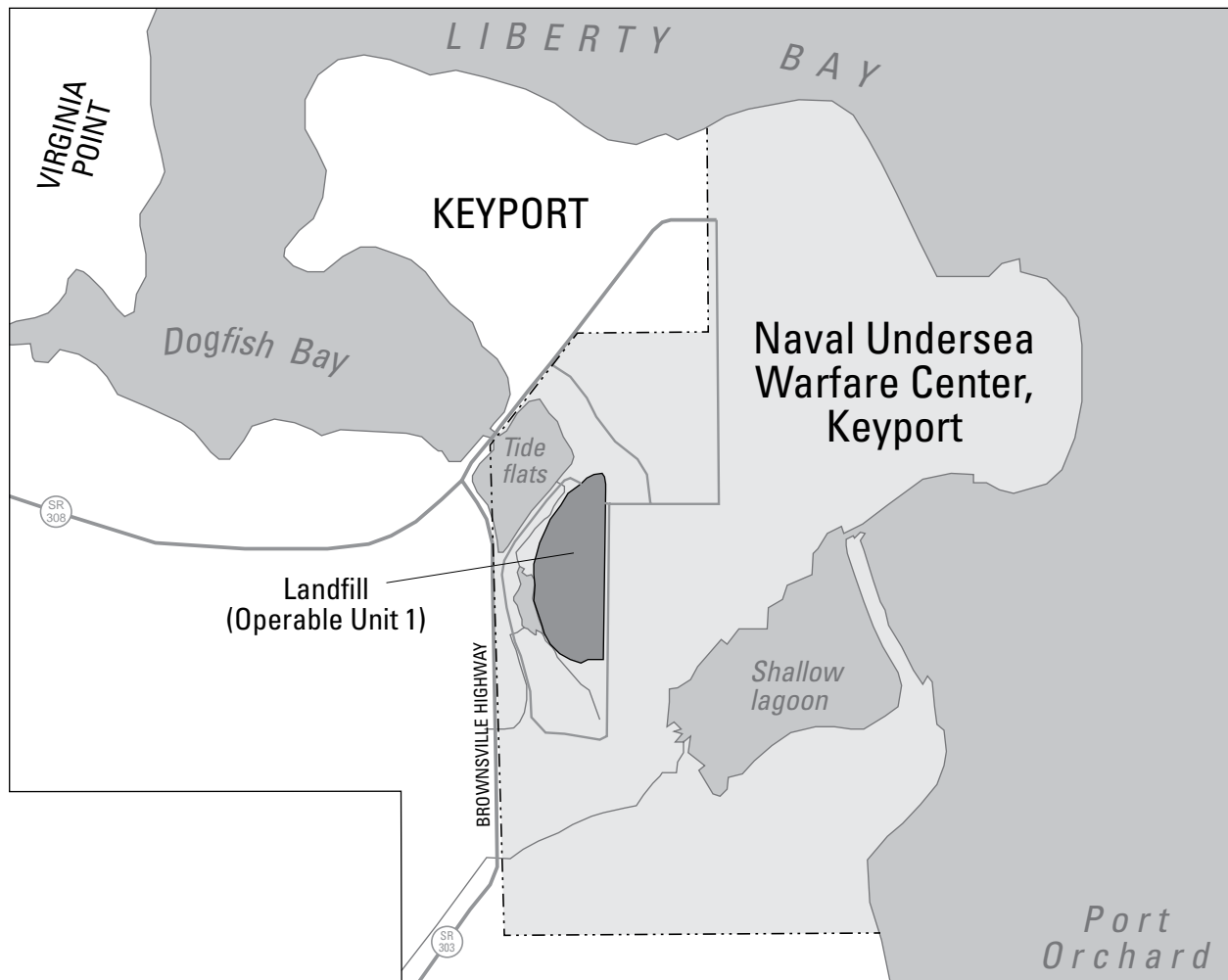


Prepared in cooperation with Department of the Navy,  
Naval Facilities Engineering Command, Northwest

## Selected Natural Attenuation Monitoring Data, Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, June 2006



Open-File Report 2007-1430



# **Selected Natural Attenuation Monitoring Data, Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, June 2006**

By R.S. Dinicola and R.L. Huffman

Prepared in cooperation with  
Department of the Navy, Naval Facilities Engineering Command, Northwest

Open-File Report 2007-1430

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

**U.S. Department of the Interior**  
DIRK KEMPTHORNE, Secretary

**U.S. Geological Survey**  
Mark D. Myers, Director

U.S. Geological Survey, Reston, Virginia: 2007

For product and ordering information:

World Wide Web: <http://www.usgs.gov/pubprod>

Telephone: 1-888-ASK-USGS

For more information on the USGS--the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:

World Wide Web: <http://www.usgs.gov>

Telephone: 1-888-ASK-USGS

Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Although this report is in the public domain, permission must be secured from the individual copyright owners to reproduce any copyrighted materials contained within this report.

Suggested citation:

Dinicola, R.S., and Huffman, R.L., 2007, Selected natural attenuation monitoring data, Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, June 2006: U.S. Geological Survey Open-File Report 2007-1430, 30 p.

## Contents

|  |    |
|--|----|
| Abstract.....  | 1  |
| Introduction.....  | 1  |
| Purpose and Scope .....  | 3  |
| Sample Collection and Analysis.....  | 6  |
| Natural Attenuation Monitoring Data.....   | 7  |
| Geochemical Data and Predominant Redox Conditions .....  | 7  |
| Volatile Organic Compounds.....  | 8  |
| VOC Concentrations Beneath the Phytoremediation Plantations .....                                      | 8  |
| VOC Concentrations in the Intermediate Aquifer .....   | 9  |
| Summary.....   | 9  |
| Acknowledgments .....  | 9  |
| References Cited.....  | 9  |
| Appendix A. Quality Assurance and Control of U.S. Geological Survey 2006<br>Geochemical Sampling ..... | 11 |

## Figures

|  |   |
|--|---|
| Figure 1. Map showing location of the Operable Unit 1 study area, Naval Undersea Warfare Center, Division Keyport, Washington .....  | 2 |
| Figure 2. Map showing location of former landfill, two phytoremediation plantations, and data collection sites at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington ..... | 4 |

## Tables

|   |    |
|---|----|
| Table 1. Wells and piezometers sampled and water levels measured at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, June 2006.....  | 5  |
| Table 2. Predominant redox conditions at wells and piezometers, and ground-water geochemical data collected at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, 1996–2006 .....                  | 12 |
| Table 3. Concentrations of selected volatile organic compounds in ground-water samples from monitoring wells and piezometers at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, 1999–2006 ..... | 24 |

## Conversion Factors, Datums, and Abbreviations and Acronyms

### Conversion Factors

| Multiply                | By     | To obtain                      |
|-------------------------|--------|--------------------------------|
| inch (in.)              | 2.54   | centimeter (cm)                |
| foot (ft)               | 0.3048 | meter (m)                      |
| mile (mi)               | 1.609  | kilometer (km)                 |
| acre                    | 4,047  | square meter (m <sup>2</sup> ) |
| acre                    | 0.4047 | hectare (ha)                   |
| gallon (gal)            | 3.785  | liter (L)                      |
| ounce, avoirdupois (oz) | 28.35  | gram (g)                       |

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

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32.$$

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

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32)/1.8.$$

### Datums

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

Horizontal coordinate information is referenced to North American Datum of 1927 (NAD 27).

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

### Abbreviations and Acronyms

| Abbreviations and Acronyms | Meaning                                  |
|----------------------------|--|
| 1,1-DCA                    | 1,1-dichloroethane                       |
| 1,2-DCA                    | 1,2-dichloroethane                       |
| 1,1-DCE                    | 1,1-dichloroethene                       |
| CA                         | chloroethane                             |
| <i>cis</i> -DCE            | <i>cis</i> -1,2-dichloroethene           |
| CO <sub>2</sub>            | carbon dioxide                           |
| DO                         | dissolved oxygen                         |
| H <sub>2</sub>             | dissolved hydrogen                       |
| mg                         | milligram                                |
| mV                         | millivolt                                |
| nM                         | nanoMolar                                |
| NUWC                       | Naval Undersea Warfare Center            |
| NWQL                       | National Water Quality Laboratory (USGS) |
| ORP                        | oxidation-reduction potential            |
| OU 1                       | Operable Unit 1                          |
| STL                        | Severn Trent Laboratories                |
| TCA                        | 1,1,1,-trichloroethane                   |
| TCE                        | trichloroethene                          |
| USEPA                      | U.S. Environmental Protection Agency     |
| USGS                       | U.S. Geological Survey                   |
| VC                         | vinyl chloride                           |
| VOC                        | volatile organic compound                |
| µg/L                       | microgram per liter                      |
| µS/cm                      | microsiemens per centimeter              |

# Selected Natural Attenuation Monitoring Data, Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, June 2006

By R.S. Dinicola and R.L. Huffman

## Abstract

Previous investigations have shown that natural attenuation and biodegradation of chlorinated volatile organic compounds (VOCs) are substantial in shallow ground water beneath the 9-acre former landfill at Operable Unit 1 (OU 1), Naval Undersea Warfare Center, Division Keyport, Washington. The U.S. Geological Survey (USGS) has continued to monitor ground-water geochemistry to assure that conditions remain favorable for contaminant biodegradation. This report presents ground-water geochemical and selected VOC data collected at OU 1 by the USGS during June 12–14, 2006, in support of long-term monitoring for natural attenuation.

For June 2006, the strongly reducing conditions (sulfate reduction and methanogenesis) most favorable for reductive dechlorination of VOCs were inferred for 5 of 15 upper-aquifer sites in the northern and southern phytoremediation plantations. Predominant redox conditions in ground water from the intermediate aquifer just downgradient from the landfill remained mildly reducing and somewhat favorable for reductive dechlorination. Since about 2003, measured dissolved hydrogen concentrations in the upper aquifer generally have been lower than those previously measured, although methane and sulfide have continued to be detected throughout the upper aquifer beneath the landfill. Overall, no widespread changes in ground-water redox conditions were measured that should result in either more or less efficient biodegradation of chlorinated VOCs.

For the northern plantation in 2006, chlorinated VOC concentrations at piezometers P1-3 and P1-4 were lower than previously measured, and trichloroethene (TCE), *cis*-1,2-dichloroethene (*cis*-DCE), or vinyl chloride (VC) were not detected at piezometers P1-1 and P1-5. The steady decrease in contaminant concentrations and the continued detection of the reductive dechlorination end-products ethene and ethane have been consistent throughout the upper aquifer beneath the northern plantation.

For the southern plantation in 2006, changes in chlorinated VOC concentrations at the piezometers were highly variable. At piezometer P1-9, the 2006 total chlorinated VOC concentration as well as the concentrations of *cis*-DCE and VC were measured at their highest levels to date; contaminant concentrations substantially decreased at piezometer P1-9 between June 2004 and June 2005. The reasons for the 2004–05 decrease in concentrations or the 2005–06 increase in concentrations are unknown. At piezometer P1-10, the consistent temporal trend of decreasing chlorinated VOC concentrations measured since 1999 ended, and the concentration of total chlorinated VOC in 2006 was the highest measured since 1999. The reductive dechlorination end-product ethene was measured at concentrations as high as 1,300 micrograms per liter in the upper aquifer beneath the southern plantation, which is reliable evidence that reductive dechlorination of VOCs is ongoing.

## Introduction

Chlorinated volatile organic compounds (VOCs) have migrated to ground water beneath the 9-acre former landfill at Operable Unit 1 (OU 1) at the Naval Undersea Warfare Center (NUWC), Division Keyport. The NUWC is on a small peninsula in Kitsap County, Washington, in an extension of Puget Sound called Liberty Bay ([fig. 1](#)). The 9-acre former landfill at OU 1 is on the narrow strip of land connecting the peninsula to the mainland and is adjacent to tidal flats that are an extension of Dogfish and Liberty Bays. The OU 1 landfill is unlined at the bottom and was constructed in a former marshland. The landfill was the primary disposal area for domestic and industrial wastes generated by NUWC Keyport from the 1930s through 1973. Paints, thinners, solvents, acids, dried sludge from a wastewater-treatment plant, and other industrial wastes were disposed of in the landfill. The most concentrated disposal area for waste paints and solvents was at the southern end of the landfill.

2 Selected Natural Attenuation Monitoring, Naval Undersea Warfare Center, Division Keyport, Washington, June 2006

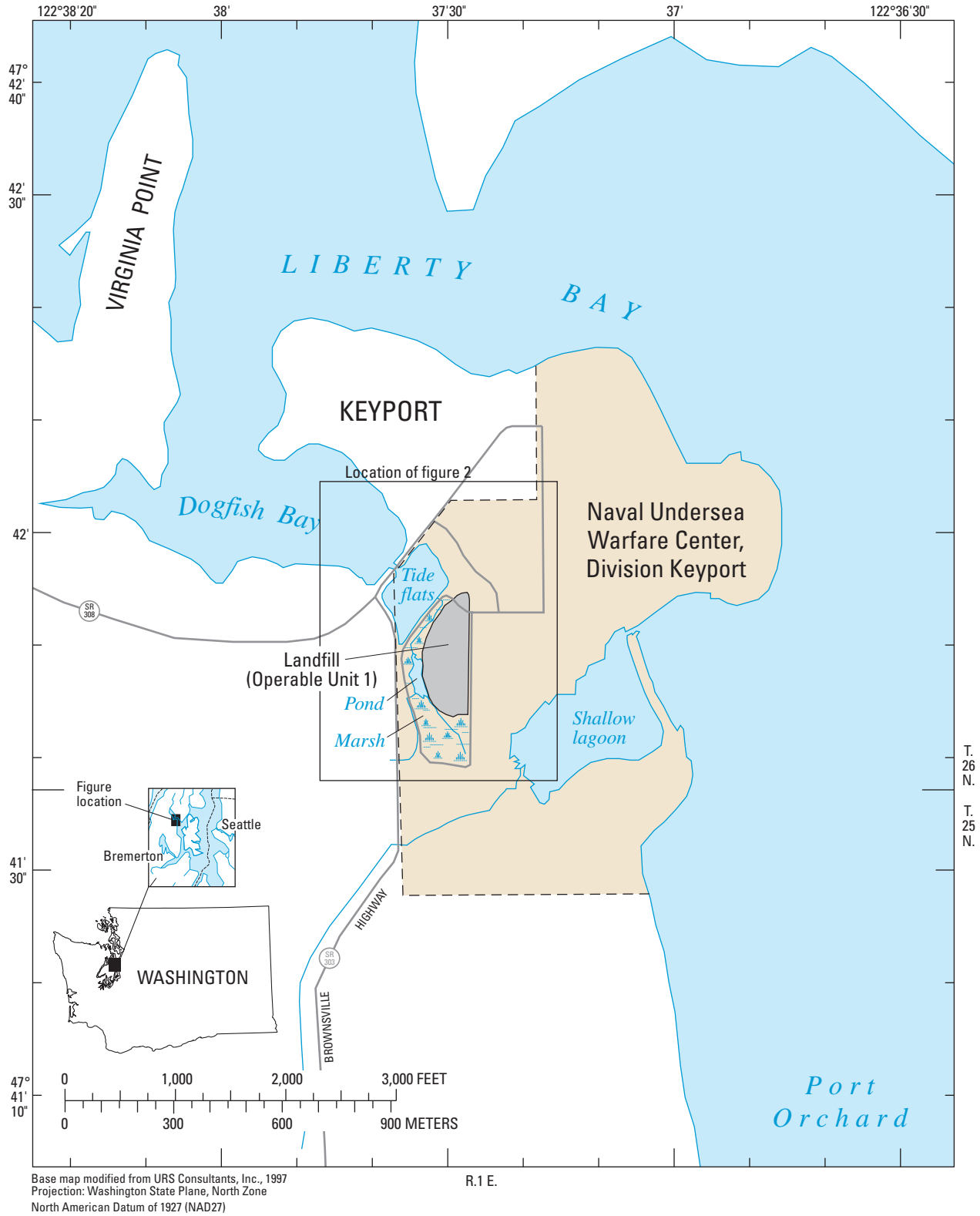


Figure 1. Location of the Operable Unit 1 study area, Naval Undersea Warfare Center, Division Keyport, Washington.



Chlorinated VOCs are present in the upper and intermediate aquifers and in surface water at OU 1. Ground water beneath OU 1 occurs within a series of aquifers that are composed of permeable sand, gravel, or fill materials separated by finer grained silt or clay layers. Contamination at OU 1 is known to occur only in about the top 60 ft of the unconsolidated deposits in the four hydrogeologic units referred to as the unsaturated zone, the upper aquifer, the middle aquitard, and the intermediate aquifer. Ground water in the unconfined upper aquifer generally flows from the east to the west toward Dogfish Bay. Ground water in the predominately confined intermediate aquifer flows toward the landfill from the south and from the west, and then flows northwest beneath the landfill toward Dogfish Bay (Dinicola and others, 2002). Two perennial freshwater creeks drain the marsh adjacent to the landfill and discharge into the tideflats of Dogfish Bay.

The predominant contaminants in ground water beneath OU 1 are trichloroethene (TCE) and its degradation byproducts *cis*-1,2-dichloroethene (*cis*-DCE) and vinyl chloride (VC). The compound 1,1,1-trichloroethane (TCA) and its degradation byproducts 1,1-dichloroethane (1,1-DCA), 1,1-dichloroethene (1,1-DCE), and chloroethane (CA) have been detected at concentrations of concern at a few locations at OU 1. A need for remedial action was identified because these hazardous compounds present a potential risk to humans (URS Consultants, Inc., 1998). Phytoremediation combined with on-going natural attenuation processes were chosen by the Navy as the preferred remedy (URS Consultants, Inc., 1998). The Navy planted two hybrid poplar plantations on the landfill ([fig. 2](#)) in the spring of 1999 to remove and control the migration of chlorinated VOCs in shallow ground water (URS Greiner, Inc., 1999). The landfill between the plantations is covered with pavement, although the area north of the northern plantation is permeable.

## Purpose and Scope

The Navy began a cooperative effort with the U.S. Geological Survey (USGS) in 1995 to investigate various natural attenuation mechanisms at OU 1. Field and laboratory studies conducted from 1996 through 2000 showed that natural attenuation and biodegradation of chlorinated VOCs in shallow ground water at OU 1 were substantial (URS Consultants, Inc., 1997; Bradley and others, 1998; Dinicola and others, 2002). The USGS has continued to monitor the geochemistry of ground water to assure that conditions remain favorable for contaminant biodegradation, and annual monitoring from 2001 through 2005 confirmed that biodegradation was continuing (Dinicola, 2006; Dinicola and Huffman, 2006).

This report presents ground-water chemical and selected VOC data collected by the USGS at OU 1 during June 12–14, 2006, in support of the long-term monitoring for natural attenuation. USGS data collected from 1996 through 2005 were presented in Dinicola and others (2002), Dinicola (2003, 2004, 2006), and Dinicola and Huffman (2004, 2006). In June 2006, the USGS collected ground-water samples from 13 wells and 9 piezometers ([table 1](#) and [fig. 2](#)). Concentrations of various geochemical constituents used to evaluate ground-water redox conditions were determined in all samples from wells and piezometers. Concentrations of VOCs also were determined by the USGS in samples from all piezometers. The Navy determined VOC concentrations in samples they collected from other OU 1 monitoring wells during 2006, but those data are not presented in this report.

4 Selected Natural Attenuation Monitoring, Naval Undersea Warfare Center, Division Keyport, Washington, June 2006

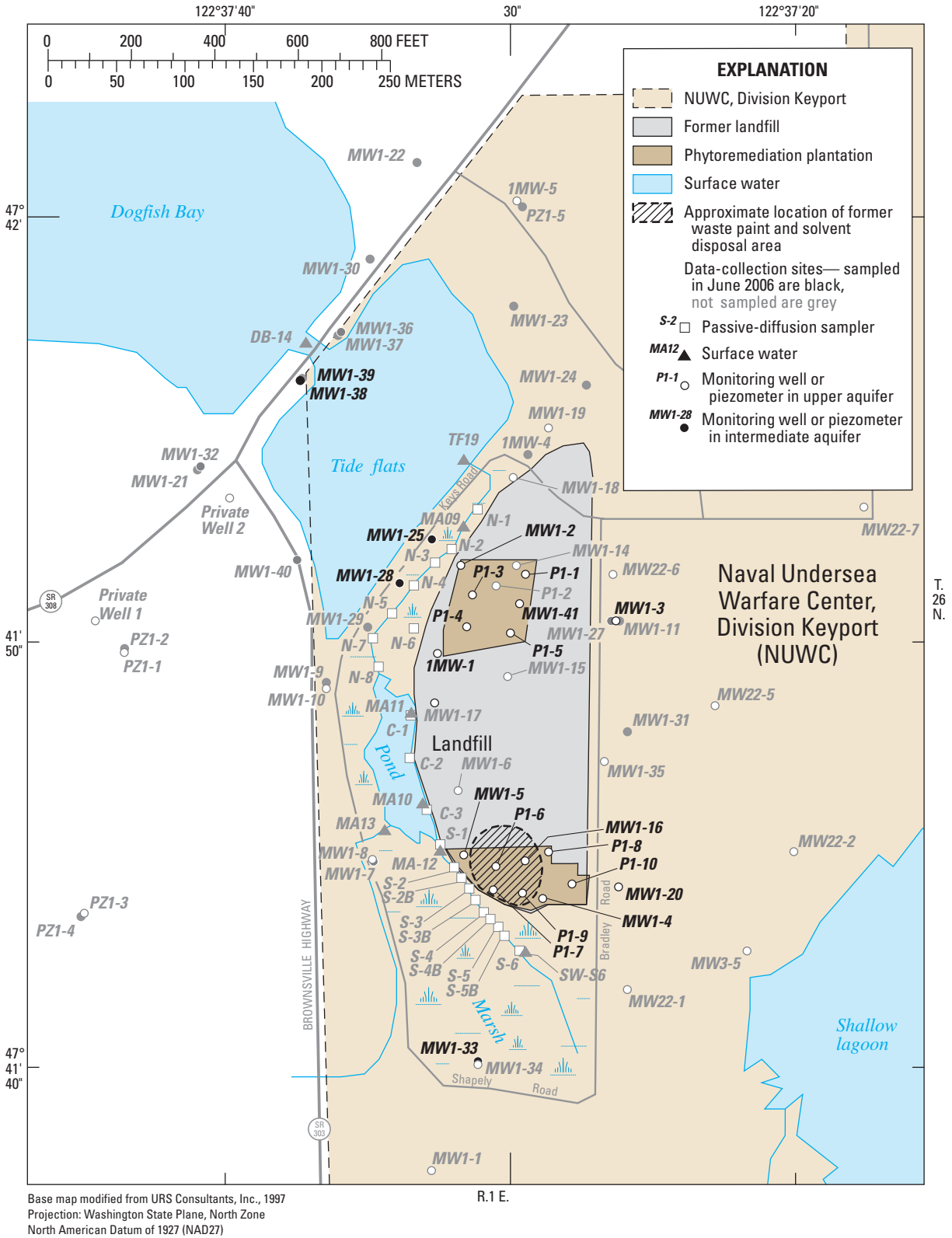


Figure 2. Location of former landfill, two phytoremediation plantations, and data collection sites at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington.

**Table 1.** Wells and piezometers sampled and water levels measured at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, June 2006.

[**Study site No.:** Location of study sites are shown in [figure 2](#). MW, monitoring well; P, piezometer; **USGS site No.:** Unique number for each site based on latitude and longitude of the site. First six digits are latitude, next seven digits are longitude, and final two digits are a sequence number to uniquely identify each site. **Altitudes of water levels and measuring points** are given in feet above or below (-) NAVD 88. **Water level** is in feet below measuring point (bmp). **Depth of well and screened interval** are in feet below land surface. **Measuring point:** Water levels in wells are usually reported as depths below land surface, although the measuring point can be any convenient fixed place near the top of the well. For these wells and piezometers, the measuring points are marked points on the tops of well casings—they vary from being near the land surface to a few feet above land surface. The altitude of the measuring point is commonly recorded so that static water levels also can be reported as altitudes; **VOCs sampled by USGS:** Y, yes, N, no. **Abbreviations:** USGS, U.S. Geological Survey; VOC, volatile organic compound; ft, foot; ft bmp, foot below measuring point; in., inch]

| Study site No.       | USGS site No.   | Date and time measured |                | Altitude of water level (ft) | Water level (ft bmp) | Altitude of measuring point (ft) | Depth of well (ft) | Casing diameter (in.) | Screened interval (ft) | VOCs sampled by USGS |
|----------------------|-----------------|------------------------|----------------|------------------------------|----------------------|----------------------------------|--------------------|-----------------------|------------------------|----------------------|
| 1MW-1                | 474151122373201 | 06-12-06               | 15:10          | 3.51                         | 6.55                 | 10.06                            | 16.5               | 2                     | 5.5–15.5               | N                    |
| MW1-2                | 474153122373101 | 06-12-06               | 11:45          | 2.45                         | 9.44                 | 11.89                            | 18.5               | 4                     | 12.5–17.5              | N                    |
| MW1-3                | 474152122372501 | 06-12-06               | 16:00          | 10.05                        | 3.50                 | 13.55                            | 11.5               | 4                     | 5.5–10.5               | N                    |
| MW1-4<br>(duplicate) | 474145122372801 | 06-13-06               | 15:30<br>15:31 | 5.72                         | 6.48                 | 12.20                            | 13.0               | 4                     | 7–12                   | N                    |
| MW1-5                | 474146122373201 | 06-13-06               | 11:40          | 2.46                         | 10.62                | 13.08                            | 12.0               | 4                     | 6–11                   | N                    |
| MW1-16               | 474146122372801 | 06-13-06               | 16:00          | 5.60                         | 7.23                 | 12.83                            | 12.0               | 2                     | 6–11                   | N                    |
| MW1-20               | 474145122372501 | 06-13-06               | 11:00          | 7.17                         | 3.27                 | 10.44                            | 16.0               | 2                     | 10–15                  | N                    |
| MW1-25               | 474154122373201 | 06-14-06               | 11:50          | 1.51                         | 10.40                | 11.91                            | 49.0               | 2                     | 38–48                  | N                    |
| MW1-28               | 474153122373301 | 06-14-06               | 12:00          | 2.38                         | 10.72                | 13.10                            | 45.0               | 2                     | 39–44                  | N                    |
| MW1-33               | 474140122373201 | 06-12-06               | 17:00          | 11.19                        | .30                  | 11.49                            | 41.0               | 2                     | 30–40                  | N                    |
| MW1-38               | 474156122373701 | 06-14-06               | 13:30          | -.65                         | 10.48                | 9.83                             | 50.0               | 2                     | 44–49                  | N                    |
| MW1-39<br>(blank)    | 474157122373701 | 06-14-06               | 13:30<br>14:30 | -.76                         | 10.61                | 9.85                             | 33.7               | 2                     | 27.7–32.7              | N                    |
| MW1-41               | 474152122372901 | 06-12-06               | 13:50          | 6.96                         | 8.31                 | 15.27                            | 15.0               | 2                     | 5–15                   | N                    |
| P1-1                 | 474153122372801 | 06-12-06               | 12:50          | 6.36                         | 8.00                 | 14.36                            | 15.0               | 1                     | 10–15                  | Y                    |
| P1-3                 | 474153122373102 | 06-12-06               | 12:00          | 3.54                         | 9.25                 | 12.79                            | 15.0               | 1                     | 10–15                  | Y                    |
| P1-4                 | 474152122373101 | 06-12-06               | 13:00          | 4.65                         | 7.90                 | 12.55                            | 15.0               | 1                     | 10–15                  | Y                    |
| P1-5                 | 474152122372801 | 06-12-06               | 14:30          | 6.34                         | 8.72                 | 15.06                            | 15.0               | 1                     | 10–15                  | Y                    |
| P1-6                 | 474146122373001 | 06-13-06               | 13:30          | 2.48                         | 10.28                | 12.76                            | 15.0               | 1                     | 10–15                  | Y                    |
| P1-7<br>(duplicate)  | 474145122373101 | 06-13-06               | 16:50<br>16:51 | 5.29                         | 6.83                 | 12.12                            | 15.0               | 1                     | 10–15                  | Y                    |
| P1-8                 | 474147122372801 | 06-13-06               | 13:30          | 6.88                         | 5.18                 | 12.06                            | 15.0               | 1                     | 10–15                  | Y                    |
| P1-9                 | 474145122372901 | 06-13-06               | 15:10          | 5.57                         | 6.34                 | 11.91                            | 15.0               | 1                     | 10–15                  | Y                    |
| P1-10                | 474145122372601 | 06-13-06               | 12:10          | 6.64                         | 5.22                 | 11.86                            | 15.0               | 1                     | 10–15                  | Y                    |

## Sample Collection and Analysis

Water-level measurements, sample collection and processing, and field analyses were in accordance with applicable USGS procedures (U.S. Geological Survey, variously dated), except that samples were collected using a peristaltic pump. Geochemical measurements and concentrations determined for samples from 13 wells and 9 piezometers included dissolved hydrogen ( $H_2$ ), dissolved oxygen (DO), filtered organic carbon, filtered nitrate plus nitrite, filtered manganese, filtered iron (II), filtered sulfate, unfiltered sulfide, dissolved methane, dissolved carbon dioxide, pH, specific conductance, oxidation-reduction potential (ORP), and filtered chloride. Concentrations of 64 VOCs were determined for samples from 9 piezometers, and concentrations of the dissolved gases ethane and ethene were determined for samples from 13 wells and 9 piezometers.

After measuring depth to water, all well and piezometer samples were collected with a peristaltic pump and single-use polyurethane tubing. A stainless-steel weight was attached to the bottom of the tubing to accurately collect the sample from the mid-screen altitude in each well. Samples were collected after approximately three casing-volumes of water were purged from the wells and after allowing pH, specific conductance, and DO to stabilize within 0.1 unit, 5 percent, and 0.3 milligram per liter (mg/L), respectively. Those three analytes and ORP were measured in a flow-through chamber using temperature compensated sensors from a YSI data sonde. The specific conductance sensor was checked daily with standard reference solutions; the pH sensor was calibrated daily with two pH standards; and the DO sensor was calibrated daily using the water-saturated air method and occasionally verified with zero dissolved-oxygen solution. Dissolved-oxygen analyses were confirmed for most samples using 0 to 1 mg/L CHEMets Rhodazine-D colorimetric ampoules (manufactured by CHEMetrics, Inc., Calverton, Virginia). These ampoules were filled directly from the sampling tube after well purging was completed.

Concentrations of iron (II) were measured in the field in samples that had been filtered through a 0.45- $\mu$ m membrane filter using a colorimetric 1,10 phenanthroline indicator method and a Hach Model 2100 spectrophotometer following Hach Method 8146 (Hach Company, 1998; adapted from American Public Health Association, 1980). Sulfide concentrations were measured in the field using a

colorimetric methylene-blue indicator method immediately using the same spectrophotometer according to Hach Method 8131 (Hach Company, 1998; procedure is equivalent to U.S. Environmental Protection Agency [USEPA] method 376.2 [U.S. Environmental Protection Agency, 1983]). Methodologies used to determine iron and sulfide concentrations also are described online at [http://www.hach.com/fmmimghach?/CODE%3AIRONFER\\_AVPP\\_OTHER\\_P1873%7C1](http://www.hach.com/fmmimghach?/CODE%3AIRONFER_AVPP_OTHER_P1873%7C1) and [http://www.hach.com/fmmimghach?/CODE%3ASULFIDE\\_NONE\\_OTHER\\_M1965%7C1](http://www.hach.com/fmmimghach?/CODE%3ASULFIDE_NONE_OTHER_M1965%7C1), respectively, accessed on October 9, 2007. Dissolved carbon dioxide ( $CO_2$ ) concentrations were measured in the field with Titret-Sodium hydroxide titrant with a pH indicator (manufactured by CHEMetrics, Inc., Calverton, Virginia).

Dissolved hydrogen ( $H_2$ ) in ground water was sampled using the bubble-strip method of Chapelle and others (1997) and concentrations were measured in the field using a reduction gas analyzer (Trace Analytical model E-001). Initial gas samples from each well were collected and analyzed after at least 20 minutes of stripping; subsequent samples were collected and analyzed at about 5-minute intervals until consecutive  $H_2$  concentrations stabilized to within 10 percent, a process that often required an hour or more.

Samples for determination of nitrate plus nitrite, manganese, sulfate, and chloride concentrations were filtered through a 0.45- $\mu$ m membrane filter into polyethylene bottles, chilled, and sent to the USGS National Water Quality Laboratory (NWQL) in Lakewood, Colorado. Manganese samples were acidified in the field with nitric acid to a pH of less than 2 and then analyzed at NWQL by inductively coupled plasma as described by Fishman (1993). Chloride and sulfate were analyzed using ion chromatography as described by Fishman (1993). Nitrate plus nitrite were analyzed colorimetrically by cadmium reduction and diazotization as described by Fishman (1993). The results for the nitrate plus nitrite analyses are referred to simply as "nitrate" in this report because nitrite was not detected historically at the site (Dinicola and others, 2002).

Samples for filtered (dissolved) organic carbon analysis were filtered through a 0.45- $\mu$ m filter, collected in amber glass bottles, acidified in the field with sulfuric acid to a pH of less than 2, chilled to less than 4°C, and shipped to NWQL. Organic carbon concentrations were determined using persulfate oxidation and infrared spectrometry as described by Brenton and Arnett (1993).

Samples for VOC analysis were collected in pre-acidified 40-mL glass vials, placed on ice, and shipped to NWQL for subsequent analysis at Severn Trent Laboratories (STL) in Denver, Colorado, using purge and trap capillary-column gas chromatography/mass spectrometry according to USEPA Method SW846 8260B (U.S. Environmental Protection Agency, 1996). Samples for analysis of ethane, ethene, and methane were collected in pre-acidified 40-mL glass vials, placed on ice, and shipped to NWQL for subsequent analysis at Severn Trent Laboratories (STL) in Denver, Colorado, using gas chromatography with a flame-ionization detector according to USEPA Method RSK SOP-175 (U.S. Environmental Protection Agency, 1994). The reporting limit for a given compound often differed between wells because of different degrees of sample dilution by STL. The VOC and dissolved gas samples were collected in pre-acidified vials supplied by STL; the vials thus could not be overfilled during sampling as is recommended in applicable USGS procedures (U.S. Geological Survey, variously dated) to avoid aeration of the sample.

Quality control of geochemical and contaminant sampling included the collection of two duplicate samples for selected redox-sensitive analytes and VOCs and analyzing one field blank sample for VOCs. No substantial quality issues were identified in those samples ([appendix A](#)).

## Natural Attenuation Monitoring Data

The ground-water chemistry data collected by the USGS at OU 1 during June 2006 in support of long-term monitoring for natural attenuation are summarized in this section. The June 2006 data include concentrations of redox-sensitive geochemical constituents and dissolved gases at 13 wells and 9 piezometers, and concentrations of VOCs at 9 piezometers. The geochemical data include concentrations of H<sub>2</sub>, DO, organic carbon, nitrate plus nitrite, manganese, iron (II), sulfate, sulfide, methane, carbon dioxide, pH, specific conductance, ORP, and chloride. The VOC data include concentrations of a subset of the 64 measured compounds and the dissolved gases ethane and ethene. Chemical concentrations are reported as less than (<) the reporting level for samples in which the analyte was neither detected nor identified.

The ground-water chemistry data are grouped with regard to location and aquifer of the well or piezometer. “Upgradient” sites are the two upper aquifer wells (MW1-3 and MW1-20) and one intermediate aquifer well (MW1-33) upgradient of the landfill. “Northern plantation” sites are all in the upper aquifer and include six wells (1MW-1, MW1-2, MW1-15, MW1-17, MW1-18, and MW1-41) and four piezometers (P1-1, P1-3, P1-4, and P1-5) in or near the northern phytoremediation plantation; piezometer P1-2 generally is dry during June and has not been sampled. “Southern plantation” sites also are all in the upper aquifer and include four wells (MW1-4, MW1-5, MW1-6, and MW1-16) and five piezometers (P1-6, P1-7, P1-8, P1-9, and P1-10) in or near the southern phytoremediation plantation. “Intermediate aquifer” sites include six intermediate aquifer wells (1MW-4, MW1-25, MW1-28, MW1-29, MW1-38, and MW1-39) that are downgradient of the landfill; no intermediate aquifer wells are in the footprint of the former landfill.

## Geochemical Data and Predominant Redox Conditions

The June 2006 data and the previous geochemical data collected by the USGS at OU 1 (Dinicola and others, 2002; Dinicola, 2003, 2004, 2006; and Dinicola and Huffman, 2004, 2006) are shown in [table 2](#) (at back of report). The predominant redox conditions for June 2006 samples were inferred primarily by DO and dissolved H<sub>2</sub> concentrations following guidelines described in Dinicola (2006).

For June 2006, predominant redox conditions in the upgradient wells in the upper aquifer (wells MW1-3 and MW1-20) were mildly reducing (manganese and iron reduction). These wells have varied between aerobic and sulfate reducing during the past 7 years ([table 2](#)). Concentrations of dissolved organic carbon have been consistently less than 2 mg/L. Redox conditions in the upgradient well in the intermediate aquifer (well MW1-33) have been consistently aerobic.

For June 2006, the strongly reducing conditions (sulfate reduction and methanogenesis) most favorable for reductive dechlorination of VOCs (Bradley, 2003) were inferred for 5 of 15 upper-aquifer sites (MW1-41, P1-1, P1-5, P1-6, and P1-9) sampled in the northern and southern plantations. The other upper-aquifer sites within the plantations had mildly reducing conditions (iron or manganese reductions). Methane



concentrations of 0.50 to 8.5 mg/L were measured at all upper-aquifer sites within the plantations in 2006, indicating that methanogenic redox conditions are common, although not predominant, throughout the former landfill. Concentrations of dissolved organic carbon, measuring 3.2 to 26 mg/L in June 2006, have been consistently greater than the 0.4 to 1.7 mg/L range measured in upgradient wells.

Predominant redox conditions in all intermediate aquifer wells downgradient of the landfill have been consistently anaerobic (table 2). Mildly reducing conditions (iron reduction) were inferred for the intermediate aquifer wells at the downgradient margin of the landfill (wells MW1-25 and MW1-28), and methane concentrations were 2.4 and 0.83 mg/L, respectively. Concentrations of dissolved organic carbon in these wells (6.3 and 6.1 mg/L in 2006, respectively) have been consistently greater than those measured in the upgradient intermediate aquifer well MW1-33 (0.4 mg/L in 2006). The mildly reducing conditions are somewhat favorable for reductive dechlorination of VOCs (Bradley, 2003).

Since 2002, measured  $H_2$  concentrations in the upper aquifer generally have been lower than those previously measured, although the continued widespread detection of methane and sulfide in shallow ground water does not suggest a trend from strongly to mildly reducing predominant redox conditions. The most substantial change in  $H_2$  concentrations measured in 2006 was at piezometer P1-9 in the southern plantation where concentrations substantially increased from less than 0.1 nM (nanomolar) in 2005 to 4.4 nM in 2006. Concentrations of manganese, iron (II), sulfide, and methane also increased at piezometer P1-9 in 2006, and the inferred predominant redox condition changed from manganese reduction to sulfate reduction. Other geochemical data for piezometer P1-9, such as chloride concentrations and specific conductance, also substantially varied at piezometer P1-9, suggesting the inherent variability in ground-water chemistry beneath a landfill. Overall, no widespread changes in ground-water redox conditions were measured that should result in either more or less efficient biodegradation of chlorinated VOCs.

## Volatile Organic Compounds

VOC data collected by the USGS from piezometers and selected wells at OU 1 from June 1999 to June 2006 are shown in table 3 (at back of report). Data for wells and piezometers are grouped with regard to location and aquifer of the well or piezometer. The "Total CVOCs" calculated for each sample is the sum of chlorinated VOC concentrations that had detected concentrations; concentrations less than the detection limit

where considered zero. Complete analytical results for the USGS data for June 2006 and previous years are available from the USGS's NWIS web site <http://waterdata.usgs.gov/wa/nwis/qwdata>, or see Dinicola and others (2002), Dinicola (2003, 2004, 2006), and Dinicola and Huffman (2004, 2006).

## VOC Concentrations Beneath the Phytoremediation Plantations

For the northern plantation in 2006, TCE, *cis*-DCE, or VC were not detected at piezometers P1-1 and P1-5. Since 1999, concentrations of most chlorinated VOCs continued to decrease at piezometers P1-3 and P1-4. The sum of concentrations of the reductive dechlorination end-products ethane and ethene were 56 and 25  $\mu\text{g/L}$  at piezometers P1-3 and P1-4. The steady decrease in contaminant concentrations and the positive detections of reductive dechlorination end-products have been consistent in the upper aquifer beneath the northern plantation.

For the southern plantation in 2006, changes in chlorinated VOC concentrations at the piezometers were highly variable. At piezometer P1-9, total chlorinated VOC, as well as *cis*-DCE and VC in 2006, were measured at their highest concentrations to date. In contrast, total chlorinated VOC concentrations between June 2004 and June 2006 decreased from 75,000 to 1,000  $\mu\text{g/L}$  at piezometer P1-9. Concentrations at piezometer P1-9 in 2006 are more consistent with previous data in that the highest contaminant concentrations at OU 1 have most often been measured at piezometer P1-9. The reasons for the 2004–05 decrease in concentrations or the 2005–06 increase in concentrations are unknown. At piezometer P1-10, the consistent temporal trend of decreasing chlorinated VOC concentrations measured since 1999 ended, and the total chlorinated VOC concentration in 2006 substantially increased. At piezometer P1-8, chlorinated VOC concentrations also increased in 2006, although they remained substantially less than the concentrations measured prior to 2003. Chlorinated VOC concentrations at piezometers P1-7 and P1-6 in 2006 generally were consistent with previous concentrations, given the relatively high year-to-year variability in contaminant concentrations in the upper aquifer beneath the southern plantation.

The sum of concentrations of the reductive dechlorination end-products ethane and ethene were 444 and 1,266  $\mu\text{g/L}$  at the most contaminated piezometers P1-7 and P1-9, respectively, and were measured at 9.5 and 72  $\mu\text{g/L}$  at piezometers P1-8 and P1-10, respectively. Those end-product concentrations are reliable evidence that reductive dechlorination of VOCs is ongoing.

## VOC Concentrations in the Intermediate Aquifer

In 2006, the reductive dechlorination end-products ethane and ethene were the only VOC concentrations analyzed in samples from the intermediate aquifer. The sum of concentrations of ethane and ethene were 21 and 18 µg/L at wells MW1-25 and MW1-28, respectively, indicating ongoing reductive dechlorination. Farther downgradient in the intermediate aquifer beneath the Highway 308 causeway at wells MW1-38 and MW1-39, ethane and ethene were not detected.

## Summary

Previous investigations have shown that natural attenuation and biodegradation of chlorinated VOCs are substantial in shallow ground water beneath the 9-acre former landfill at Operable Unit 1 (OU 1), Naval Undersea Warfare Center (NUWC), Division Keyport, Washington. The U.S. Geological Survey (USGS) has continued to monitor ground-water geochemistry to assure that conditions remain favorable for contaminant biodegradation. This report presents the ground-water geochemical and selected VOC data collected at OU 1 by the USGS during June 12–14, 2006, in support of long-term monitoring for natural attenuation. Data include concentrations of redox-sensitive geochemical constituents and dissolved gases at 13 wells and 9 piezometers, and concentrations of VOCs at 9 piezometers.

For June 2006, the strongly reducing conditions (sulfate reduction and methanogenesis) most favorable for reductive dechlorination of VOCs were inferred for 5 of 15 upper-aquifer sites in the northern and southern plantations. Predominant redox conditions in ground water from the intermediate aquifer just downgradient of the landfill remained mildly reducing and somewhat favorable for reductive dechlorination. Since about 2003, measured H<sub>2</sub> concentrations in the upper aquifer generally have been lower than those previously measured, although methane and sulfide have continued to be detected throughout the upper aquifer beneath the landfill. Overall, no widespread changes in ground-water redox conditions were measured that should result in either more or less efficient biodegradation of chlorinated VOCs.

For the northern plantation in 2006, chlorinated VOC concentrations at piezometers P1-3 and P1-4 were lower than previously measured, and TCE, *cis*-DCE, or VC were not detected at piezometers P1-1 and P1-5. The steady decrease in contaminant concentrations has been consistent in the

upper aquifer beneath the northern plantation. The reductive dechlorination end-products ethene and ethane were measured at concentrations as high as 61 micrograms per liter in the upper aquifer beneath the northern plantation, which is reliable evidence that reductive dechlorination of VOCs is ongoing.

For the southern plantation in 2006, changes in chlorinated VOC concentrations at the piezometers were highly variable. At piezometer P1-9, total chlorinated VOCs, as well as *cis*-DCE and VC in 2006, were measured at their highest concentrations to date; contaminant concentrations between June 2004 and June 2005 substantially decreased at piezometer P1-9 for reasons unknown. At piezometer P1-10, the consistent temporal trend of decreasing chlorinated VOC concentrations measured since 1999 ended, and the total chlorinated VOC concentration in 2006 substantially increased. The reductive dechlorination end-products ethene and ethane were measured at concentrations as high as 1,300 µg/L in the upper aquifer beneath the southern plantation, which is reliable evidence that reductive dechlorination of VOCs is ongoing.

## Acknowledgments

The author thanks Douglas Thelin of the Naval Facilities Engineering Command Northwest for his guidance and funding for the continued monitoring. Gene Ellis of the Naval Undersea Warfare Center, Division Keyport, Washington, provided logistical support for field activities. U.S. Geological Survey, Tacoma, Washington, staff Stephen Cox, Greg Justin, and Karen Payne assisted with data collection and analysis.

## References Cited

- American Public Health Association, 1980, Standard methods for the examination of water and wastewater (15th ed.): Washington, D.C.
- Bradley, P.M., 2003, History and ecology of chloroethene degradation—A review: *Bioremediation Journal*, v. 7, no. 2, p. 81–109.
- Bradley, P.M., Landmeyer, J.E., and Dinicola, R.S., 1998, Anaerobic oxidation of [1,2-14C] dichloroethene under Mn(IV)-reducing conditions: *Applied and Environmental Microbiology*, v. 64, no. 4, p. 1560–1562.

## 10 Selected Natural Attenuation Monitoring, Naval Undersea Warfare Center, Division Keyport, Washington, June 2006

- Brenton, R.W., and Arnett, T.L., 1993, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of dissolved organic carbon by UV-promoted persulfate oxidation and infrared spectrometry: U.S. Geological Survey Open-File Report 92-480, 12 p.
- Chapelle, F.H., Vroblesky, D.A., Woodward, J.C., and Lovely, D.R., 1997, Practical considerations for measuring hydrogen concentrations in groundwater: *Environmental Science and Technology*, v. 31, no. 10, p. 2873–2877.
- Dinicola, R.S., 2003, Natural attenuation monitoring data during June 2001, Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington: U.S. Geological Survey Open-File Report 03-344, 17 p.
- Dinicola, R.S., 2004, Selected natural attenuation monitoring data, Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington: U.S. Geological Survey Open-File Report 2004-1203, 19 p.
- Dinicola, R.S., 2006, Continued biodegradation of chloroethene compounds in ground water at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington: U.S. Geological Survey Scientific Investigations Report 2006-5056, 42 p.
- Dinicola, R.S., Cox, S.E., Landmeyer, J.E., and Bradley, P.M., 2002, Natural attenuation of chlorinated volatile organic compounds in ground water at Operable Unit 1, Naval Undersea Weapons Center, Division Keyport, Washington: U.S. Geological Survey Water-Resources Investigations Report 02-4119, 19 p.
- Dinicola, R.S., and Huffman, R.L., 2004, Selected natural attenuation monitoring data, Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, June 2003: U.S. Geological Survey Open-File Report 2004-1330, 19 p.
- Dinicola, R.S., and Huffman, R.L., 2006, Selected natural attenuation monitoring data, Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, June 2005: U.S. Geological Survey Open-File Report 2006-1374, 27 p.
- Fishman, M.J., ed., 1993, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of inorganic and organic constituents in water and fluvial sediments: U.S. Geological Survey Open-File Report 93-125, 217 p.
- Hach Company, 1998, DR/2010 Spectrophotometer Procedures Manual: Loveland, Colo., Hach Company.
- URS Consultants, Inc., 1997, Final summary data assessment report for Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington: Seattle, Wash., prepared by URS Consultants for Engineering Field Activity, Northwest, Naval Facilities Engineering Command, Poulso, Wash., 3 Volumes.
- URS Consultants, Inc., 1998, Final record of decision for Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington: Seattle, Wash., prepared by URS Consultants, for Engineering Field Activity, Northwest, Naval Facilities Engineering Command, Poulso, Wash., 111 p.
- URS Greiner, Inc., 1999, Phytoremediation closure report for Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington: Seattle, Wash., prepared by URS Greiner, Inc. for Engineering Field Activity, Northwest, Naval Facilities Engineering Command, Poulso, Wash.
- U.S. Environmental Protection Agency, 1983, Methods for chemical analysis of water and wastes—Office of Research chemical analysis of water and wastes: Washington, D.C., Office of Research and Development Report EPA 600/4-79-020, 552 p.
- U.S. Environmental Protection Agency, 1994, RSKSOP 175 rev. no. 2, Sample preparations and calculations for dissolved gas analysis in water samples using a GC headspace equilibration technique: U.S. Environmental Protection Agency Test Methods, Region 1, 14 p., accessed October 2007 at <http://www.epa.gov/region1/info/testmethods/pdfs/RSKsop175v2.pdf>
- U.S. Environmental Protection Agency, 1996, VOCs by GC/MS Capillary column technique, SW-846, Chap. 4.3.2: U.S. Environmental Protection Agency Test Methods, 16 p., accessed October 2007 at <http://www.epa.gov/epaoswer/hazwaste/test/pdfs/chap4.pdf>
- U.S. Geological Survey, variously dated, National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chaps. A1–A9, available online at <http://pubs.water.usgs.gov/twri9A>



## Appendix A. Quality Assurance and Control of U.S. Geological Survey 2006 Geochemical Sampling

Quality assurance and control of geochemical sampling included the collection of duplicate and field blank samples for selected redox-sensitive analytes and volatile organic compounds (VOCs). Field blanks were collected by pumping VOC-free water through previously used and cleaned tubing to determine possible sampling contamination in samples collected at known contaminated wells only; new tubing was used to sample from wells that were known to be uncontaminated or slightly contaminated and from piezometers sampled for the first time. Complete laboratory quality assurance and control data from Severn-Trent Laboratories is on file with the USGS office in Tacoma, Washington.

Duplicate sample results compared favorably for all constituents (Appendix [table A1](#)). A duplicate sample was collected and analyzed by NWQL for organic carbon, manganese, nitrate and nitrite, sulfate, chloride, ethene, and ethane for well MW1-4. The duplicate results for these constituents agreed within 10 percent. A duplicate sample was collected and analyzed for piezometer P1-7 and the chlorinated VOC concentrations agreed within 15 percent ([table 3](#)).

Chloroethenes, chloroethanes, and benzene, toluene, ethylbenzene, and xylene (BTEX) were not detected in the field blank sample of pumped VOC-free water (site P1-39FB). No ethene, ethane, or chloroethene or chloroethane compounds of interest were detected in the laboratory method blanks.

**Table A1.** Quality assurance data collected by the U.S. Geological Survey at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, 2006.

[Study site No.: Location of study sites are shown in [figure 2](#). MW, monitoring well; P, piezometer. D denotes duplicate sample; FB denotes field blank sample. **Volatile organic compounds (VOCs):** PCE, tetrachloroethene; TCE, trichloroethene; *cis*-DCE, *cis*-1,2-dichloroethene; *trans*-DCE, *trans*-1,2-dichloroethene; VC, vinyl chloride; TCA, 1,1,1-trichloroethane; 1,1-DCA, 1,1-dichloroethane, 1,1-DCE, 1,1-dichloroethene; CA, chloroethane; BTEX, benzene, toluene, ethylbenzene, and xylene; CVOCs, sum of all chloroethenes and chloroethane concentrations shown in table. **Abbreviations:** mg/L, milligram per liter; nd, not detected; µg/L, microgram per liter; nd, not detected. **Symbols:** <, actual value is less than the value shown; –, not analyzed]

| Study site No. | Date sampled | PCE    | TCE    | <i>cis</i> -DCE | <i>trans</i> -DCE | VC     | Ethane | Ethene | 1,1,1-TCA | 1,1-DCA | CA     | 1,1-DCE |
|----------------|--------------|--------|--------|-----------------|-------------------|--------|--------|--------|-----------|---------|--------|---------|
|                |              | (µ/L)  | (µg/L) | (µg/L)          | (µg/L)            | (µg/L) | (µg/L) | (µg/L) | (µg/L)    | (µg/L)  | (µg/L) | (µg/L)  |
| P1-7           | 06-13-06     | <2,000 | 24,000 | 43,000          | <2,000            | 3,800  | 44     | 400    | <2,000    | <2,000  | <4,000 | <2,000  |
| P1-7D          | 06-13-06     | <2,000 | 28,000 | 48,000          | <2,000            | 4,200  | –      | –      | <2,000    | <2,000  | <4,000 | <2,000  |
| MW1-4          | 06-13-06     | –      | –      | –               | –                 | –      | 39     | 200    | –         | –       | –      | –       |
| MW1-4D         | 06-33-06     | –      | –      | –               | –                 | –      | 35     | 180    | –         | –       | –      | –       |
| MW1-39FB       | 06-14-06     | <1.0   | <1.0   | <1.0            | <1.0              | <1.0   | –      | –      | <1.0      | <1.0    | <2.0   | <1.0    |

| Study site No. | Date sampled | Total       |              | Dissolved oxygen (mg/L) | Filtered NO <sub>2</sub> + NO <sub>3</sub> (mg/L) | Dissolved organic carbon, filtered (mg/L) | Manganese, filtered (mg/L) | Iron (II), filtered (mg/L) | Sulfate, filtered (mg/L) | Sulfide, unfiltered (mg/L) | Dissolved methane (mg/L) | Dissolved carbon dioxide (mg/L) | Chloride, filtered (mg/L) |
|----------------|--------------|-------------|--------------|-------------------------|---|---|----------------------------|----------------------------|--------------------------|----------------------------|--------------------------|---------------------------------|---------------------------|
|                |              | BTEX (µg/L) | CVOCs (µg/L) |                         |   |   |                            |                            |                          |                            |                          |                                 |                           |
| P1-7           | 06-13-06     | nd          | 70,800       | 0.5                     | <0.06   | 7.6                                       | 2.0                        | 1.82                       | 20.2                     | <0.01                      | 2.1                      | –                               | 48.8                      |
| P1-7D          | 06-13-06     | nd          | –            | –                       | –   | –   | –                          | –                          | –                        | –                          | –                        | –                               | –                         |
| MW1-4          | 06-13-06     | –           | –            | .1                      | <.06  | 3.9                                       | .79                        | .19                        | 5.7                      | .01                        | 2.1                      | 30                              | 19.6                      |
| MW1-4D         | 06-13-06     | –           | –            | .1                      | <.06  | 3.6                                       | .77                        | .19                        | 5.7                      | .02                        | 1.9                      | 35                              | 19.8                      |
| MW1-39FB       | 06-06-06     | nd          | nd           | –                       | <.06  | .2  | <.006                      | –                          | <.2                      | –                          | –                        | –                               | <.20                      |

12 Selected Natural Attenuation Monitoring, Naval Undersea Warfare Center, Division Keyport, Washington, June 2006

**Table 2.** Predominant redox conditions at wells and piezometers, and ground-water geochemical data collected at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, 1996–2006.

[Shaded rows indicate 2006 data. All other data were published in Dinicola and others (2002), Dinicola (2003, 2004), and Dinicola and Huffman, 2004, 2006; prior to 2000, bicarbonate was calculated from an unfiltered sample. Reported concentrations less than the detection limit usually are estimated. **Study site No.:** Location of study sites are shown in [figure 2](#). MW, monitoring well; P, piezometer. **Predominant redox condition:** A, aerobic; An, anaerobic, but specific redox condition could not be determined; Fe, iron reducing; M, methanogenic; Mn, manganese reducing; S, sulfate reducing. **Dissolved hydrogen:** A range of dissolved hydrogen concentrations are shown when equilibration at a single value was never achieved. Selected 2002 dissolved-hydrogen data were rejected (R) because of interference from downhole instruments. **Dissolved oxygen:** Selected 1996 dissolved-oxygen data were rejected (R) because of inadequate well purging. **Abbreviations:** nM, nanomolar; mg/L, milligram per liter;  $\mu$ S/cm, microSiemen per centimeter at 25 degrees Celsius; ORP, oxidation-reduction potential; mV, millivolt. **Symbols:** <, actual value is less than value shown; >, actual value is greater than value shown; –, not analyzed]

| Study site No.      | Date sampled | Predominant redox condition | Dissolved hydrogen (nM) | Dissolved oxygen (mg/L) | Total organic carbon, unfiltered (mg/L) | Dissolved organic carbon, filtered (mg/L) | Nitrate + nitrite, filtered (mg/L as N) | Manganese, filtered (mg/L) | Iron (II), filtered (mg/L) | Sulfate, filtered (mg/L) |
|---------------------|--------------|-----------------------------|-------------------------|-------------------------|---|---|---|----------------------------|----------------------------|--------------------------|
| Upgradient          |              |                             |                         |                         |   |   |   |                            |                            |                          |
| MW1–3               | 06-09-99     | Fe                          | 0.8                     | 0.4                     | –                                       | –   | –                                       | 0.07                       | <0.01                      | –                        |
|                     | 06-20-00     | Fe                          | .2                      | .3                      | 2.0                                     | –   | 0.99                                    | .08                        | <.01                       | 13                       |
|                     | 06-12-01     | A                           | –                       | 4.0                     | 2.3                                     | 1.1                                       | 1.1                                     | .04                        | .02                        | 14                       |
|                     | 06-10-02     | S                           | 2.7                     | .4                      | –                                       | 1.4                                       | 1.6                                     | .10                        | .01                        | 11                       |
|                     | 06-17-03     | A                           | –                       | 4.3                     | –                                       | 1.7                                       | 1.8                                     | .09                        | .05                        | 12                       |
|                     | 06-15-04     | Mn/Fe                       | .2                      | .2                      | –                                       | 1.6                                       | –                                       | .09                        | <.01                       | 12                       |
|                     | 06-20-05     | Mn/Fe                       | <.1                     | .1                      | –                                       | 1.4                                       | 1.6                                     | .10                        | .01                        | 15                       |
|                     | 06-12-06     | Mn/Fe                       | <.1                     | .1                      | –                                       | 1.4                                       | 1.6                                     | .11                        | <.01                       | 14                       |
| MW1–20              | 06-08-99     | Fe                          | .9                      | .3                      | –                                       | –   | –                                       | .35                        | .03                        | –                        |
|                     | 06-21-00     | Fe                          | .4                      | <.1                     | 2.2                                     | –   | <.05                                    | .24                        | .11                        | 16                       |
|                     | 06-13-01     | S                           | 2.1                     | .2                      | 3.0                                     | 1.4                                       | <.05                                    | .28                        | .01                        | 20                       |
|                     | 06-12-02     | An                          | >100R                   | .1                      | –                                       | 1.4                                       | <.05                                    | .16                        | .01                        | 17                       |
|                     | 06-17-03     | Fe                          | .5                      | .2                      | –                                       | 1.7                                       | <.06                                    | .24                        | .05                        | 18                       |
|                     | 06-15-04     | Mn/Fe                       | .1                      | .9                      | –                                       | 1.6                                       | –                                       | .23                        | .03                        | 18                       |
|                     | 06-20-05     | Mn/Fe                       | .1                      | .4                      | –                                       | 1.5                                       | <.06                                    | .25                        | .21                        | 16                       |
|                     | 06-13-06     | Mn/Fe                       | .1                      | .1                      | –                                       | 1.7                                       | <.06                                    | .21                        | .08                        | 16                       |
| MW1–33              | 10-07-98     | A                           | –                       | 3.3                     | .1                                      | –   | –                                       | .003                       | <.01                       | –                        |
|                     | 06-21-00     | A                           | –                       | 3.8                     | .7                                      | –   | 1.3                                     | <.002                      | <.01                       | 7.5                      |
|                     | 06-11-01     | A                           | –                       | 3.8                     | 1.5                                     | 1.4                                       | 1.1                                     | <.003                      | <.01                       | 8.2                      |
|                     | 06-10-02     | A                           | –                       | 3.4                     | –                                       | 1.2                                       | 1.1                                     | <.002                      | <.01                       | 7.3                      |
|                     | 06-17-03     | A                           | –                       | 3.0                     | –                                       | .7  | .98                                     | <.004                      | <.01                       | 7.4                      |
|                     | 06-15-04     | A                           | –                       | –                       | –                                       | .6  | –                                       | <.008                      | <.01                       | 6.6                      |
|                     | 06-20-05     | A                           | –                       | 3.5                     | –                                       | .5  | 1.7                                     | <.006                      | <.01                       | 6.3                      |
|                     | 06-12-06     | A                           | –                       | 3.9                     | –                                       | .4  | 1.8                                     | <.006                      | .02                        | 5.7                      |
| Northern plantation |              |                             |                         |                         |   |   |   |                            |                            |                          |
| 1MW-1               | 09-17-96     | Fe                          | 0.4                     | 2.8R                    | 7.0                                     | –   | <0.02                                   | 0.18                       | 0.24                       | 7.5                      |
|                     | 04-16-97     | Fe                          | .8                      | .4                      | –                                       | –   | .11                                     | –                          | 8.0                        | 1.4                      |
|                     | 03-05-98     | Fe/S                        | .2                      | .1                      | 8.3                                     | –   | –                                       | .39                        | 12                         | –                        |
|                     | 10-09-98     | Fe                          | .2                      | .5                      | –                                       | –   | –                                       | .08                        | .39                        | –                        |
|                     | 06-21-00     | Mn/Fe                       | .1                      | .5                      | 12                                      | –   | <.05                                    | .96                        | 13                         | .9                       |
|                     | 06-11-01     | Fe                          | .6                      | .7                      | 13                                      | 12  | <.05                                    | .24                        | 2.9                        | 2.2                      |
|                     | 06-10-02     | Fe                          | .4                      | .2                      | –                                       | 14  | <.05                                    | .37                        | 7.3                        | 1.7                      |
|                     | 06-17-03     | Fe                          | .1                      | .1                      | –                                       | 10  | <.06                                    | .17                        | 1.2                        | 2.2                      |
|                     | 06-16-04     | Fe                          | .2                      | .1                      | –                                       | 7.7                                       | –                                       | .09                        | .38                        | 2.0                      |
|                     | 06-21-05     | Fe                          | .1                      | .1                      | –                                       | 9.5                                       | <.06                                    | .12                        | 1.8                        | 1.7                      |
|                     |              | 06-12-06                    | Mn/Fe                   | <.1                     | .2                                      | –   | 8.5                                     | <.06                       | .12                        | .8                       |

**Table 2.** Predominant redox conditions at wells and piezometers, and ground-water geochemical data collected at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, 1996–2006.—Continued

[Shaded rows indicate 2006 data. All other data were published in Dinicola and others (2002), Dinicola (2003, 2004), and Dinicola and Huffman, 2004, 2006; prior to 2000, bicarbonate was calculated from an unfiltered sample. Reported concentrations less than the detection limit usually are estimated. **Study site No.:** Location of study sites are shown in [figure 2](#). MW, monitoring well; P, piezometer. **Predominant redox condition:** A, aerobic; An, anaerobic, but specific redox condition could not be determined; Fe, iron reducing; M, methanogenic; Mn, manganese reducing; S, sulfate reducing. **Dissolved hydrogen:** A range of dissolved hydrogen concentrations are shown when equilibration at a single value was never achieved. Selected 2002 dissolved-hydrogen data were rejected (R) because of interference from downhole instruments. **Dissolved oxygen:** Selected 1996 dissolved-oxygen data were rejected (R) because of inadequate well purging. **Abbreviations:** nM, nanomolar; mg/L, milligram per liter;  $\mu\text{S}/\text{cm}$ , microSiemen per centimeter at 25 degrees Celsius; ORP, oxidation-reduction potential; mV, millivolt. **Symbols:** <, actual value is less than value shown; >, actual value is greater than value shown; –, not analyzed]

| Study site No.      | Date sampled | Predominant redox condition | Sulfide, unfiltered (mg/L) | Dissolved methane (mg/L) | Dissolved carbon dioxide (mg/L) | Bicarbonate, filtered (mg/L) | pH (units) | Specific conductance ( $\mu\text{S}/\text{cm}$ ) | ORP (mV) | Chloride, filtered (mg/L) |
|---------------------|--------------|-----------------------------|----------------------------|--------------------------|---------------------------------|------------------------------|------------|--|----------|---------------------------|
| Upgradient          |              |                             |                            |                          |                                 |                              |            |  |          |                           |
| MW1-3               | 06-09-99     | Fe                          | <0.01                      | –                        | –                               | 81                           | 6.0        | 202  | –        | –                         |
|                     | 06-20-00     | Fe                          | <.01                       | 0.02                     | –                               | 82                           | 5.9        | 205  | 180      | 8.4                       |
|                     | 06-12-01     | A                           | <.01                       | .12                      | –                               | 90                           | 6.1        | 203  | 220      | 10                        |
|                     | 06-10-02     | S                           | <.01                       | .06                      | 140                             | 80                           | 5.8        | 182  | 400      | 9.7                       |
|                     | 06-17-03     | A                           | –                          | .02                      | 80                              | –                            | 6.0        | 199  | 200      | 10                        |
|                     | 06-15-04     | Mn/Fe                       | <.01                       | .01                      | –                               | 73                           | 5.7        | 205  | 195      | 9.1                       |
|                     | 06-20-05     | Mn/Fe                       | <.01                       | –                        | <50                             | –                            | 6.0        | 192  | –        | 7.5                       |
|                     | 06-12-06     | Mn/Fe                       | <.01                       | .004                     | 40                              | –                            | 5.5        | 243  | 136      | 7.0                       |
| MW1-20              | 06-08-99     | Fe                          | <.01                       | –                        | –                               | 260                          | 6.7        | 546  | –        | –                         |
|                     | 06-21-00     | Fe                          | <.01                       | .01                      | –                               | 240                          | 6.8        | 530  | 79       | 14                        |
|                     | 06-13-01     | S                           | <.01                       | .27                      | –                               | 260                          | 6.4        | 544  | 250      | 33                        |
|                     | 06-12-02     | An                          | <.01                       | .06                      | 97                              | 250                          | 7.0        | 701  | 180      | 29                        |
|                     | 06-17-03     | Fe                          | –                          | .09                      | 90                              | –                            | 6.3        | 491  | 290      | 32                        |
|                     | 06-15-04     | Mn/Fe                       | <.01                       | .03                      | –                               | 260                          | 6.4        | 552  | 98       | 35                        |
|                     | 06-20-05     | Mn/Fe                       | <.01                       | –                        | 80                              | –                            | 6.3        | 520  | 87       | 28                        |
|                     | 06-13-06     | Mn/Fe                       | <.01                       | .03                      | 60                              | –                            | 6.3        | 574  | 70       | 31                        |
| MW1-33              | 10-07-98     | A                           | <.01                       | –                        | –                               | 78                           | 6.6        | 177  | –        | –                         |
|                     | 06-21-00     | A                           | <.01                       | .05                      | –                               | 74                           | 6.7        | 164  | 160      | 4.0                       |
|                     | 06-11-01     | A                           | <.01                       | .07                      | –                               | 71                           | 6.2        | 154  | 300      | 3.6                       |
|                     | 06-10-02     | A                           | <.01                       | .004                     | 31                              | 81                           | 6.5        | 138  | 360      | 3.4                       |
|                     | 06-17-03     | A                           | <.01                       | .01                      | 25                              | –                            | 6.3        | 156  | 110      | 3.7                       |
|                     | 06-15-04     | A                           | –                          | <.005                    | 13                              | –                            | 6.7        | 165  | –        | 4.0                       |
|                     | 06-20-05     | A                           | –                          | –                        | 18                              | –                            | 6.6        | 154  | –        | 4.1                       |
|                     | 06-12-06     | A                           | –                          | .002                     | 18                              | –                            | 6.7        | 159  | 72       | 4.3                       |
| Northern plantation |              |                             |                            |                          |                                 |                              |            |  |          |                           |
| 1MW-1               | 09-17-96     | Fe                          | <0.01                      | 10                       | –                               | 640                          | 7.9        | –  | –        | 43                        |
|                     | 04-16-97     | Fe                          | .01                        | 29                       | –                               | 1,100                        | 7.2        | –  | –        | –                         |
|                     | 03-05-98     | Fe/S                        | .06                        | –                        | –                               | –                            | –          | –  | –        | –                         |
|                     | 10-09-98     | Fe                          | .01                        | –                        | –                               | 660                          | 7.7        | 1,080  | –        | –                         |
|                     | 06-21-00     | Mn/Fe                       | <.01                       | .39                      | –                               | 590                          | 7.0        | 1,070  | -92      | 44                        |
|                     | 06-11-01     | Fe                          | <.01                       | 5.6                      | –                               | 550                          | 7.1        | 974  | -110     | 50                        |
|                     | 06-10-02     | Fe                          | <.01                       | 14                       | 77                              | 520                          | 7.7        | 835  | -160     | 54                        |
|                     | 06-17-03     | Fe                          | <.01                       | 7.1                      | 50                              | –                            | 7.3        | 847  | –        | 54                        |
|                     | 06-16-04     | Fe                          | .03                        | 1.8                      | 18                              | –                            | 7.0        | 843  | -184     | 57                        |
|                     | 06-21-05     | Fe                          | .02                        | –                        | 20                              | –                            | 7.1        | 827  | -108     | 48                        |
|                     |              | 06-12-06                    | Mn/Fe                      | .01                      | 3.4                             | 10                           | –          | 7.4  | 787      | -134                      |

14 Selected Natural Attenuation Monitoring, Naval Undersea Warfare Center, Division Keyport, Washington, June 2006

**Table 2.** Predominant redox conditions at wells and piezometers, and ground-water geochemical data collected at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, 1996–2006.—Continued

[Shaded rows indicate 2006 data. All other data were published in Dinicola and others (2002), Dinicola (2003, 2004), and Dinicola and Huffman, 2004, 2006; prior to 2000, bicarbonate was calculated from an unfiltered sample. Reported concentrations less than the detection limit usually are estimated. **Study site No.:** Location of study sites are shown in figure 2. MW, monitoring well; P, piezometer. **Predominant redox condition:** A, aerobic; An, anaerobic, but specific redox condition could not be determined; Fe, iron reducing; M, methanogenic; Mn, manganese reducing; S, sulfate reducing. **Dissolved hydrogen:** A range of dissolved hydrogen concentrations are shown when equilibration at a single value was never achieved. Selected 2002 dissolved-hydrogen data were rejected (R) because of interference from downhole instruments. **Dissolved oxygen:** Selected 1996 dissolved-oxygen data were rejected (R) because of inadequate well purging. **Abbreviations:** nM, nanomolar; mg/L, milligram per liter;  $\mu$ S/cm, microSiemen per centimeter at 25 degrees Celsius; ORP, oxidation-reduction potential; mV, millivolt. **Symbols:** <, actual value is less than value shown; >, actual value is greater than value shown; –, not analyzed]

| Study site No.                | Date sampled | Predominant redox condition | Dissolved hydrogen (nM) | Dissolved oxygen (mg/L) | Total organic carbon, unfiltered (mg/L) | Dissolved organic carbon, filtered (mg/L) | Nitrate + nitrite, filtered (mg/L as N) | Manganese, filtered (mg/L) | Iron (II), filtered (mg/L) | Sulfate, filtered (mg/L) |
|-------------------------------|--------------|-----------------------------|-------------------------|-------------------------|---|---|---|----------------------------|----------------------------|--------------------------|
| Northern plantation—Continued |              |                             |                         |                         |   |   |   |                            |                            |                          |
| MW1–2                         | 09-17-96     | A                           | 0.5                     | 2.4R                    | 6.0                                     | –   | <0.02                                   | 0.05                       | 0.23                       | 4.6                      |
|                               | 04-16-97     | Fe                          | .7                      | .2                      | –                                       | –   | <.02                                    | –                          | .13                        | 4.6                      |
|                               | 03-02-98     | Fe                          | .3                      | –                       | –                                       | –   | –                                       | –                          | .16                        | –                        |
|                               | 10-07-98     | Fe                          | .1                      | .1                      | –                                       | –   | –                                       | .05                        | .14                        | –                        |
|                               | 06-09-99     | Fe                          | .9                      | .2                      | –                                       | –   | –                                       | .08                        | .09                        | –                        |
|                               | 06-21-00     | Fe                          | .3                      | .1                      | 6.0                                     | –   | <.05                                    | .06                        | .10                        | 4.3                      |
|                               | 06-12-01     | S                           | 3.5                     | .3                      | 5.3                                     | 5.0                                       | <.05                                    | .08                        | .29                        | 5.4                      |
|                               | 06-11-02     | An                          | >20R                    | .1                      | –                                       | 45  | <.05                                    | .09                        | .27                        | 4.2                      |
|                               | 06-18-03     | Fe                          | .2                      | .1                      | –                                       | 6.0                                       | <.06                                    | .10                        | .29                        | 4.3                      |
|                               | 06-17-04     | Fe                          | .2                      | .2                      | –                                       | 6.7                                       | –                                       | .10                        | 1.0                        | 4.3                      |
| 06-22-05                      | Fe           | <.1                         | <.1                     | –                       | 6.2                                     | <.06                                      | .10                                     | .44                        | 4.4                        |                          |
| 06-12-06                      | Fe           | .1                          | .1                      | –                       | 5.9                                     | <.06                                      | .10                                     | .76                        | 3.7                        |                          |
| MW1–15                        | 09-16-96     | Fe                          | .2                      | <.1                     | 50                                      | –   | <.02                                    | 5.7                        | 68                         | .1                       |
|                               | 04-16-97     | Fe/S                        | .8                      | <.1                     | –                                       | –   | <.02                                    | –                          | 77                         | .1                       |
|                               | 03-05-98     | S                           | 1.2                     | <.1                     | 33                                      | –   | –                                       | 18                         | 51                         | –                        |
|                               | 10-09-98     | S                           | 2.9                     | <.1                     | –                                       | –   | –                                       | 5.8                        | 64                         | –                        |
|                               | 06-15-04     | S                           | 3.2                     | .8                      | –                                       | 27  | –                                       | 6.3                        | 36                         | <.2                      |
| MW1–17                        | 09-17-96     | Fe                          | .7                      | <.1                     | 23                                      | –   | <.02                                    | 1.3                        | 62                         | 4.3                      |
|                               | 04-16-97     | Fe                          | .6                      | <.1                     | –                                       | –   | <.02                                    | –                          | 37                         | 68                       |
|                               | 10-09-98     | Fe                          | –                       | <.1                     | –                                       | –   | –                                       | .80                        | 56                         | –                        |
|                               | 06-22-00     | S                           | 1.2                     | <.1                     | 11                                      | –   | –                                       | 1.2                        | 68                         | –                        |
|                               | 06-12-01     | S                           | 2.0–2.7                 | .4                      | 9.2                                     | 8.0                                       | <.05                                    | 1.2                        | 48                         | 12                       |
|                               | 06-17-04     | S                           | 2.5                     | <.1                     | –                                       | 7.5                                       | –                                       | .68                        | >10                        | 18                       |
|                               | 06-20-05     | S                           | 1.5                     | <.1                     | –                                       | 6.1                                       | <.06                                    | .43                        | 27                         | 7.8                      |
| MW1–18                        | 09-17-96     | Fe/S                        | 1.0                     | <.1                     | 28                                      | –   | <.02                                    | 4.0                        | 12                         | 4.6                      |
|                               | 04-16-97     | Fe                          | .5                      | <.1                     | –                                       | –   | .05                                     | –                          | 23                         | 8.2                      |
|                               | 10-07-98     | Fe                          | –                       | .2                      | –                                       | –   | –                                       | .77                        | 3.3                        | –                        |
|                               | 06-16-04     | Fe                          | .7                      | .2                      | –                                       | 23  | –                                       | 4.1                        | >10                        | .2                       |
| MW1–41                        | 06-09-99     | S                           | 1.0                     | .3                      | –                                       | –   | –                                       | 2.2                        | 60                         | –                        |
|                               | 06-21-00     | S                           | 1.2                     | .1                      | 22                                      | –   | <.05                                    | 3.5                        | 55                         | <.3                      |
|                               | 06-11-01     | S                           | 2.0                     | .3                      | 14                                      | 14  | <.05                                    | 3.7                        | 66                         | 30                       |
|                               | 06-10-02     | S                           | 2.2                     | .8                      | –                                       | 20  | <.05                                    | 3.6                        | 52                         | .4                       |
|                               | 06-18-03     | S                           | 1.9                     | .1                      | –                                       | 19  | <.06                                    | 3.9                        | 50                         | <.2                      |
|                               | 06-17-04     | S                           | 2.2                     | .1                      | –                                       | 19  | –                                       | 4.0                        | 57                         | <.2                      |
|                               | 06-20-05     | Fe/S                        | .8                      | .1                      | –                                       | 17  | <.06                                    | 3.9                        | 73                         | <.2                      |
|                               | 06-12-06     | Fe/S                        | .7                      | <.1                     | –                                       | 18  | <.06                                    | 3.8                        | 28                         | <.2                      |
| P1–1                          | 06-09-99     | Fe                          | .7                      | .4                      | –                                       | –   | –                                       | 4.0                        | 59                         | –                        |
|                               | 06-11-02     | S                           | 1.4                     | <.1                     | –                                       | 17  | <.05                                    | 2.7                        | 40                         | <.1                      |
|                               | 06-18-03     | S                           | 1.5                     | <.1                     | –                                       | 18  | <.06                                    | 3.4                        | 32                         | <.2                      |
|                               | 06-17-04     | S                           | 1.9                     | .1                      | –                                       | 16  | –                                       | 3.1                        | 39                         | <.2                      |
|                               | 06-22-05     | Fe/S                        | .6                      | <.1                     | –                                       | 15  | <.06                                    | 3.1                        | 68                         | <.2                      |
|                               | 06-12-06     | Fe/S                        | .3                      | <.1                     | –                                       | 16  | <.06                                    | 2.9                        | 54                         | <.2                      |

**Table 2.** Predominant redox conditions at wells and piezometers, and ground-water geochemical data collected at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, 1996–2006.—Continued

[Shaded rows indicate 2006 data. All other data were published in Dinicola and others (2002), Dinicola (2003, 2004), and Dinicola and Huffman, 2004, 2006; prior to 2000, bicarbonate was calculated from an unfiltered sample. Reported concentrations less than the detection limit usually are estimated. **Study site No.:** Location of study sites are shown in figure 2. MW, monitoring well; P, piezometer. **Predominant redox condition:** A, aerobic; An, anaerobic, but specific redox condition could not be determined; Fe, iron reducing; M, methanogenic; Mn, manganese reducing; S, sulfate reducing. **Dissolved hydrogen:** A range of dissolved hydrogen concentrations are shown when equilibration at a single value was never achieved. Selected 2002 dissolved-hydrogen data were rejected (R) because of interference from downhole instruments. **Dissolved oxygen:** Selected 1996 dissolved-oxygen data were rejected (R) because of inadequate well purging. **Abbreviations:** nM, nanomolar; mg/L, milligram per liter;  $\mu$ S/cm, microSiemen per centimeter at 25 degrees Celsius; ORP, oxidation-reduction potential; mV, millivolt. **Symbols:** <, actual value is less than value shown; >, actual value is greater than value shown; –, not analyzed]

| Study site No.                | Date sampled | Predominant redox condition | Sulfide, unfiltered (mg/L) | Dissolved methane (mg/L) | Dissolved carbon dioxide (mg/L) | Bicarbonate, filtered (mg/L) | pH (units) | Specific conductance ( $\mu$ S/cm) | ORP (mV) | Chloride, filtered (mg/L) |
|-------------------------------|--------------|-----------------------------|----------------------------|--------------------------|---------------------------------|------------------------------|------------|------------------------------------|----------|---------------------------|
| Northern plantation—Continued |              |                             |                            |                          |                                 |                              |            |                                    |          |                           |
| MW1-2                         | 09-17-96     | A                           | <0.01                      | 1.2                      | –                               | 510                          | 6.9        | –                                  | –        | 50                        |
|                               | 04-16-97     | Fe                          | <.01                       | 2.5                      | –                               | 1,100                        | 6.7        | –                                  | –        | –                         |
|                               | 03-02-98     | Fe                          | –                          | –                        | –                               | –                            | –          | –                                  | –        | –                         |
|                               | 10-07-98     | Fe                          | <.01                       | –                        | –                               | 300                          | 6.7        | 868                                | –        | –                         |
|                               | 06-09-99     | Fe                          | <.01                       | –                        | –                               | 490                          | 6.8        | 901                                | –        | –                         |
|                               | 06-21-00     | Fe                          | <.01                       | .04                      | –                               | 460                          | 6.8        | 870                                | 37       | 36                        |
|                               | 06-12-01     | S                           | <.01                       | .78                      | –                               | 470                          | 6.5        | 853                                | 27       | 48                        |
|                               | 06-11-02     | An                          | <.01                       | .92                      | 200                             | 500                          | 6.6        | 829                                | 200      | 37                        |
|                               | 06-18-03     | Fe                          | <.01                       | .98                      | 160                             | –                            | 6.4        | 870                                | 62       | 41                        |
|                               | 06-17-04     | Fe                          | –                          | .33                      | 50                              | –                            | 6.6        | 858                                | –        | 40                        |
| 06-22-05                      | Fe           | <.01                        | –                          | 75                       | –                               | 6.3                          | 720        | -14                                | 35       |                           |
| 06-12-06                      | Fe           | <.01                        | .50                        | 115                      | –                               | 6.5                          | 815        | -47                                | 34       |                           |
| MW1-15                        | 09-16-96     | Fe                          | <.01                       | 8.8                      | –                               | 1,200                        | –          | –                                  | –        | 18                        |
|                               | 04-16-97     | Fe/S                        | .03                        | 44                       | –                               | 1,600                        | 6.3        | –                                  | –        | –                         |
|                               | 03-05-98     | S                           | <.01                       | –                        | –                               | –                            | –          | –                                  | –        | –                         |
|                               | 10-09-98     | S                           | <.01                       | –                        | –                               | 750                          | 6.3        | 1,110                              | –        | –                         |
|                               | 06-15-04     | S                           | <.01                       | .22                      | 760                             | –                            | 6.3        | 1,200                              | –        | 16                        |
| MW1-17                        | 09-17-96     | Fe                          | <.01                       | 8.9                      | –                               | 760                          | 6.5        | –                                  | –        | 61                        |
|                               | 04-16-97     | Fe                          | .02                        | 23                       | –                               | 1,200                        | 6.6        | –                                  | –        | –                         |
|                               | 10-09-98     | Fe                          | .02                        | –                        | –                               | 510                          | 6.4        | 1,740                              | –        | –                         |
|                               | 06-22-00     | S                           | .02                        | 2.8                      | –                               | 450                          | 6.5        | 1,260                              | -41      | 160                       |
|                               | 06-12-01     | S                           | .01                        | 9.4                      | –                               | 500                          | 6.5        | 1,200                              | -280     | 120                       |
|                               | 06-17-04     | S                           | –                          | .37                      | 70                              | –                            | 6.5        | 318                                | –        | 150                       |
|                               | 06-20-05     | S                           | .04                        | –                        | 80                              | –                            | 6.3        | 563                                | -144     | 74                        |
| MW1-18                        | 09-17-96     | Fe/S                        | <.01                       | 11                       | –                               | 880                          | 7.0        | –                                  | –        | 86                        |
|                               | 04-16-97     | Fe                          | <.01                       | 52                       | –                               | 1,500                        | 6.8        | –                                  | –        | –                         |
|                               | 10-07-98     | Fe                          | <.01                       | –                        | –                               | 920                          | 6.6        | 1,780                              | –        | –                         |
|                               | 06-16-04     | Fe                          | <.01                       | 5.3                      | 70                              | –                            | 7.1        | 945                                | –        | 47                        |
| MW1-41                        | 06-09-99     | S                           | .01                        | –                        | –                               | 860                          | 6.6        | 1,260                              | –        | –                         |
|                               | 06-21-00     | S                           | <.01                       | 1.9                      | –                               | 1,000                        | 6.5        | 1,500                              | -75      | 8.3                       |
|                               | 06-11-01     | S                           | .02                        | 25                       | –                               | 980                          | 6.3        | 1,330                              | -89      | 9.9                       |
|                               | 06-10-02     | S                           | .04                        | 21                       | 540                             | 830                          | 6.3        | 1,190                              | -68      | 7.9                       |
|                               | 06-18-03     | S                           | .03                        | 14                       | 500                             | –                            | 6.3        | 1,280                              | 93       | 9.5                       |
|                               | 06-17-04     | S                           | .02                        | 7.4                      | 450                             | –                            | 6.1        | 1,300                              | -165     | 11                        |
|                               | 06-20-05     | Fe/S                        | .01                        | –                        | 500                             | –                            | 6.4        | 1,300                              | –        | 8.7                       |
|                               | 06-12-06     | Fe/S                        | .02                        | 8.5                      | 310                             | –                            | 6.3        | 1,240                              | -103     | 8.4                       |
| P1-1                          | 06-09-99     | Fe                          | <.01                       | –                        | –                               | 930                          | 6.4        | 1,350                              | –        | –                         |
|                               | 06-11-02     | S                           | <.01                       | 29                       | 400                             | 650                          | 6.3        | 987                                | -80      | 9.3                       |
|                               | 06-18-03     | S                           | .02                        | –                        | 450                             | –                            | 6.2        | 1,030                              | 78       | 11                        |
|                               | 06-17-04     | S                           | .02                        | 3.7                      | 430                             | –                            | 6.0        | 987                                | -153     | 9.2                       |
|                               | 06-22-05     | Fe                          | <.01                       | 10                       | 370                             | –                            | 6.3        | 847                                | -72      | 7.1                       |
|                               | 06-12-06     | Fe/S                        | .01                        | 7.8                      | 225                             | –                            | 6.2        | 979                                | -108     | 7.2                       |

**Table 2.** Predominant redox conditions at wells and piezometers, and ground-water geochemical data collected at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, 1996–2006.—Continued

[Shaded rows indicate 2006 data. All other data were published in Dinicola and others (2002), Dinicola (2003, 2004), and Dinicola and Huffman, 2004, 2006; prior to 2000, bicarbonate was calculated from an unfiltered sample. Reported concentrations less than the detection limit usually are estimated. **Study site No.:** Location of study sites are shown in figure 2. MW, monitoring well; P, piezometer. **Predominant redox condition:** A, aerobic; An, anaerobic, but specific redox condition could not be determined; Fe, iron reducing; M, methanogenic; Mn, manganese reducing; S, sulfate reducing. **Dissolved hydrogen:** A range of dissolved hydrogen concentrations are shown when equilibration at a single value was never achieved. Selected 2002 dissolved-hydrogen data were rejected (R) because of interference from downhole instruments. **Dissolved oxygen:** Selected 1996 dissolved-oxygen data were rejected (R) because of inadequate well purging. **Abbreviations:** nM, nanomolar; mg/L, milligram per liter; µS/cm, microSiemen per centimeter at 25 degrees Celsius; ORP, oxidation-reduction potential; mV, millivolt. **Symbols:** <, actual value is less than value shown; >, actual value is greater than value shown; –, not analyzed]

| Study site No.                | Date sampled | Predominant redox condition | Dissolved hydrogen (nM) | Dissolved oxygen (mg/L) | Total organic carbon, unfiltered (mg/L) | Dissolved organic carbon, filtered (mg/L) | Nitrate + nitrite, filtered (mg/L as N) | Manganese, filtered (mg/L) | Iron (II), filtered (mg/L) | Sulfate, filtered (mg/L) |
|-------------------------------|--------------|-----------------------------|-------------------------|-------------------------|---|---|---|----------------------------|----------------------------|--------------------------|
| Northern plantation—Continued |              |                             |                         |                         |   |   |   |                            |                            |                          |
| P1-3                          | 06-09-99     | Fe                          | 0.4                     | 0.2                     | –                                       | –   | –                                       | 1.0                        | 19                         | –                        |
|                               | 06-11-02     | Fe                          | .3                      | <.1                     | –                                       | 45  | <0.05                                   | 2.6                        | 39                         | 1.0                      |
|                               | 06-18-03     | Fe                          | .3                      | .1                      | –                                       | 19  | <.06                                    | 2.0                        | 29                         | 1.8                      |
|                               | 06-17-04     | Fe                          | .7                      | <.1                     | –                                       | 21  | –                                       | 2.8                        | >10                        | .55                      |
|                               | 06-22-05     | Fe                          | .2                      | <.1                     | –                                       | 20  | <.06                                    | 2.8                        | 60                         | .38                      |
|                               | 06-12-06     | Fe                          | .2                      | <.1                     | –                                       | 20  | <.06                                    | 2.5                        | 39                         | .2                       |
| P1-4                          | 06-09-99     | Fe                          | .7                      | .3                      | –                                       | –   | –                                       | .34                        | 2.6                        | –                        |
|                               | 06-13-01     | Fe                          | .1                      | .5                      | 9.8                                     | 8.7                                       | <.05                                    | .38                        | 3.4                        | 3.8                      |
|                               | 06-11-02     | Fe                          | .2                      | .1                      | –                                       | 8.0                                       | <.05                                    | 2.6                        | 3.7                        | 3.5                      |
|                               | 06-18-03     | Fe                          | .2                      | .1                      | –                                       | 7.0                                       | <.06                                    | .43                        | 4.1                        | 4.0                      |
|                               | 06-17-04     | Fe                          | .1                      | .1                      | –                                       | 7.6                                       | –                                       | .42                        | 3.0                        | 4.0                      |
|                               | 06-21-05     | Fe                          | .1                      | .1                      | –                                       | 6.7                                       | <.06                                    | .38                        | 2.3                        | 4.6                      |
|                               | 06-12-06     | Fe                          | .1                      | <.1                     | –                                       | 6.8                                       | <.06                                    | .35                        | 1.8                        | 4.3                      |
| P1-5                          | 06-08-99     | S                           | 3.0                     | .3                      | –                                       | –   | –                                       | 3.1                        | 72                         | –                        |
|                               | 06-10-02     | S                           | 1.7                     | .1                      | –                                       | 25  | <.05                                    | 2.6                        | 62                         | <.6                      |
|                               | 06-18-03     | S                           | 2.2                     | .1                      | –                                       | 24  | <.06                                    | 3.1                        | 54                         | <.2                      |
|                               | 06-17-04     | S                           | 2.1                     | <.1                     | –                                       | 23  | –                                       | 3.1                        | >10                        | <.2                      |
|                               | 06-21-05     | Fe/S                        | .8                      | .1                      | –                                       | 22  | <.06                                    | 3.5                        | 74                         | .1                       |
|                               | 06-12-06     | Fe/S                        | .8                      | <.1                     | –                                       | 21  | <.06                                    | 3.6                        | 66                         | .1                       |
| Southern plantation           |              |                             |                         |                         |   |   |   |                            |                            |                          |
| MW1-4                         | 09-17-96     | Fe                          | 0.5                     | 2.8R                    | 2.0                                     | –   | <0.02                                   | 0.28                       | 1.8                        | 7.1                      |
|                               | 04-16-97     | Fe                          | .6                      | .4                      | –                                       | –   | .24                                     | –                          | <.01                       | 8.6                      |
|                               | 03-03-98     | S                           | 1.7                     | .2                      | 4.0                                     | –   | –                                       | .10                        | .01                        | –                        |
|                               | 10-08-98     | Fe                          | .2                      | .5                      | –                                       | –   | –                                       | –                          | .28                        | –                        |
|                               | 06-07-99     | Fe                          | .9                      | .1                      | –                                       | –   | –                                       | .20                        | 1.2                        | –                        |
|                               | 06-22-00     | Fe                          | .2                      | .1                      | 8.6                                     | –   | –                                       | .70                        | –                          | 5.5                      |
|                               | 06-14-01     | S                           | 0.9–3.2                 | .5                      | 2.9                                     | 2.5                                       | .08                                     | .54                        | 1.6                        | 5.4                      |
|                               | 06-13-02     | S                           | 2.4                     | .1                      | –                                       | 3.8                                       | .08                                     | .47                        | 1.2                        | 5.5                      |
|                               | 06-20-03     | Fe                          | .8                      | .1                      | –                                       | 2.5                                       | <.06                                    | .53                        | .22                        | 5.7                      |
|                               | 06-18-04     | Fe                          | .2                      | .1                      | –                                       | 2.7                                       | –                                       | .61                        | .12                        | 5.9                      |
|                               | 06-23-05     | Mn/Fe                       | .3                      | .1                      | –                                       | .7  | <.06                                    | .14                        | .03                        | 8.8                      |
|                               | 06-13-06     | Mn/Fe                       | <.1                     | .1                      | –                                       | 3.9                                       | <.06                                    | .79                        | .19                        | 5.7                      |
|                               | MW1-5        | 09-17-96                    | S                       | 1.2                     | <.1                                     | 15  | –                                       | <.02                       | 1.6                        | 19                       |
| 04-16-97                      |              | Fe                          | .5                      | <.1                     | –                                       | –   | .08                                     | –                          | 3.1                        | 2.8                      |
| 03-04-98                      |              | Fe                          | .7                      | <.1                     | 12                                      | –   | –                                       | 1.3                        | 4.5                        | –                        |
| 10-08-98                      |              | S                           | 2.4                     | <.1                     | –                                       | –   | –                                       | 1.5                        | 11                         | –                        |
| 06-08-99                      |              | Fe                          | .6                      | .3                      | –                                       | –   | –                                       | 1.2                        | 31                         | –                        |
| 06-22-00                      |              | Fe                          | –                       | <.1                     | 17                                      | –   | –                                       | 1.5                        | 39                         | 6.4                      |
| 06-13-01                      |              | Fe                          | .8                      | .3                      | 10                                      | 9.6                                       | .12                                     | 1.5                        | 25                         | 6.0                      |
| 06-13-02                      |              | S                           | 3.4                     | .5                      | –                                       | 11  | .14                                     | 1.5                        | 20                         | 6.3                      |
| 06-20-03                      |              | Fe                          | .1                      | .1                      | –                                       | 11  | <.06                                    | 1.5                        | 30                         | 6.8                      |
| 06-18-04                      |              | Fe                          | .1                      | .4                      | –                                       | 7.2                                       | –                                       | 1.8                        | >10                        | 5.6                      |
| 06-22-05                      |              | Fe                          | <.1                     | .0                      | –                                       | 8.2                                       | .16                                     | 1.2                        | 27                         | 6.7                      |
| 06-13-06                      |              | Fe                          | <.1                     | .1                      | –                                       | 7.8                                       | .08                                     | 1.3                        | 14                         | 6.0                      |

**Table 2.** Predominant redox conditions at wells and piezometers, and ground-water geochemical data collected at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, 1996–2006.—Continued

[Shaded rows indicate 2006 data. All other data were published in Dinicola and others (2002), Dinicola (2003, 2004), and Dinicola and Huffman, 2004, 2006; prior to 2000, bicarbonate was calculated from an unfiltered sample. Reported concentrations less than the detection limit usually are estimated. **Study site No.:** Location of study sites are shown in [figure 2](#). MW, monitoring well; P, piezometer. **Predominant redox condition:** A, aerobic; An, anaerobic, but specific redox condition could not be determined; Fe, iron reducing; M, methanogenic; Mn, manganese reducing; S, sulfate reducing. **Dissolved hydrogen:** A range of dissolved hydrogen concentrations are shown when equilibration at a single value was never achieved. Selected 2002 dissolved-hydrogen data were rejected (R) because of interference from downhole instruments. **Dissolved oxygen:** Selected 1996 dissolved-oxygen data were rejected (R) because of inadequate well purging. **Abbreviations:** nM, nanomolar; mg/L, milligram per liter;  $\mu\text{S}/\text{cm}$ , microSiemen per centimeter at 25 degrees Celsius; ORP, oxidation-reduction potential; mV, millivolt. **Symbols:** <, actual value is less than value shown; >, actual value is greater than value shown; –, not analyzed]

| Study site No.                | Date sampled | Predominant redox condition | Sulfide, unfiltered (mg/L) | Dissolved methane (mg/L) | Dissolved carbon dioxide (mg/L) | Bicarbonate, filtered (mg/L) | pH (units) | Specific conductance ( $\mu\text{S}/\text{cm}$ ) | ORP (mV) | Chloride, filtered (mg/L) |
|-------------------------------|--------------|-----------------------------|----------------------------|--------------------------|---------------------------------|------------------------------|------------|--|----------|---------------------------|
| Northern plantation—Continued |              |                             |                            |                          |                                 |                              |            |  |          |                           |
| P1-3                          | 06-09-99     | Fe                          | 0.04                       | –                        | –                               | 730                          | 6.8        | 1,470  | –        | –                         |
|                               | 06-11-02     | Fe                          | .03                        | 24                       | 400                             | 820                          | 6.4        | 1,340  | -73      | 61                        |
|                               | 06-18-03     | Fe                          | .03                        | –                        | 350                             | –                            | 6.4        | 1,400  | 73       | 90                        |
|                               | 06-17-04     | Fe                          | <.01                       | 5.7                      | 330                             | –                            | 6.5        | 1,350  | –        | 57                        |
|                               | 06-22-05     | Fe                          | .03                        | 8.4                      | 320                             | –                            | 6.4        | 1,200  | -88      | 68                        |
|                               | 06-12-06     | Fe                          | .03                        | 7.1                      | 330                             | –                            | 6          | 1,440  | -152     | 51                        |
| P1-4                          | 06-09-99     | Fe                          | .02                        | –                        | –                               | 450                          | 6.9        | 867  | –        | –                         |
|                               | 06-13-01     | Fe                          | <.01                       | .93                      | –                               | 390                          | 6.6        | 761  | -78      | 53                        |
|                               | 06-11-02     | Fe                          | <.01                       | 5.9                      | 90                              | 380                          | 6.7        | 734  | -86      | 56                        |
|                               | 06-18-03     | Fe                          | .01                        | 4.2                      | 70                              | –                            | 6.6        | 778  | 65       | 59                        |
|                               | 06-17-04     | Fe                          | .02                        | 1.8                      | 60                              | –                            | 6.4        | 782  | -163     | 48                        |
|                               | 06-21-05     | Fe                          | <.01                       | 1.8                      | 42                              | –                            | 6.6        | 750  | -83      | 47                        |
| 06-12-06                      | Fe           | <.01                        | 1.7                        | 32                       | –                               | 6.4                          | 823        | -94  | 44       |                           |
| P1-5                          | 06-08-99     | S                           | .01                        | –                        | –                               | 850                          | 6.2        | 1,320  | –        | –                         |
|                               | 06-10-02     | S                           | .02                        | 23                       | 400                             | 730                          | 6.2        | 1,200  | -59      | 17                        |
|                               | 06-18-03     | S                           | .02                        | 18                       | 650                             | –                            | 6.2        | 1,150  | 65       | 16                        |
|                               | 06-17-04     | S                           | –                          | 5.8                      | 450                             | –                            | 6.4        | 1,160  | –        | 14                        |
|                               | 06-21-05     | Fe/S                        | .04                        | 9.4                      | 400                             | –                            | 6.3        | 1,150  | -65      | 13                        |
| 06-12-06                      | Fe/S         | .05                         | 6.8                        | 370                      | –                               | 5.8                          | 1,100      | -106   | 9.9      |                           |
| Southern plantation           |              |                             |                            |                          |                                 |                              |            |  |          |                           |
| MW1-4                         | 09-17-96     | Fe                          | <0.01                      | 1.2                      | –                               | 130                          | 6.9        | –  | –        | 15                        |
|                               | 04-16-97     | Fe                          | <.01                       | .70                      | –                               | 270                          | 7.3        | –  | –        | –                         |
|                               | 03-03-98     | S                           | <.01                       | –                        | –                               | –                            | –          | –  | –        | –                         |
|                               | 10-08-98     | Fe                          | <.01                       | –                        | –                               | 170                          | 6.7        | 368  | –        | –                         |
|                               | 06-07-99     | Fe                          | <.01                       | –                        | –                               | 180                          | 6.6        | 350  | –        | –                         |
|                               | 06-22-00     | Fe                          | <.01                       | .56                      | –                               | 230                          | 6.8        | 412  | -26      | 19                        |
|                               | 06-14-01     | S                           | <.01                       | 3.7                      | –                               | 180                          | 6.5        | 360  | -8       | 22                        |
|                               | 06-13-02     | S                           | <.01                       | 5.2                      | 60                              | 190                          | 6.6        | 442  | -14      | 20                        |
|                               | 06-20-03     | Fe                          | <.01                       | 3.7                      | 40                              | –                            | 6.7        | 324  | –        | 17                        |
|                               | 06-18-04     | Fe                          | <.01                       | 1.1                      | 50                              | –                            | 6.0        | 320  | 91       | 23                        |
|                               | 06-23-05     | Mn                          | <.01                       | –                        | <10                             | –                            | 7.9        | 203  | 45       | 7.3                       |
| 06-13-06                      | Mn/Fe        | .01                         | 2.1                        | 30                       | –                               | 6.6                          | 362        | -1   | 20       |                           |
| MW1-5                         | 09-17-96     | S                           | <.01                       | 2.4                      | –                               | 410                          | 6.7        | –  | –        | 21                        |
|                               | 04-16-97     | Fe                          | .03                        | 18                       | –                               | 1,400                        | 6.6        | –  | –        | –                         |
|                               | 03-04-98     | Fe                          | <.01                       | –                        | –                               | –                            | –          | –  | –        | –                         |
|                               | 10-08-98     | S                           | <.01                       | –                        | –                               | 410                          | 6.4        | 1,740  | –        | –                         |
|                               | 06-08-99     | Fe                          | .01                        | –                        | –                               | 510                          | 6.5        | 855  | –        | –                         |
|                               | 06-22-00     | Fe                          | <.01                       | 1.1                      | –                               | 460                          | 6.6        | 790  | -80      | 19                        |
|                               | 06-13-01     | Fe                          | .01                        | 2.4                      | –                               | 470                          | 6.4        | 766  | -70      | 12                        |
|                               | 06-13-02     | S                           | .02                        | 7.4                      | 180                             | 740                          | 6.5        | 608  | -77      | 9.6                       |
|                               | 06-20-03     | Fe                          | .03                        | 4.9                      | 180                             | –                            | 6.4        | 711  | –        | 10                        |
|                               | 06-18-04     | Fe                          | –                          | 2.4                      | 200                             | –                            | 6.5        | 795  | –        | 9.8                       |
|                               | 06-22-05     | Fe                          | .02                        | –                        | 70                              | –                            | 6.3        | 520  | -95      | 9.5                       |
| 06-13-06                      | Fe           | .02                         | 1.9                        | 50                       | –                               | 6.5                          | 603        | -85  | 8.5      |                           |

**Table 2.** Predominant redox conditions at wells and piezometers, and ground-water geochemical data collected at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, 1996–2006.—Continued

[Shaded rows indicate 2006 data. All other data were published in Dinicola and others (2002), Dinicola (2003, 2004), and Dinicola and Huffman, 2004, 2006; prior to 2000, bicarbonate was calculated from an unfiltered sample. Reported concentrations less than the detection limit usually are estimated. **Study site No.:** Location of study sites are shown in [figure 2](#). MW, monitoring well; P, piezometer. **Predominant redox condition:** A, aerobic; An, anaerobic, but specific redox condition could not be determined; Fe, iron reducing; M, methanogenic; Mn, manganese reducing; S, sulfate reducing. **Dissolved hydrogen:** A range of dissolved hydrogen concentrations are shown when equilibration at a single value was never achieved. Selected 2002 dissolved-hydrogen data were rejected (R) because of interference from downhole instruments. **Dissolved oxygen:** Selected 1996 dissolved-oxygen data were rejected (R) because of inadequate well purging. **Abbreviations:** nM, nanomolar; mg/L, milligram per liter;  $\mu$ S/cm, microSiemen per centimeter at 25 degrees Celsius; ORP, oxidation-reduction potential; mV, millivolt. **Symbols:** <, actual value is less than value shown; >, actual value is greater than value shown; –, not analyzed]

| Study site No.                | Date sampled | Predominant redox condition | Dissolved hydrogen (nM) | Dissolved oxygen (mg/L) | Total organic carbon, unfiltered (mg/L) | Dissolved organic carbon, filtered (mg/L) | Nitrate + nitrite, filtered (mg/L as N) | Manganese, filtered (mg/L) | Iron (II), filtered (mg/L) | Sulfate, filtered (mg/L) |
|-------------------------------|--------------|-----------------------------|-------------------------|-------------------------|---|---|---|----------------------------|----------------------------|--------------------------|
| Southern plantation—Continued |              |                             |                         |                         |   |   |   |                            |                            |                          |
| MW1-6                         | 09-17-96     | S                           | 1.1                     | <0.1                    | 33                                      | –   | 1.2                                     | 1.2                        | 30                         | 0.1                      |
|                               | 04-16-97     | Fe/S                        | .5                      | <.1                     | –                                       | –   | .07                                     | –                          | 36                         | 4.1                      |
|                               | 10-08-98     | Fe                          | .2                      | <.1                     | –                                       | –   | –                                       | 1.1                        | 32                         | –                        |
|                               | 06-22-04     | Fe                          | –                       | .2                      | –                                       | 26  | –                                       | 1.1                        | >10                        | .1                       |
| MW1-16                        | 09-17-96     | S                           | 2.1                     | <.1                     | 480                                     | –   | <.02                                    | 3.9                        | 130                        | .2                       |
|                               | 04-16-97     | Fe/S                        | .8                      | <.1                     | –                                       | –   | <.02                                    | –                          | 120                        | 2.2                      |
|                               | 03-04-98     | Fe                          | .7                      | .3                      | 350                                     | –   | –                                       | 18                         | 100                        | –                        |
|                               | 10-08-98     | M                           | 9.6                     | <.1                     | –                                       | –   | –                                       | 5.4                        | 180                        | –                        |
|                               | 06-07-99     | M                           | 6.8                     | .6                      | –                                       | –   | –                                       | >5                         | 140                        | –                        |
|                               | 06-22-00     | S                           | –                       | .1                      | 61                                      | –   | –                                       | 1.9                        | 60                         | 1.2                      |
|                               | 06-14-01     | S                           | 1.7                     | .2                      | 64                                      | 66  | .33                                     | 2.4                        | 56                         | 1.1                      |
|                               | 06-13-02     | M                           | 4.6–7.6                 | .9                      | –                                       | 71  | <.05                                    | 3.2                        | 38                         | .4                       |
|                               | 06-20-03     | S                           | 2.2                     | .2                      | –                                       | 29  | <.6                                     | 2.1                        | 37                         | .6                       |
|                               | 06-22-04     | –                           | –                       | .1                      | –                                       | 36  | –                                       | 2.1                        | >10                        | .1                       |
|                               | 06-23-05     | Fe/S                        | .5                      | .1                      | –                                       | 20  | <.06                                    | 2.0                        | 66                         | .39                      |
|                               | 06-13-06     | –                           | –                       | .1                      | –                                       | 17  | <.06                                    | 1.7                        | 14.1                       | 20                       |
| P1-6                          | 06-08-99     | S                           | 1.8                     | .1                      | –                                       | –   | –                                       | .12                        | .02                        | –                        |
|                               | 06-14-01     | S                           | 1.8                     | .2                      | 34                                      | 34  | .23                                     | .45                        | .95                        | 4.9                      |
|                               | 06-13-02     | S                           | 1.6                     | <.1                     | –                                       | 26  | <.05                                    | .88                        | 1.0                        | 4.3                      |
|                               | 06-20-03     | Fe                          | .3                      | .2                      | –                                       | 4.1                                       | <.06                                    | .08                        | .13                        | 7.5                      |
|                               | 06-18-04     | S                           | 1.5                     | .1                      | –                                       | 10  | –                                       | .11                        | 1.0                        | 7.2                      |
|                               | 06-23-05     | Fe/S                        | .3                      | .1                      | –                                       | 5.8                                       | <.06                                    | .17                        | .15                        | 6.3                      |
| 06-13-06                      | S            | 1.1                         | .1                      | –                       | 26                                      | <.06                                      | .91                                     | 1.4                        | 3.4                        |                          |
| P1-7                          | 06-08-99     | S                           | 1.2                     | .1                      | –                                       | –   | –                                       | .61                        | 2.1                        | –                        |
|                               | 06-22-00     | Mn/Fe                       | –                       | .1                      | 19                                      | –   | –                                       | 2.6                        | 3.2                        | 24                       |
|                               | 06-14-01     | Mn/Fe                       | .2                      | .2                      | 11                                      | 11  | <.05                                    | 2.3                        | 2.0                        | 18                       |
|                               | 06-14-02     | Mn/Fe                       | .2                      | 1.3                     | –                                       | 8.9                                       | <.05                                    | 2.2                        | 1.9                        | 12                       |
|                               | 06-20-03     | Mn/Fe                       | .1                      | .1                      | –                                       | 5.6                                       | <.06                                    | 1.9                        | 1.3                        | 7.5                      |
|                               | 06-18-04     | Mn/Fe                       | .1                      | <.1                     | –                                       | 6.9                                       | –                                       | 2.4                        | 2.0                        | 9.8                      |
|                               | 06-22-05     | Mn/Fe                       | <.1                     | .1                      | –                                       | 8.8                                       | <.06                                    | 2.1                        | 1.9                        | 26                       |
| 06-13-06                      | Mn/Fe        | <.1                         | .5                      | –                       | 7.6                                     | <.06                                      | 2.0                                     | 1.8                        | 20                         |                          |
| P1-8                          | 06-07-99     | S                           | 1.8                     | <.1                     | –                                       | –   | –                                       | .20                        | .08                        | –                        |
|                               | 06-14-01     | Fe                          | .7                      | .1                      | 5                                       | 4.7                                       | .06                                     | .16                        | .22                        | .1                       |
|                               | 06-13-02     | Fe                          | .6                      | .3                      | –                                       | 8.8                                       | <.05                                    | .21                        | .38                        | .3                       |
|                               | 06-20-03     | Fe                          | .6                      | .1                      | –                                       | 2.3                                       | <.06                                    | .09                        | .12                        | .4                       |
|                               | 06-18-04     | Mn/Fe                       | .3                      | .4                      | –                                       | 3.0                                       | –                                       | .13                        | .01                        | .4                       |
|                               | 06-23-05     | Mn/Fe                       | .2                      | .2                      | –                                       | 14  | <.06                                    | .12                        | .12                        | <.2                      |
|                               | 06-13-06     | Mn/Fe                       | .3                      | <.1                     | –                                       | 3.2                                       | <.06                                    | .14                        | .02                        | .4                       |



**Table 2.** Predominant redox conditions at wells and piezometers, and ground-water geochemical data collected at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, 1996–2006.—Continued

[Shaded rows indicate 2006 data. All other data were published in Dinicola and others (2002), Dinicola (2003, 2004), and Dinicola and Huffman, 2004, 2006; prior to 2000, bicarbonate was calculated from an unfiltered sample. Reported concentrations less than the detection limit usually are estimated. **Study site No.:** Location of study sites are shown in figure 2. MW, monitoring well; P, piezometer. **Predominant redox condition:** A, aerobic; An, anaerobic, but specific redox condition could not be determined; Fe, iron reducing; M, methanogenic; Mn, manganese reducing; S, sulfate reducing. **Dissolved hydrogen:** A range of dissolved hydrogen concentrations are shown when equilibration at a single value was never achieved. Selected 2002 dissolved-hydrogen data were rejected (R) because of interference from downhole instruments. **Dissolved oxygen:** Selected 1996 dissolved-oxygen data were rejected (R) because of inadequate well purging. **Abbreviations:** nM, nanomolar; mg/L, milligram per liter;  $\mu\text{S}/\text{cm}$ , microSiemen per centimeter at 25 degrees Celsius; ORP, oxidation-reduction potential; mV, millivolt. **Symbols:** <, actual value is less than value shown; >, actual value is greater than value shown; –, not analyzed]

| Study site No.                | Date sampled | Predominant redox condition | Sulfide, unfiltered (mg/L) | Dissolved methane (mg/L) | Dissolved carbon dioxide (mg/L) | Bicarbonate, filtered (mg/L) | pH (units) | Specific conductance ( $\mu\text{S}/\text{cm}$ ) | ORP (mV) | Chloride, filtered (mg/L) |
|-------------------------------|--------------|-----------------------------|----------------------------|--------------------------|---------------------------------|------------------------------|------------|--|----------|---------------------------|
| Southern plantation—Continued |              |                             |                            |                          |                                 |                              |            |  |          |                           |
| MW1-6                         | 09-17-96     | S                           | <0.01                      | 7.0                      | –                               | 840                          | 6.7        | –  | –        | 27                        |
|                               | 04-16-97     | Fe/S                        | .15                        | 15                       | –                               | 1,100                        | 6.5        | –  | –        | –                         |
|                               | 10-08-98     | Fe                          | .01                        | –                        | –                               | 720                          | 6.4        | 1,170  | –        | –                         |
|                               | 06-22-04     | Fe                          | –                          | 3.7                      | 250                             | –                            | 6.2        | 945  | –        | 11                        |
| MW1-16                        | 09-17-96     | S                           | <.01                       | 4.3                      | –                               | 1,400                        | 6.5        | –  | –        | 150                       |
|                               | 04-16-97     | Fe/S                        | .06                        | 29                       | –                               | 1,800                        | 6.5        | –  | –        | –                         |
|                               | 03-04-98     | Fe                          | .01                        | –                        | –                               | –                            | –          | –  | –        | –                         |
|                               | 10-08-98     | M                           | <.01                       | –                        | –                               | 1,600                        | 6.3        | 3,370  | –        | –                         |
|                               | 06-07-99     | M                           | .01                        | –                        | –                               | 1,200                        | 6.7        | 1,820  | –        | –                         |
|                               | 06-22-00     | S                           | .02                        | 1.2                      | –                               | 510                          | 6.7        | 902  | -130     | 43                        |
|                               | 06-14-01     | S                           | .08                        | 10                       | –                               | 610                          | 6.4        | 953  | –        | 40                        |
|                               | 06-13-02     | M                           | .04                        | 24                       | 270                             | 700                          | 6.5        | 1,400  | -140     | 17                        |
|                               | 06-20-03     | S                           | .06                        | 9.7                      | 240                             | –                            | 6.5        | 835  | –        | 6.8                       |
|                               | 06-22-04     | –                           | .50                        | 4.3                      | 230                             | –                            | 6.3        | 817  | –        | 6.9                       |
|                               | 06-23-05     | Fe/S                        | .12                        | –                        | 225                             | –                            | 6.6        | 767  | -110     | 3.8                       |
|                               | 06-13-06     | –                           | .06                        | 3.0                      | 70                              | –                            | 6.7        | 737  | -139     | 3.5                       |
| P1-6                          | 06-08-99     | S                           | .04                        | –                        | –                               | 300                          | 6.8        | 574  | –        | –                         |
|                               | 06-14-01     | S                           | .12                        | 6.3                      | –                               | 350                          | 6.4        | 657  | -38      | 47                        |
|                               | 06-13-02     | S                           | .11                        | 11                       | 170                             | 380                          | 6.4        | 604  | -11      | 37                        |
|                               | 06-20-03     | Fe                          | .07                        | 4.8                      | 40                              | –                            | 8.1        | 278  | –        | 13                        |
|                               | 06-18-04     | S                           | .10                        | .37                      | <10                             | –                            | 8.6        | 268  | –        | 18                        |
|                               | 06-23-05     | Fe/S                        | .12                        | 1.4                      | 24                              | –                            | 7.1        | 332  | -53      | 24                        |
|                               |              | 06-13-06                    | S                          | .14                      | 2.6                             | 30                           | –          | 6.6  | 757      | -85                       |
| P1-7                          | 06-08-99     | S                           | <.01                       | –                        | –                               | 310                          | 6.7        | 627  | –        | –                         |
|                               | 06-22-00     | Mn/Fe                       | <.01                       | 1.5                      | –                               | 400                          | 6.8        | 851  | -35      | 55                        |
|                               | 06-14-01     | Mn/Fe                       | <.01                       | 4.0                      | –                               | 320                          | 6.5        | 666  | -32      | 41                        |
|                               | 06-14-02     | Mn/Fe                       | <.01                       | 6.0                      | 87                              | 300                          | 6.6        | 601  | -41      | 60                        |
|                               | 06-20-03     | Mn/Fe                       | <.01                       | 4.8                      | 50                              | –                            | 6.6        | 498  | –        | 42                        |
|                               | 06-18-04     | Mn/Fe                       | <.01                       | 1.7                      | 40                              | –                            | 6.7        | 613  | –        | 56                        |
|                               | 06-22-05     | Mn/Fe                       | <.01                       | 2.3                      | 37                              | –                            | 6.5        | 637  | -20      | 55                        |
|                               |              | 06-13-06                    | Mn/Fe                      | <.01                     | 2.1                             | –                            | –          | 6.6  | 639      | -60                       |
| P1-8                          | 06-07-99     | S                           | .01                        | –                        | –                               | 210                          | 7.6        | 381  | –        | –                         |
|                               | 06-14-01     | Fe                          | .02                        | 6.9                      | –                               | 200                          | 7.0        | 363  | -73      | 18                        |
|                               | 06-13-02     | Fe                          | .02                        | 11                       | 40                              | 104                          | 6.9        | 482  | -46      | 35                        |
|                               | 06-20-03     | Fe                          | <.01                       | 9.6                      | <10                             | –                            | 7.2        | 285  | –        | 3.3                       |
|                               | 06-18-04     | Mn/Fe                       | .01                        | 1.7                      | <10                             | –                            | 7.4        | 336  | -218     | 5.9                       |
|                               | 06-23-05     | Mn/Fe                       | <.01                       | 3.4                      | <10                             | –                            | 7.5        | 308  | -147     | 4.2                       |
|                               |              | 06-13-06                    | Mn/Fe                      | <.01                     | 4.5                             | <10                          | –          | 7.5  | 332      | -124                      |

**Table 2.** Predominant redox conditions at wells and piezometers, and ground-water geochemical data collected at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, 1996–2006.—Continued

[Shaded rows indicate 2006 data. All other data were published in Dinicola and others (2002), Dinicola (2003, 2004), and Dinicola and Huffman, 2004, 2006; prior to 2000, bicarbonate was calculated from an unfiltered sample. Reported concentrations less than the detection limit usually are estimated. **Study site No.:** Location of study sites are shown in [figure 2](#). MW, monitoring well; P, piezometer. **Predominant redox condition:** A, aerobic; An, anaerobic, but specific redox condition could not be determined; Fe, iron reducing; M, methanogenic; Mn, manganese reducing; S, sulfate reducing. **Dissolved hydrogen:** A range of dissolved hydrogen concentrations are shown when equilibration at a single value was never achieved. Selected 2002 dissolved-hydrogen data were rejected (R) because of interference from downhole instruments. **Dissolved oxygen:** Selected 1996 dissolved-oxygen data were rejected (R) because of inadequate well purging. **Abbreviations:** nM, nanomolar; mg/L, milligram per liter;  $\mu$ S/cm, microSiemen per centimeter at 25 degrees Celsius; ORP, oxidation-reduction potential; mV, millivolt. **Symbols:** <, actual value is less than value shown; >, actual value is greater than value shown; –, not analyzed]

| Study site No.                | Date sampled | Predominant redox condition | Dissolved hydrogen (nM) | Dissolved oxygen (mg/L) | Total organic carbon, unfiltered (mg/L) | Dissolved organic carbon, filtered (mg/L) | Nitrate + nitrite, filtered (mg/L as N) | Manganese, filtered (mg/L) | Iron (II), filtered (mg/L) | Sulfate, filtered (mg/L) |
|-------------------------------|--------------|-----------------------------|-------------------------|-------------------------|---|---|---|----------------------------|----------------------------|--------------------------|
| Southern plantation—Continued |              |                             |                         |                         |   |   |   |                            |                            |                          |
| P1–9                          | 06-08-99     | M                           | 19                      | 0.3                     | –                                       | –   | –                                       | 0.90                       | 0.03                       | –                        |
|                               | 06-22-00     | S/M                         | –                       | .1                      | 10                                      | –   | –                                       | .69                        | .20                        | 6.6                      |
|                               | 06-14-01     | M                           | 6.7                     | .1                      | 2.3                                     | 1.7                                       | <0.05                                   | .19                        | .05                        | 7.6                      |
|                               | 06-13-02     | An                          | –                       | .6                      | –                                       | 9.8                                       | <.05                                    | 1.2                        | .42                        | 5.6                      |
|                               | 06-20-03     | Fe                          | .2                      | .1                      | –                                       | 3.7                                       | <.06                                    | .24                        | <.01                       | 7.0                      |
|                               | 06-18-04     | Mn/Fe                       | .2                      | .1                      | –                                       | 4.0                                       | –                                       | .26                        | .14                        | 7.3                      |
|                               | 06-23-05     | Mn                          | <.1                     | .1                      | –                                       | 1.4                                       | <.06                                    | .11                        | .01                        | 8.7                      |
|                               | 06-13-06     | S                           | 4.4                     | .2                      | –                                       | 9.6                                       | <.06                                    | 1.4                        | .33                        | 5.3                      |
| P1–10                         | 06-07-99     | Fe                          | .7                      | .3                      | –                                       | –   | –                                       | .10                        | .11                        | –                        |
|                               | 06-22-00     | Fe                          | –                       | <.1                     | 7.2                                     | –   | –                                       | .07                        | .25                        | <.3                      |
|                               | 06-13-01     | S                           | 2.0                     | .2                      | 3.0                                     | 4.2                                       | <.05                                    | .07                        | .20                        | .06                      |
|                               | 06-12-02     | Fe                          | .3                      | .1                      | –                                       | 3.5                                       | <.05                                    | .05                        | .41                        | <.1                      |
|                               | 06-19-03     | Fe                          | .2                      | .1                      | –                                       | 3.5                                       | <.06                                    | .42                        | .34                        | 2.6                      |
|                               | 06-18-04     | Mn/Fe                       | .1                      | .1                      | –                                       | 3.5                                       | –                                       | .58                        | .35                        | <.2                      |
|                               | 06-22-05     | Mn/Fe                       | .1                      | .1                      | –                                       | 3.3                                       | <.06                                    | .74                        | .24                        | <.2                      |
|                               | 06-13-06     | Mn/Fe                       | <.1                     | .1                      | –                                       | 3.4                                       | <.06                                    | .92                        | .15                        | <.2                      |
| Intermediate aquifer          |              |                             |                         |                         |   |   |   |                            |                            |                          |
| 1MW–4                         | 09-17-96     | Fe                          | 0.6                     | 1.6R                    | 23                                      | –   | <0.02                                   | 0.77                       | 1.5                        | 0.04                     |
|                               | 04-16-97     | S                           | 1.8                     | <.1                     | –                                       | –   | .03                                     | –                          | 1.7                        | .4                       |
|                               | 06-17-04     | S                           | 2.7                     | .1                      | –                                       | 15  | –                                       | .97                        | 2.0                        | .8                       |
| MW1–25                        | 09-17-96     | Fe                          | .4                      | 2.7R                    | 7.4                                     | –   | .14                                     | .16                        | .74                        | 16                       |
|                               | 04-17-97     | Fe                          | .8                      | .1                      | –                                       | –   | <.02                                    | –                          | .88                        | 15                       |
|                               | 03-05-98     | Fe                          | .3                      | .3                      | 7.9                                     | –   | –                                       | .20                        | .73                        | –                        |
|                               | 10-05-98     | Fe                          | .2                      | .1                      | –                                       | –   | –                                       | .19                        | .99                        | –                        |
|                               | 06-22-00     | Fe                          | .4                      | .2                      | 6.5                                     | –   | –                                       | .16                        | .80                        | 13                       |
|                               | 06-12-01     | S                           | 2.8–4.3                 | .2                      | 7.1                                     | 6.8                                       | <.05                                    | .16                        | .99                        | 13                       |
|                               | 06-14-02     | S                           | 0.7–2.4                 | .1                      | –                                       | 6.2                                       | <.05                                    | .18                        | 1.1                        | 9.7                      |
|                               | 06-19-03     | Fe                          | .3                      | .1                      | –                                       | 6.5                                       | <.06                                    | .18                        | 1.1                        | 11                       |
|                               | 06-16-04     | Fe                          | .2                      | .1                      | –                                       | 6.2                                       | –                                       | .17                        | 1.0                        | 10                       |
|                               | 06-21-05     | Fe                          | .1                      | .1                      | –                                       | 5.9                                       | <.06                                    | .16                        | 1.0                        | 9.5                      |
|                               | 06-14-06     | Fe                          | .1                      | .1                      | –                                       | 6.3                                       | <.06                                    | .14                        | .97                        | 8.1                      |
| MW1–28                        | 09-16-96     | Fe                          | .3                      | 2.1R                    | 7.2                                     | –   | <.02                                    | .20                        | 1.0                        | 48                       |
|                               | 04-17-97     | Fe                          | 1.0                     | <.1                     | –                                       | –   | .04                                     | –                          | .99                        | 51                       |
|                               | 03-05-98     | Fe                          | .4                      | .5                      | 7.7                                     | –   | –                                       | .20                        | .67                        | –                        |
|                               | 10-07-98     | Fe                          | .6                      | <.1                     | –                                       | –   | –                                       | .19                        | 1.0                        | –                        |
|                               | 06-22-00     | Fe                          | .3                      | <.1                     | 13                                      | –   | –                                       | .16                        | .66                        | 44                       |
|                               | 06-12-01     | S/M                         | 4.1–5.7                 | .5                      | 10                                      | 6.9                                       | <.05                                    | .16                        | .90                        | 45                       |
|                               | 06-14-02     | An                          | >100R                   | .1                      | –                                       | 7.0                                       | <.05                                    | .16                        | .92                        | 39                       |
|                               | 06-19-03     | S                           | 2.5                     | .1                      | –                                       | 6.8                                       | <.06                                    | .16                        | .66                        | 39                       |
|                               | 06-16-04     | Mn/Fe                       | .2                      | .1                      | –                                       | 5.9                                       | –                                       | .18                        | <.01                       | 36                       |
|                               | 06-21-05     | Fe                          | .1                      | .2                      | –                                       | 6.3                                       | <.06                                    | .16                        | .98                        | 37                       |
|                               |              | 06-14-06                    | Fe                      | .1                      | .1                                      | –   | 6.1                                     | <.06                       | .16                        | .78                      |

**Table 2.** Predominant redox conditions at wells and piezometers, and ground-water geochemical data collected at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, 1996–2006.—Continued

[Shaded rows indicate 2006 data. All other data were published in Dinicola and others (2002), Dinicola (2003, 2004), and Dinicola and Huffman, 2004, 2006; prior to 2000, bicarbonate was calculated from an unfiltered sample. Reported concentrations less than the detection limit usually are estimated. **Study site No.:** Location of study sites are shown in figure 2. MW, monitoring well; P, piezometer. **Predominant redox condition:** A, aerobic; An, anaerobic, but specific redox condition could not be determined; Fe, iron reducing; M, methanogenic; Mn, manganese reducing; S, sulfate reducing. **Dissolved hydrogen:** A range of dissolved hydrogen concentrations are shown when equilibration at a single value was never achieved. Selected 2002 dissolved-hydrogen data were rejected (R) because of interference from downhole instruments. **Dissolved oxygen:** Selected 1996 dissolved-oxygen data were rejected (R) because of inadequate well purging. **Abbreviations:** nM, nanomolar; mg/L, milligram per liter;  $\mu\text{S}/\text{cm}$ , microSiemen per centimeter at 25 degrees Celsius; ORP, oxidation-reduction potential; mV, millivolt. **Symbols:** <, actual value is less than value shown; >, actual value is greater than value shown; –, not analyzed]

| Study site No.                | Date sampled | Predominant redox condition | Sulfide, unfiltered (mg/L) | Dissolved methane (mg/L) | Dissolved carbon dioxide (mg/L) | Bicarbonate, filtered (mg/L) | pH (units) | Specific conductance ( $\mu\text{S}/\text{cm}$ ) | ORP (mV) | Chloride, filtered (mg/L) |
|-------------------------------|--------------|-----------------------------|----------------------------|--------------------------|---------------------------------|------------------------------|------------|--|----------|---------------------------|
| Southern plantation—Continued |              |                             |                            |                          |                                 |                              |            |  |          |                           |
| P1-9                          | 06-08-99     | M                           | <0.01                      | –                        | –                               | 270                          | 6.6        | 680  | –        | –                         |
|                               | 06-22-00     | S/M                         | <.01                       | 1.7                      | –                               | 250                          | 6.8        | 548  | -17      | 59                        |
|                               | 06-14-01     | M                           | <.01                       | 1.4                      | –                               | 200                          | 7.8        | 289  | -120     | 14                        |
|                               | 06-13-02     | An                          | <.01                       | 7.5                      | 91                              | 280                          | 6.5        | 601  | 17       | 71                        |
|                               | 06-20-03     | Fe                          | .01                        | 2.5                      | 27                              | –                            | 7.0        | 353  | –        | 23                        |
|                               | 06-18-04     | Mn/Fe                       | <.01                       | .71                      | 35                              | –                            | 6.7        | 330  | -97      | 26                        |
|                               | 06-23-05     | Mn                          | <.01                       | .02                      | <10                             | –                            | 8.3        | 202  | 22       | 12                        |
|                               | 06-13-06     | S                           | .01                        | 3.2                      | 37                              | –                            | 6.6        | 728  | -9       | 112                       |
| P1-10                         | 06-07-99     | Fe                          | <.01                       | –                        | –                               | 300                          | 6.7        | 560  | –        | –                         |
|                               | 06-22-00     | Fe                          | <.01                       | 1.3                      | –                               | 290                          | 7.1        | 500  | -19      | 15                        |
|                               | 06-13-01     | S                           | <.01                       | 4.9                      | –                               | 290                          | 7.2        | 476  | -24      | 15                        |
|                               | 06-12-02     | Fe                          | <.01                       | 18                       | 51                              | 270                          | 6.8        | 438  | 8        | 14                        |
|                               | 06-19-03     | Fe                          | <.01                       | 8.2                      | 30                              | –                            | 6.6        | 425  | –        | 16                        |
|                               | 06-18-04     | Mn/Fe                       | <.01                       | .33                      | 45                              | –                            | 6.3        | 422  | -69      | 9.5                       |
|                               | 06-23-05     | Mn/Fe                       | <.01                       | .71                      | 40                              | –                            | 6.6        | 420  | 4        | 11                        |
|                               | 06-13-06     | Mn/Fe                       | <.01                       | 6.3                      | 29                              | –                            | 6.6        | 437  | -15      | 26                        |
| Intermediate aquifer          |              |                             |                            |                          |                                 |                              |            |  |          |                           |
| 1MW-4                         | 09-17-96     | Fe                          | <0.01                      | 16                       | –                               | 780                          | 7.3        | –  | –        | 25                        |
|                               | 04-16-97     | S                           | .02                        | 47                       | –                               | 1,300                        | 7.3        | –  | –        | –                         |
|                               | 06-17-04     | S                           | .06                        | 4.5                      | 120                             | –                            | 6.5        | 1,200  | –        | 25                        |
| MW1-25                        | 09-17-96     | Fe                          | <.01                       | 3.6                      | –                               | 360                          | 7.1        | –  | –        | 140                       |
|                               | 04-17-97     | Fe                          | <.01                       | 7.9                      | –                               | 1,000                        | 7.0        | –  | –        | –                         |
|                               | 03-05-98     | Fe                          | <.01                       | –                        | –                               | –                            | –          | –  | –        | –                         |
|                               | 10-05-98     | Fe                          | <.01                       | –                        | –                               | 450                          | 6.9        | 1,240  | –        | –                         |
|                               | 06-22-00     | Fe                          | <.01                       | .79                      | –                               | 380                          | 6.9        | 1,230  | -49      | 170                       |
|                               | 06-12-01     | S                           | <.01                       | 4.7                      | –                               | 440                          | 6.7        | 1,180  | -36      | 160                       |
|                               | 06-14-02     | S                           | <.01                       | 7.0                      | 83                              | 370                          | 6.7        | 1,030  | -60      | 170                       |
|                               | 06-19-03     | Fe                          | <.01                       | 8.1                      | 65                              | –                            | 6.7        | 1,180  | -17      | 170                       |
|                               | 06-16-04     | Fe                          | <.01                       | 1.4                      | 40                              | –                            | 7.1        | 1,210  | –        | 160                       |
|                               | 06-21-05     | Fe                          | <.01                       | 2.1                      | 33                              | –                            | 6.9        | 1,150  | -9       | 160                       |
|                               | 06-14-06     | Fe                          | <.01                       | 2.4                      | 27                              | –                            | 6.9        | 1,090  | -71      | 140                       |
| MW1–28                        | 09-16-96     | Fe                          | <.01                       | 1.7                      | –                               | 350                          | –          | –  | –        | 380                       |
|                               | 04-17-97     | Fe                          | <.01                       | 5.3                      | –                               | 1,100                        | 7.4        | –  | –        | –                         |
|                               | 03-05-98     | Fe                          | <.01                       | –                        | –                               | –                            | –          | –  | –        | –                         |
|                               | 10-07-98     | Fe                          | .02                        | –                        | –                               | 320                          | 6.6        | 2,630  | –        | –                         |
|                               | 06-22-00     | Fe                          | <.01                       | .45                      | –                               | 480                          | 7.3        | 2,460  | -87      | 510                       |
|                               | 06-12-01     | S/M                         | <.01                       | 4.1                      | –                               | 480                          | 7.4        | 2,200  | -220     | 490                       |
|                               | 06-14-02     | An                          | <.01                       | 3.9                      | 40                              | 470                          | 7.2        | 2,580  | -110     | 460                       |
|                               | 06-19-03     | S                           | <.01                       | 1.7                      | 32                              | –                            | 7.1        | 2,440  | -40      | 490                       |
|                               | 06-16-04     | Mn/Fe                       | <.01                       | .77                      | 21                              | –                            | 7.2        | 2,280  | –        | 450                       |
|                               | 06-21-05     | Fe                          | <.01                       | 1.0                      | 23                              | –                            | 6.9        | 2,210  | -124     | 472                       |
|                               |              | 06-14-06                    | Fe                         | .01                      | .83                             | 21                           | –          | 7.0  | 2,110    | -127                      |

**Table 2.** Predominant redox conditions at wells and piezometers, and ground-water geochemical data collected at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, 1996–2006.—Continued

[Shaded rows indicate 2006 data. All other data were published in Dinicola and others (2002), Dinicola (2003, 2004), and Dinicola and Huffman, 2004, 2006; prior to 2000, bicarbonate was calculated from an unfiltered sample. Reported concentrations less than the detection limit usually are estimated. **Study site No.:** Location of study sites are shown in [figure 2](#). MW, monitoring well; P, piezometer. **Predominant redox condition:** A, aerobic; An, anaerobic, but specific redox condition could not be determined; Fe, iron reducing; M, methanogenic; Mn, manganese reducing; S, sulfate reducing. **Dissolved hydrogen:** A range of dissolved hydrogen concentrations are shown when equilibration at a single value was never achieved. Selected 2002 dissolved-hydrogen data were rejected (R) because of interference from downhole instruments. **Dissolved oxygen:** Selected 1996 dissolved-oxygen data were rejected (R) because of inadequate well purging. **Abbreviations:** nM, nanomolar; mg/L, milligram per liter;  $\mu$ S/cm, microSiemen per centimeter at 25 degrees Celsius; ORP, oxidation-reduction potential; mV, millivolt. **Symbols:** <, actual value is less than value shown; >, actual value is greater than value shown; –, not analyzed]

| Study site No.                 | Date sampled | Predominant redox condition | Dissolved hydrogen (nM) | Dissolved oxygen (mg/L) | Total organic carbon, unfiltered (mg/L) | Dissolved organic carbon, filtered (mg/L) | Nitrate + nitrite, filtered (mg/L as N) | Manganese, filtered (mg/L) | Iron (II), filtered (mg/L) | Sulfate, filtered (mg/L) |
|--------------------------------|--------------|-----------------------------|-------------------------|-------------------------|---|---|---|----------------------------|----------------------------|--------------------------|
| Intermediate aquifer—Continued |              |                             |                         |                         |   |   |   |                            |                            |                          |
| MW1–29                         | 09-16-96     | Mn/Fe                       | 0.0                     | 1.9R                    | –                                       | –   | <0.02                                   | 0.86                       | 2.0                        | 1.8                      |
|                                | 04-17-97     | Fe                          | .7                      | <.1                     | –                                       | –   | .29                                     | –                          | 2.1                        | 1.1                      |
|                                | 06-16-04     | Fe                          | .9                      | <.1                     | –                                       | 3.2                                       | –                                       | .99                        | 3.0                        | <.09                     |
| MW1–38                         | 10-09-98     | Fe                          | –                       | .1                      | –                                       | –   | –                                       | .20                        | .08                        | –                        |
|                                | 06-20-00     | Fe                          | .1                      | .2                      | 5.6                                     | –   | <.05                                    | .08                        | .10                        | 2.3                      |
|                                | 06-12-02     | S                           | 1.4                     | <.1                     | 5.0                                     | –   | <.05                                    | .08                        | .42                        | 2.9                      |
|                                | 06-16-04     | Mn/Fe                       | .2                      | .1                      | –                                       | 4.9                                       | –                                       | .06                        | .04                        | 1.2                      |
|                                | 06-24-05     | Fe                          | .3                      | .1                      | –                                       | 4.4                                       | <.06                                    | .06                        | .09                        | 3.3                      |
|                                | 06-14-06     | Mn/Fe                       | .1                      | .1                      | –                                       | 2.4                                       | <.06                                    | .01                        | .05                        | 1.0                      |
| MW1–39                         | 09-16-96     | Fe/S                        | .6                      | 2.0R                    | 4.4                                     | –   | <.02                                    | .02                        | <.01                       | .7                       |
|                                | 04-17-97     | S                           | 4.5                     | <.1                     | –                                       | –   | <.02                                    | –                          | .05                        | 13                       |
|                                | 03-03-98     | Fe/S                        | .3                      | .3                      | 3.7                                     | –   | –                                       | .10                        | .03                        | –                        |
|                                | 10-09-98     | Fe/S                        | .5                      | <.1                     | –                                       | –   | –                                       | <.01                       | .04                        | –                        |
|                                | 06-07-99     | Fe/S                        | 1.0                     | .3                      | –                                       | –   | –                                       | .10                        | .02                        | –                        |
|                                | 06-20-00     | Fe/S                        | .5                      | .1                      | 2.4                                     | –   | <.05                                    | .01                        | .07                        | .2                       |
|                                | 06-12-01     | S                           | 1.4                     | .3                      | 3.4                                     | 3.3                                       | <.05                                    | .01                        | <.01                       | .1                       |
|                                | 06-12-02     | M                           | >30R                    | <.1                     | –                                       | 2.8                                       | <.05                                    | .01                        | .1                         | .1                       |
|                                | 06-19-03     | S                           | 1.8                     | .1                      | –                                       | 2.5                                       | <.06                                    | .01                        | <.01                       | 1.2                      |
|                                | 06-16-04     | S                           | 2.0                     | .1                      | –                                       | 2.4                                       | –                                       | .01                        | .05                        | .1                       |
| 06-14-06                       | Fe/S         | .7                          | .1                      | –                       | 4.5                                     | <.06                                      | .05                                     | .05                        | 1.7                        |                          |

**Table 2.** Predominant redox conditions at wells and piezometers, and ground-water geochemical data collected at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, 1996–2006.—Continued

[Shaded rows indicate 2006 data. All other data were published in Dinicola and others (2002), Dinicola (2003, 2004), and Dinicola and Huffman, 2004, 2006; prior to 2000, bicarbonate was calculated from an unfiltered sample. Reported concentrations less than the detection limit usually are estimated. **Study site No.:** Location of study sites are shown in [figure 2](#). MW, monitoring well; P, piezometer. **Predominant redox condition:** A, aerobic; An, anaerobic, but specific redox condition could not be determined; Fe, iron reducing; M, methanogenic; Mn, manganese reducing; S, sulfate reducing. **Dissolved hydrogen:** A range of dissolved hydrogen concentrations are shown when equilibration at a single value was never achieved. Selected 2002 dissolved-hydrogen data were rejected (R) because of interference from downhole instruments. **Dissolved oxygen:** Selected 1996 dissolved-oxygen data were rejected (R) because of inadequate well purging. **Abbreviations:** nM, nanomolar; mg/L, milligram per liter;  $\mu\text{S}/\text{cm}$ , microSiemen per centimeter at 25 degrees Celsius; ORP, oxidation-reduction potential; mV, millivolt. **Symbols:** <, actual value is less than value shown; >, actual value is greater than value shown; –, not analyzed]

| Study site No.                 | Date sampled | Predominant redox condition | Sulfide, unfiltered (mg/L) | Dissolved methane (mg/L) | Dissolved carbon dioxide (mg/L) | Bicarbonate, filtered (mg/L) | pH (units) | Specific conductance ( $\mu\text{S}/\text{cm}$ ) | ORP (mV) | Chloride, filtered (mg/L) |
|--------------------------------|--------------|-----------------------------|----------------------------|--------------------------|---------------------------------|------------------------------|------------|--|----------|---------------------------|
| Intermediate aquifer—Continued |              |                             |                            |                          |                                 |                              |            |  |          |                           |
| MW1–29                         | 09-16-96     | Mn/Fe                       | 0.02                       | 8.1                      | –                               | 300                          | –          | –  | –        | 500                       |
|                                | 04-17-97     | Fe                          | <.01                       | 18                       | –                               | 710                          | 7.3        | –  | –        | –                         |
|                                | 06-16-04     | Fe                          | <.01                       | –                        | 18                              | –                            | 7.3        | 2,660  | –        | 660                       |
| MW1–38                         | 10-09-98     | Fe                          | .02                        | –                        | –                               | 310                          | 7.8        | 1,460  | –        | –                         |
|                                | 06-20-00     | Fe                          | .03                        | .10                      | –                               | 300                          | 7.8        | 1,240  | -130     | 230                       |
|                                | 06-12-02     | S                           | .04                        | 1.1                      | 7.7                             | 310                          | 7.6        | 1,350  | -160     | 230                       |
|                                | 06-16-04     | Mn/Fe                       | .03                        | .13                      | 11                              | –                            | 7.4        | 1,130  | –        | 200                       |
|                                | 06-24-05     | Fe                          | .03                        | .05                      | <10                             | –                            | 7.7        | 1,210  | -116     | 230                       |
|                                | 06-14-06     | Mn/Fe                       | <.01                       | .41                      | <10                             | –                            | 7.5        | 1,120  | -55      | 62                        |
| MW1–39                         | 09-16-96     | Fe/S                        | .04                        | 1.6                      | –                               | 140                          | –          | –  | –        | 85                        |
|                                | 04-17-97     | S                           | .06                        | 6.1                      | –                               | 360                          | 7.9        | –  | –        | –                         |
|                                | 03-03-98     | Fe/S                        | .05                        | –                        | –                               | –                            | –          | –  | –        | –                         |
|                                | 10-09-98     | Fe/S                        | .07                        | –                        | –                               | 170                          | 8.1        | 502  | –        | –                         |
|                                | 06-07-99     | Fe/S                        | <.01                       | –                        | –                               | 180                          | 8.0        | 512  | –        | –                         |
|                                | 06-20-00     | Fe/S                        | .08                        | .41                      | –                               | 180                          | 8.0        | 481  | -130     | 61                        |
|                                | 06-12-01     | S                           | .05                        | 2.7                      | –                               | 170                          | 7.8        | 472  | -130     | 61                        |
|                                | 06-12-02     | M                           | .06                        | 4.8                      | 2.4                             | 180                          | 7.9        | 464  | -120     | 60                        |
|                                | 06-19-03     | S                           | .05                        | 5.4                      | <10                             | –                            | 7.7        | 456  | 32       | 58                        |
|                                | 06-16-04     | S                           | .07                        | .72                      | <10                             | –                            | 7.4        | 451  | -216     | 58                        |
| 06-14-06                       | Fe/S         | .06                         | 1.2                        | <10                      | –                               | 8.0                          | 461        | -138   | 210      |                           |

**Table 3.** Concentrations of selected volatile organic compounds in ground-water samples from monitoring wells and piezometers at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, 1999–2006.

[Data collected by the U.S. Geological Survey. Shaded rows indicate 2006 data. All other data were published in Dinicola and others (2002), Dinicola (2003, 2004), and Dinicola and Huffman (2004). Reported concentrations less than the detection limit are estimated. Laboratory data qualifier codes, such as “D” for dilution, are not shown. **Study site No.:** Location of study sites are shown in [figure 2](#). MW, monitoring well; P, piezometer. **Volatile organic compounds (VOCs):** PCE, tetrachloroethene; TCE, trichloroethene; *cis*-DCE, *cis*-1,2-dichloroethene; *trans*-DCE, *trans*-1,2-dichloroethene; VC, vinyl chloride; 1,1,1-TCA, 1,1,1-trichloroethane; 1,1-DCA, 1,1-dichloroethane; CA, chloroethane; 1,1-DCE, 1,1-dichloroethene; total BTEX, sum of benzene, toluene, ethylbenzene, and xylene; Total CVOCs, sum of chlorinated volatile organic compounds. Methane data are presented for diffusion samplers only. **Abbreviations:** E, estimated value; µg/L, microgram per liter; <, actual value is less than value shown; nd, not detected; –, not analyzed]

| Study site No.      | Date sampled | PCE (µg/L) | TCE (µg/L) | <i>cis</i> -DCE (µg/L) | <i>trans</i> -DCE (µg/L) | VC (µg/L) | Ethane (µg/L) | Ethene (µg/L) |
|---------------------|--------------|------------|------------|------------------------|--------------------------|-----------|---------------|---------------|
| Upgradient          |              |            |            |                        |                          |           |               |               |
| MW1-3               | 06-15-04     | –          | –          | –                      | –                        | –         | <5.0          | <5.0          |
|                     | 06-12-06     | –          | –          | –                      | –                        | –         | <5.0          | <5.0          |
| MW1-20              | 06-12-02     | <0.20      | <0.20      | <0.20                  | <0.20                    | <0.20     | –             | –             |
|                     | 06-15-04     | –          | –          | –                      | –                        | –         | <5.0          | <5.0          |
|                     | 06-13-06     | –          | –          | –                      | –                        | –         | <5.0          | <5.0          |
| MW1-33              | 06-15-04     | –          | –          | –                      | –                        | –         | <5.0          | <5.0          |
|                     | 06-12-06     | –          | –          | –                      | –                        | –         | <5.0          | <5.0          |
| Northern plantation |              |            |            |                        |                          |           |               |               |
| 1MW-1               | 06-16-04     | <20        | <20        | 130                    | 130                      | 730       | 10            | 50            |
|                     | 06-12-06     | –          | –          | –                      | –                        | –         | 21            | 61            |
| MW1-2               | 06-17-04     | <50        | 12         | 630                    | 13                       | 110       | 5.9           | 1.1           |
|                     | 06-12-06     | –          | –          | –                      | –                        | –         | 5.0           | <5.0          |
| MW1-15              | 06-15-04     | <1.0       | <1.0       | .32                    | <1.0                     | .26       | <5.0          | <5.0          |
| MW1-17              | 06-17-04     | <1.0       | <1.0       | .68                    | .23                      | .48       | 2.4           | <5.0          |
| MW1-18              | 06-16-04     | <1.0       | <1.0       | <1.0                   | <1.0                     | <1.0      | 19            | 18            |
| MW1-41              | 06-17-04     | <1.0       | <1.0       | .27                    | <1.0                     | .23       | 10            | <100          |
|                     | 06-12-06     | –          | –          | –                      | –                        | –         | <100          | <100          |
| P1-1                | 06-09-99     | <2         | 11         | 6.1                    | <1                       | <4        | –             | –             |
|                     | 06-11-02     | <.2        | <.20       | .16                    | .11                      | <.2       | –             | –             |
|                     | 06-18-03     | <1.0       | <1.0       | .28                    | <1.0                     | <1.0      | –             | –             |
|                     | 06-17-04     | <1.0       | <1.0       | <1.0                   | <1.0                     | <1.0      | 29            | 8.6           |
|                     | 06-22-05     | <1.0       | <1.0       | .16                    | <1.0                     | <1.0      | <100          | <100          |
|                     | 06-12-06     | <1.0       | <1.0       | <1.0                   | <1.0                     | <1.0      | <100          | <100          |
| P1-3                | 06-09-99     | <16        | 35         | 450                    | 20                       | 120       | –             | –             |
|                     | 06-11-02     | <.2        | <.20       | 53                     | 4.3                      | 72        | –             | –             |
|                     | 06-18-03     | <2.0       | <2.0       | 58                     | 4.5                      | 79        | –             | –             |
|                     | 06-17-04     | <1.0       | <1.0       | 15                     | 2.4                      | 41        | 33            | 27            |
|                     | 06-22-05     | <1.0       | <1.0       | 11                     | 1.3                      | 35        | 44            | 30            |
|                     | 06-12-06     | <1.0       | <1.0       | 4.6                    | 1.2                      | 16        | 35            | 21            |
| P1-4                | 06-09-99     | <130       | 160        | 4,800                  | 56                       | 540       | –             | –             |
|                     | 06-13-01     | <20        | <20        | 4,900                  | 46                       | 650       | –             | –             |
|                     | 06-11-02     | <.2        | 1.2        | 3,600                  | 41                       | 640       | –             | –             |
|                     | 06-18-03     | <100       | <100       | 3,200                  | 42                       | 440       | –             | –             |
|                     | 06-17-04     | <130       | <130       | 2,300                  | 29                       | 370       | 7.1           | 29            |
|                     | 06-21-05     | <67        | <67        | 2,100                  | 30                       | 360       | 7             | 20            |
|                     | 06-12-06     | <50        | <50        | 1,600                  | 24                       | 280       | 6             | 19            |
| P1-5                | 06-08-99     | <13        | 440        | 400                    | 3.5                      | 11        | –             | –             |
|                     | 06-10-02     | <.20       | <.20       | .28                    | .78                      | .4        | –             | –             |
|                     | 06-18-03     | <25        | <25        | 7.8                    | <25                      | <25       | –             | –             |
|                     | 06-17-04     | <10        | <10        | <10                    | <10                      | <10       | 23            | <10           |
|                     | 06-21-05     | <10        | <10        | <10                    | <10                      | <10       | 23            | <100          |
|                     | 06-12-06     | <10        | <10        | <10                    | <10                      | <10       | 16            | <100          |

**Table 3.** Concentrations of selected volatile organic compounds in ground-water samples from monitoring wells and piezometers at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, 1999–2006.—Continued

[Data collected by the U.S. Geological Survey. Shaded rows indicate 2006 data. All other data were published in Dinicola and others (2002), Dinicola (2003, 2004), and Dinicola and Huffman (2004). Reported concentrations less than the detection limit are estimated. Laboratory data qualifier codes, such as “D” for dilution, are not shown. **Study site No.:** Location of study sites are shown in figure 2. MW, monitoring well; P, piezometer. **Volatile organic compounds (VOCs):** PCE, tetrachloroethene; TCE, trichloroethene; *cis*-DCE, *cis*-1,2-dichloroethene; *trans*-DCE, *trans*-1,2-dichloroethene; VC, vinyl chloride; 1,1,1-TCA, 1,1,1-trichloroethane; 1,1-DCA, 1,1-dichloroethane; CA, chloroethane; 1,1-DCE, 1,1-dichloroethene; total BTEX, sum of benzene, toluene, ethylbenzene, and xylene; Total CVOCs, sum of chlorinated volatile organic compounds. Methane data are presented for diffusion samplers only. **Abbreviations:** E, estimated value; µg/L, micrograms per liter; <, actual value is less than value shown; nd, not detected; –, not analyzed]

| Study site No.      | Date sampled | 1,1,1-TCA (µg/L) | 1,1-DCA (µg/L) | CA (µg/L) | 1,1-DCE (µg/L) | Total BTEX (µg/L) | Total CVOCs (µg/L) |
|---------------------|--------------|------------------|----------------|-----------|----------------|-------------------|--------------------|
| Upgradient          |              |                  |                |           |                |                   |                    |
| MW1-3               | 06-15-04     | –                | –              | –         | –              | –                 | –                  |
|                     | 06-12-06     | –                | –              | –         | –              | –                 | –                  |
| MW1-20              | 06-12-02     | <0.20            | <0.20          | <0.20     | <0.20          | nd                | nd                 |
|                     | 06-15-04     | –                | –              | –         | –              | –                 | –                  |
|                     | 06-12-06     | –                | –              | –         | –              | –                 | –                  |
| MW1-33              | 06-15-04     | –                | –              | –         | –              | –                 | –                  |
|                     | 06-12-06     | –                | –              | –         | –              | –                 | –                  |
| Northern plantation |              |                  |                |           |                |                   |                    |
| 1MW-1               | 06-16-04     | <20              | 11             | <40       | <20            | nd                | 1,000              |
|                     | 06-12-06     | –                | –              | –         | –              | –                 | –                  |
| MW1-2               | 06-17-04     | <50              | <50            | <100      | <50            | nd                | 770                |
|                     | 06-12-06     | –                | –              | –         | –              | –                 | –                  |
| MW1-15              | 06-15-04     | <1.0             | <1.0           | .88       | <1.0           | 30                | 1.5                |
| MW1-17              | 06-17-04     | <1.0             | <1.0           | <2.0      | <1.0           | .31               | 1.4                |
| MW1-18              | 06-16-04     | <1.0             | <1.0           | <2.0      | <1.0           | nd                | nd                 |
| MW1-41              | 06-17-04     | <1.0             | <1.0           | 1.7       | <1.0           | nd                | 2.2                |
|                     | 06-12-06     | –                | –              | –         | –              | –                 | –                  |
| P1-1                | 06-09-99     | <2               | .24            | <4        | <2             | 19                | 17                 |
|                     | 06-11-02     | <.20             | .46            | <.2       | <.20           | 6.8               | .73                |
|                     | 06-18-03     | <1.0             | .26            | <2.0      | <1.0           | 3.9               | .54                |
|                     | 06-17-04     | <1.0             | <1.0           | <2.0      | <1.0           | 4.4               | nd                 |
|                     | 06-22-05     | <1.0             | <1.0           | .19       | <1.0           | 3.5               | .35                |
|                     | 06-12-06     | <1.0             | <1.0           | <2.0      | <1.0           | 3.1               | nd                 |
| P1-3                | 06-09-99     | <16              | <16            | 3.6       | <16            | nd                | 630                |
|                     | 06-11-02     | <.20             | .60            | 9.9       | .20            | 3.3               | 140                |
|                     | 06-18-03     | <2.0             | .56            | 5.2       | <2.0           | 1.7               | 150                |
|                     | 06-17-04     | <1.0             | .38            | 6.9       | <1.0           | 2.4               | 66                 |
|                     | 06-22-05     | <1.0             | .31            | 2.6       | <1.0           | 2.3               | 50                 |
|                     | 06-12-06     | <1.0             | .32            | 4.4       | <1.0           | 2.2               | 26                 |
| P1-4                | 06-09-99     | <130             | <130           | <270      | <130           | nd                | 5,600              |
|                     | 06-13-01     | <20              | <20            | <20       | <20            | nd                | 5,600              |
|                     | 06-11-02     | <.20             | <10            | .8        | 9.9            | 1.1               | 4,300              |
|                     | 06-18-03     | <100             | <100           | <200      | <100           | nd                | 3,700              |
|                     | 06-17-04     | <130             | <130           | <270      | <130           | nd                | 2,700              |
|                     | 06-21-05     | <67              | <67            | <130      | <67            | nd                | 2,500              |
|                     | 06-12-06     | <50              | <50            | <100      | <50            | nd                | 1,900              |
| P1-5                | 06-08-99     | <13              | <13            | 15        | <13            | 47                | 870                |
|                     | 06-10-02     | <.20             | .27            | 20.9      | <.20           | 18                | 23                 |
|                     | 06-18-03     | <25              | <25            | 19        | <25            | nd                | 27                 |
|                     | 06-17-04     | <10              | <10            | 23        | <10            | 4.5               | 23                 |
|                     | 06-21-05     | <10              | <10            | 21        | <10            | 8.2               | 21                 |
|                     | 06-12-06     | <10              | <10            | 14        | <10            | 4.2               | 14                 |

**Table 3.** Concentrations of selected volatile organic compounds in ground-water samples from monitoring wells and piezometers at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, 1999–2006.—Continued

[Data collected by the U.S. Geological Survey. Shaded rows indicate 2006 data. All other data were published in Dinicola and others (2002), Dinicola (2003, 2004), and Dinicola and Huffman (2004). Reported concentrations less than the detection limit are estimated. Laboratory data qualifier codes, such as “D” for dilution, are not shown. **Study site No.:** Location of study sites are shown in figure 2. MW, monitoring well; P, piezometer. **Volatile organic compounds (VOCs):** PCE, tetrachloroethene; TCE, trichloroethene; *cis*-DCE, *cis*-1,2-dichloroethene; *trans*-DCE, *trans*-1,2-dichloroethene; VC, vinyl chloride; 1,1,1-TCA, 1,1,1-trichloroethane; 1,1-DCA, 1,1-dichloroethane; CA, chloroethane; 1,1-DCE, 1,1-dichloroethene; total BTEX, sum of benzene, toluene, ethylbenzene, and xylene; Total CVOCs, sum of chlorinated volatile organic compounds. Methane data are presented for diffusion samplers only. **Abbreviations:** E, estimated value; µg/L, micrograms per liter; <, actual value is less than value shown; nd, not detected; –, not analyzed]

| Study site No.      | Date sampled | PCE (µg/L) | TCE (µg/L) | <i>cis</i> -DCE (µg/L) | <i>trans</i> -DCE (µg/L) | VC (µg/L) | Ethane (µg/L) | Ethene (µg/L) |
|---------------------|--------------|------------|------------|------------------------|--------------------------|-----------|---------------|---------------|
| Southern plantation |              |            |            |                        |                          |           |               |               |
| MW1-4               | 06-18-04     | <1,000     | 32,000     | 15,000                 | <1,000                   | 1,600     | 32            | 200           |
|                     | 06-13-06     | –          | –          | –                      | –                        | –         | 39            | 200           |
| MW1-5               | 06-18-04     | <1.0       | .26        | .29                    | <1.0                     | .74       | 6.7           | <50           |
|                     | 06-13-06     | –          | –          | –                      | –                        | –         | 9             | 30            |
| MW1-6               | 06-22-04     | <1.0       | <1.0       | <1.0                   | <1.0                     | <1.0      | <100          | <100          |
| MW1-16              | 06-22-04     | <10        | <10        | 2.3                    | 4.2                      | 2.2       | 38            | 33            |
|                     | 06-13-06     | –          | –          | –                      | –                        | –         | 23            | 6.8           |
| P1-6                | 06-08-99     | <400       | 74         | 16,000                 | 170                      | 5,400     | –             | –             |
|                     | 06-14-01     | <20        | 370        | 16,000                 | 220                      | 9,900     | –             | –             |
|                     | 06-13-02     | <20        | <20        | 3,700                  | 170                      | 5,100     | –             | –             |
|                     | 06-18-03     | <50        | 470        | 1,100                  | 39                       | 1,300     | –             | –             |
|                     | 06-18-04     | <20        | <20        | 220                    | 11                       | 570       | 7.0           | 210           |
|                     | 06-22-05     | <130       | <130       | 4,200                  | 90                       | 2,900     | 30            | 590           |
|                     | 06-13-06     | <100       | <100       | 300                    | 77                       | 770       | 82            | 1,300         |
| P1-7                | 06-08-99     | <670       | 26,000     | 35,000                 | 210                      | 3,100     | –             | –             |
|                     | 06-22-00     | 3.6        | 27,000     | 44,000                 | 220                      | 3,800     | –             | –             |
|                     | 06-14-01     | <20        | 26,000     | 37,000                 | 190                      | 4,000     | –             | –             |
|                     | 06-14-02     | <20        | 37,000     | 62,000                 | 400                      | 5,700     | –             | –             |
|                     | 06-20-03     | <2,000     | 28,000     | 35,000                 | <2,000                   | 2,800     | –             | –             |
|                     | 06-18-04     | <3,300     | 37,000     | 61,000                 | <3,300                   | 5,100     | 36            | 520           |
|                     | 06-22-05     | <2,000     | 28,000     | 59,000                 | 330                      | 5,000     | 45            | 480           |
|                     | 06-13-06     | <2,000     | 24,000     | 43,000                 | <2,000                   | 3,800     | 44            | 400           |
| P1-8                | 06-07-99     | <710       | 190        | 25,000                 | 210                      | 3,400     | –             | –             |
|                     | 06-14-01     | <20        | 810        | 8,600                  | 62                       | 4,200     | –             | –             |
|                     | 06-13-02     | <20        | <20        | 24,000                 | 190                      | 7,700     | –             | –             |
|                     | 06-20-03     | <10        | 230        | 31                     | <10                      | 7.2       | –             | –             |
|                     | 06-18-04     | <1.0       | .26        | 2.7                    | <1.0                     | 23        | <50           | 4.2           |
|                     | 06-23-05     | <1.0       | <1.0       | 7                      | <1.0                     | 21        | <50           | <50           |
|                     | 06-13-06     | <20        | <20        | 620                    | 4.0                      | 58        | <50           | 9.5           |
| P1-9                | 06-08-99     | <2,000     | 48,000     | 88,000                 | 470                      | 7,200     | –             | –             |
|                     | 06-22-00     | 5.0        | 88,000     | 64,000                 | 320                      | 5,800     | –             | –             |
|                     | 06-14-01     | <40        | 29,000     | 7,300                  | 32                       | 450       | –             | –             |
|                     | 06-13-02     | <20        | 90,000     | 79,000                 | 590                      | 7,900     | –             | –             |
|                     | 06-20-03     | <1,000     | 60,000     | 27,000                 | <1,000                   | 1,800     | –             | –             |
|                     | 06-18-04     | <1,300     | 50,000     | 23,000                 | <1,300                   | 2,100     | 16            | 200           |
|                     | 06-23-05     | <20        | 230        | 700                    | 3.2                      | 97        | <5            | 4             |
|                     | 06-13-06     | <5,000     | 74,000     | 140,000                | 850                      | 10,000    | 66            | 1,200         |



**Table 3.** Concentrations of selected volatile organic compounds in ground-water samples from monitoring wells and piezometers at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, 1999–2006.—Continued

[Data collected by the U.S. Geological Survey. Shaded rows indicate 2006 data. All other data were published in Dinicola and others (2002), Dinicola (2003, 2004), and Dinicola and Huffman (2004). Reported concentrations less than the detection limit are estimated. Laboratory data qualifier codes, such as “D” for dilution, are not shown. **Study site No.:** Location of study sites are shown in figure 2. MW, monitoring well; P, piezometer. **Volatile organic compounds (VOCs):** PCE, tetrachloroethene; TCE, trichloroethene; *cis*-DCE, *cis*-1,2-dichloroethene; *trans*-DCE, *trans*-1,2-dichloroethene; VC, vinyl chloride; 1,1,1-TCA, 1,1,1-trichloroethane; 1,1-DCA, 1,1-dichloroethane; CA, chloroethane; 1,1-DCE, 1,1-dichloroethene; total BTEX, sum of benzene, toluene, ethylbenzene, and xylene; Total CVOCs, sum of chlorinated volatile organic compounds. Methane data are presented for diffusion samplers only. **Abbreviations:** E, estimated value; µg/L, micrograms per liter; <, actual value is less than value shown; nd, not detected; –, not analyzed]

| Study site No.      | Date sampled | 1,1,1-TCA (µg/L) | 1,1-DCA (µg/L) | CA (µg/L) | 1,1-DCE (µg/L) | Total BTEX (µg/L) | Total CVOCs (µg/L) |
|---------------------|--------------|------------------|----------------|-----------|----------------|-------------------|--------------------|
| Southern plantation |              |                  |                |           |                |                   |                    |
| MW1-4               | 06-18-04     | <1,000           | <1,000         | <2,000    | <1,000         | nd                | 49,000             |
|                     | 06-13-06     | –                | –              | –         | –              | –                 | –                  |
| MW1-5               | 06-18-04     | <1.0             | .36            | 3         | <1.0           | 0.92              | 4.6                |
|                     | 06-13-06     | –                | –              | –         | –              | –                 | –                  |
| MW1-6               | 06-22-04     | <1.0             | <1.0           | 1.7       | <1.0           | 1.9               | 1.7                |
| MW1-16              | 06-22-04     | <10              | 590            | 290       | <10            | 370               | 900                |
|                     | 06-13-06     | –                | –              | –         | –              | –                 | –                  |
| P1-6                | 06-08-99     | <400             | 1,500          | 300       | <400           | nd                | 23,000             |
|                     | 06-14-01     | <20              | 4,800          | 610       | 11             | 88                | 32,000             |
|                     | 06-13-02     | <20              | 4,300          | 1,400     | <20            | 63                | 15,000             |
|                     | 06-18-03     | <50              | 380            | 270       | <50            | nd                | 3,600              |
|                     | 06-18-04     | <20              | 200            | 88        | <20            | nd                | 1,100              |
|                     | 06-22-05     | <130             | <130           | 400       | <130           | nd                | 7,600              |
|                     | 06-13-06     | <100             | 1,200          | 2,600     | <100           | 68                | 4,900              |
| P1-7                | 06-08-99     | <670             | <670           | <1,300    | <670           | nd                | 64,000             |
|                     | 06-22-00     | .24              | 17             | 8.4       | 72             | 18                | 75,000             |
|                     | 06-14-01     | <20              | <20            | <20       | 44             | nd                | 68,000             |
|                     | 06-14-02     | <20              | 14             | <20       | 64             | nd                | 105,000            |
|                     | 06-20-03     | <2,000           | <2,000         | <4,000    | <2,000         | nd                | 69,000             |
|                     | 06-18-04     | <3,300           | <3,300         | <6,700    | <3,300         | nd                | 103,000            |
|                     | 06-22-05     | <2,000           | <2,000         | <4,000    | <2,000         | nd                | 92,000             |
| 06-13-06            | <2,000       | <2,000           | <4,000         | <2,000    | nd             | 71,000            |                    |
| P1-8                | 06-07-99     | <710             | <710           | <1,400    | <710           | nd                | 29,000             |
|                     | 06-14-01     | <20              | <20            | <20       | <20            | nd                | 14,000             |
|                     | 06-13-02     | <20              | <20            | <20       | 16             | nd                | 32,000             |
|                     | 06-20-03     | <10              | 4.2            | <20       | <10            | nd                | 270                |
|                     | 06-18-04     | <1.0             | <1.0           | <2.0      | <1.0           | nd                | 26                 |
|                     | 06-23-05     | <1.0             | <1.0           | <2.0      | <1.0           | nd                | 28                 |
|                     | 06-13-06     | <20              | <20            | <40       | <20            | nd                | 680                |
| P1-9                | 06-08-99     | <2,000           | <2,000         | <4,000    | <2,000         | nd                | 140,000            |
|                     | 06-22-00     | <10              | 2.6            | <20       | 47             | 36                | 160,000            |
|                     | 06-14-01     | <40              | <40            | <40       | <40            | nd                | 37,000             |
|                     | 06-13-02     | <20              | <20            | <20       | 54             | 11                | 180,000            |
|                     | 06-20-03     | <1,000           | <1,000         | <2,000    | <1,000         | nd                | 89,000             |
|                     | 06-18-04     | <1,300           | <1,300         | <2,700    | <1,300         | nd                | 75,000             |
|                     | 06-23-05     | <20              | <20            | <40       | <20            | nd                | 1,000              |
| 06-13-06            | <5,000       | <5,000           | <10,000        | <5,000    | nd             | 220,000           |                    |

**Table 3.** Concentrations of selected volatile organic compounds in ground-water samples from monitoring wells and piezometers at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, 1999–2006.—Continued

[Data collected by the U.S. Geological Survey. Shaded rows indicate 2006 data. All other data were published in Dinicola and others (2002), Dinicola (2003, 2004), and Dinicola and Huffman (2004). Reported concentrations less than the detection limit are estimated. Laboratory data qualifier codes, such as “D” for dilution, are not shown. **Study site No.:** Location of study sites are shown in figure 2. MW, monitoring well; P, piezometer. **Volatile organic compounds (VOCs):** PCE, tetrachloroethene; TCE, trichloroethene; *cis*-DCE, *cis*-1,2-dichloroethene; *trans*-DCE, *trans*-1,2-dichloroethene; VC, vinyl chloride; 1,1,1-TCA, 1,1,1-trichloroethane; 1,1-DCA, 1,1-dichloroethane; CA, chloroethane; 1,1-DCE, 1,1-dichloroethene; total BTEX, sum of benzene, toluene, ethylbenzene, and xylene; Total CVOCs, sum of chlorinated volatile organic compounds. Methane data are presented for diffusion samplers only. **Abbreviations:** E, estimated value; µg/L, micrograms per liter; <, actual value is less than value shown; nd, not detected; –, not analyzed]

| Study site No.                | Date sampled | PCE (µg/L) | TCE (µg/L) | <i>cis</i> -DCE (µg/L) | <i>trans</i> -DCE (µg/L) | VC (µg/L) | Ethane (µg/L) | Ethene (µg/L) |
|-------------------------------|--------------|------------|------------|------------------------|--------------------------|-----------|---------------|---------------|
| Southern plantation—Continued |              |            |            |                        |                          |           |               |               |
| P1-10                         | 06-07-99     | <1,000     | 14,000     | 34,000                 | 270                      | 2,500     | –             | –             |
|                               | 06-22-00     | 1.00       | 8,700      | 13,000                 | 100                      | 2,300     | –             | –             |
|                               | 06-13-01     | <20        | 6,600      | 12,000                 | 68                       | 1,900     | –             | –             |
|                               | 06-12-02     | <20        | 4,600      | 7,000                  | 55                       | 2,000     | –             | –             |
|                               | 06-19-03     | <400       | 2,300      | 9,400                  | <400                     | 1,100     | –             | –             |
|                               | 06-18-04     | <200       | 1,600      | 3,900                  | <200                     | 890       | 12            | 46            |
|                               | 06-23-05     | <100       | 1,100      | 3,000                  | 29                       | 700       | 3             | 7             |
|                               | 06-13-06     | <1,000     | 2,200      | 27,000                 | 160                      | 2,500     | 19            | 53            |
| Intermediate aquifer          |              |            |            |                        |                          |           |               |               |
| 1MW-4                         | 06-17-04     | <1.0       | <1.0       | <1.0                   | <1.0                     | <1.0      | 5.3           | <50           |
| MW1-25                        | 06-14-02     | <20        | 280        | 1,800                  | 31                       | 280       | –             | –             |
|                               | 06-19-03     | <67        | 14         | 1,800                  | 34                       | 210       | –             | –             |
|                               | 06-06-04     | –          | –          | –                      | –                        | –         | 4.7           | 15            |
|                               | 06-21-05     | <67        | <67        | 1,700                  | 30                       | 220       | 6             | 13            |
|                               | 06-14-06     | –          | –          | –                      | –                        | –         | 7             | 14            |
| MW1-28                        | 06-14-02     | <20        | 69         | 1,600                  | 72                       | 700       | –             | –             |
|                               | 06-19-03     | <50        | <50        | 1,200                  | 68                       | 470       | –             | –             |
|                               | 06-16-04     | –          | –          | –                      | –                        | –         | 3.8           | 26            |
|                               | 06-21-05     | <67        | <67        | 1,550                  | 84                       | 650       | 4             | 22            |
|                               | 06-14-06     | –          | –          | –                      | –                        | –         | <50           | 18            |
| MW1-38                        | 06-12-02     | <.20       | <.20       | <.20                   | <.20                     | <.20      | –             | –             |
|                               | 06-16-04     | –          | –          | –                      | –                        | –         | <5.0          | <5.0          |
|                               | 06-21-05     | <1.0       | <1.0       | <1.0                   | <1.0                     | <1.0      | <5.0          | <5.0          |
|                               | 06-14-06     | –          | –          | –                      | –                        | –         | <5            | <5.0          |
| MW1-39                        | 06-19-03     | <1.0       | <1.0       | .56                    | <1.0                     | 1.3       | –             | –             |
|                               | 06-16-04     | –          | –          | –                      | –                        | –         | <5.0          | <5.0          |
|                               | 06-14-06     | –          | –          | –                      | –                        | –         | <50           | <50           |

**Table 3.** Concentrations of selected volatile organic compounds in ground-water samples from monitoring wells and piezometers at Operable Unit 1, Naval Undersea Warfare Center, Division Keyport, Washington, 1999–2006.—Continued

[Data collected by the U.S. Geological Survey. Shaded rows indicate 2006 data. All other data were published in Dinicola and others (2002), Dinicola (2003, 2004), and Dinicola and Huffman (2004). Reported concentrations less than the detection limit are estimated. Laboratory data qualifier codes, such as “D” for dilution, are not shown. **Study site No.:** Location of study sites are shown in figure 2. MW, monitoring well; P, piezometer. **Volatile organic compounds (VOCs):** PCE, tetrachloroethene; TCE, trichloroethene; *cis*-DCE, *cis*-1,2-dichloroethene; *trans*-DCE, *trans*-1,2-dichloroethene; VC, vinyl chloride; 1,1,1-TCA, 1,1,1-trichloroethane; 1,1-DCA, 1,1-dichloroethane; CA, chloroethane; 1,1-DCE, 1,1-dichloroethene; total BTEX, sum of benzene, toluene, ethylbenzene, and xylene; Total CVOCs, sum of chlorinated volatile organic compounds. Methane data are presented for diffusion samplers only. **Abbreviations:** E, estimated value; µg/L, micrograms per liter; <, actual value is less than value shown; nd, not detected; –, not analyzed]

| Study site No.                | Date sampled | 1,1,1-TCA (µg/L) | 1,1-DCA (µg/L) | CA (µg/L) | 1,1-DCE (µg/L) | Total BTEX (µg/L) | Total CVOCs (µg/L) |
|-------------------------------|--------------|------------------|----------------|-----------|----------------|-------------------|--------------------|
| Southern plantation—Continued |              |                  |                |           |                |                   |                    |
| P1-10                         | 06-07-99     | <1,000           | <1,000         | <2,000    | <1,000         | nd                | 51,000             |
|                               | 06-22-00     | <.1              | 1.2            | .13       | 16             | 12                | 24,000             |
|                               | 06-13-01     | <20              | <20            | <20       | 11             | nd                | 21,000             |
|                               | 06-12-02     | <20              | <20            | <20       | <20            | nd                | 14,000             |
|                               | 06-19-03     | <400             | <400           | <800      | <400           | nd                | 13,000             |
|                               | 06-18-04     | <200             | <200           | <400      | <200           | nd                | 6,400              |
|                               | 06-23-05     | <100             | <100           | <200      | <100           | nd                | 4,800              |
|                               | 06-13-06     | <1,000           | <1,000         | <2,000    | <1,000         | nd                | 32,000             |
| Intermediate aquifer          |              |                  |                |           |                |                   |                    |
| 1MW-4                         | 06-17-04     | <1.0             | <1.0           | <2.0      | <1.0           | nd                | nd                 |
| MW1-25                        | 06-14-02     | <20              | <20            | <20       | <20            | nd                | 2,400              |
|                               | 06-19-03     | <67              | <67            | <130      | <67            | nd                | 2,100              |
|                               | 06-06-04     | –                | –              | –         | –              | –                 | –                  |
|                               | 06-21-05     | <67              | <67            | <130      | <67            | nd                | 2,000              |
|                               | 06-14-06     | –                | –              | –         | –              | –                 | –                  |
| MW1-28                        | 06-14-02     | <20              | <20            | <20       | <20            | nd                | 2,400              |
|                               | 06-19-03     | <50              | <50            | <100      | <50            | nd                | 1,700              |
|                               | 06-16-04     | –                | –              | –         | –              | –                 | –                  |
|                               | 06-21-05     | <67              | <67            | <130      | <67            | nd                | 2,300              |
|                               | 06-14-06     | –                | –              | –         | –              | –                 | –                  |
| MW1-38                        | 06-12-02     | <.20             | <.20           | <.20      | <.20           | nd                | nd                 |
|                               | 06-16-04     | –                | –              | –         | –              | –                 | –                  |
|                               | 06-21-05     | <1.0             | <1.0           | <2.0      | <1.0           | nd                | nd                 |
|                               | 06-14-06     | –                | –              | –         | –              | –                 | –                  |
| MW1-39                        | 06-19-03     | <1.0             | <1.0           | <2.0      | <1.0           | nd                | 2.0                |
|                               | 06-16-04     | –                | –              | –         | –              | –                 | –                  |

This page intentionally blank

Manuscript approved for publication, December 11, 2007

Prepared by the USGS Publishing Network,

Publishing Service Center, Tacoma, Washington

Bill Gibbs

Ginger Renslow

Linda S. Rogers

Bobbie Jo Richey

For more information concerning the research in this report, contact the

Director, Washington Water Science Center

U.S. Geological Survey

934 Broadway — Suite 300

Tacoma, Washington 98402

<http://wa.water.usgs.gov>

