09 12:42	7.96	4.07	3.89
17PS-02	4/21/09 12:43	7.90	4.01	3.89
17PS-03	4/21/09 12:41	7.80	3.92	3.88

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