Comparison of Passive Diffusion Bag Samplers and Submersible Pump Sampling Methods for Monitoring Volatile Organic Compounds in Ground Water at Area 6, Naval Air Station Whidbey Island, Washington

Prepared in cooperation with the
DEPARTMENT OF THE NAVY, ENGINEERING FIELD ACTIVITY,
NORTHWEST NAVAL FACILITIES ENGINEERING COMMAND

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 02-4203

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By Raegan L. Huffman

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Tacoma, Washington
2002

U.S. DEPARTMENT OF THE INTERIOR

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U.S. GEOLOGICAL SURVEY

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CONVERSION FACTORS AND VERTICAL DATUM

CONVERSION FACTORS

Multiply	By	To obtain
acre	0.4047	hectare
foot (ft)	0.3048	meter
inch (in)	25.4	millimeter
mile (mi)	1.609	kilometer

Temperature in degrees Celsius (^{o}C) may be converted to degrees Fahrenheit (^{o}F) as follows:

$$^{o}F=1.8\ ^{o}C+32.$$

Temperature in degrees Fahrenheit (^{o}F) may be converted to degrees Celsius (^{o}C) as follows:

$$^{o}C=(^{o}F-32)/1.8.$$

Chemical concentrations in water are given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter. For concentrations less than 7,000 mg/L, milligrams per liter is equivalent to "parts per million" and micrograms per liter is equivalent to "parts per billion."

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

VERTICAL DATUM

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Comparison of Passive Diffusion Bag Samplers and Submersible Pump Sampling Methods for Monitoring Volatile Organic Compounds in Ground Water at Area 6, Naval Air Station Whidbey Island, Washington

By Raegan L. Huffman

ABSTRACT

Ground-water samples were collected in April 1999 at Naval Air Station Whidbey Island, Washington, with passive diffusion samplers and a submersible pump to compare concentrations of volatile organic compounds (VOCs) in water samples collected using the two sampling methods. Single diffusion samplers were installed in wells with 10-foot screened intervals, and multiple diffusion samplers were installed in wells with 20- to 40-foot screened intervals. The diffusion samplers were recovered after 20 days and the wells were then sampled using a submersible pump. VOC concentrations in the 10-foot screened wells in water samples collected with diffusion samplers closely matched concentrations in samples collected with the submersible pump. Analysis of VOC concentrations in samples collected from the 20- to 40-foot screened wells with multiple diffusion samplers indicated vertical concentration variation within the screened interval, whereas the analysis of VOC concentrations in samples collected with the submersible pump indicated mixing during pumping. The results obtained using the two sampling methods indicate that the samples collected with the diffusion samplers were comparable with and can be considerably less expensive than samples collected using a submersible pump.

INTRODUCTION

Ground water contaminated with volatile organic compounds (VOCs) underlies many sites around the Nation, and monitoring of ground-water contamination is commonly one of the most costly elements associated with long-term site remediation. As remediation proceeds at these sites and VOC concentrations in ground water decrease, it is often beneficial to more precisely locate the remaining contamination to allow optimization of remediation strategies that may originally have been designed for widespread high concentration contamination. Therefore, methods that minimize the cost and maximize the usefulness of ground-water sampling are needed.

The purpose of this report is to compare VOC concentrations in ground-water samples collected using water-filled, low-density polyethylene passive diffusion bag samplers with VOC concentrations in samples collected using a conventional sampling method with a submersible pump. Comparison samples were collected from 11 monitoring wells at Area 6, Naval Air Station Whidbey Island in Washington State. The methods for construction, installment, and retrieval of diffusion samplers as described by D.A. Vroblesky and T.R. Campbell (U.S. Geological Survey, written commun., January 1999) were followed. This study was done by the U.S. Geological Survey in cooperation with the U.S. Navy.

Background

The typical approach to sampling wells for VOCs involves using pumps or bailers to purge wells prior to collecting the sample. Commonly, at least three casing volumes of water are purged, or enough water is purged so that selected water-quality parameters stabilize. There are potential technical and economic shortcomings to these traditional purge and sample methods. Purging three or more casing volumes prior to sampling is sometimes unnecessary and may produce undesirable effects (Gibs and Imbriotta, 1990; Kearl and others, 1992; Powell and Puls, 1993; Barcelona and others, 1994). Simply lowering pumps or bailers into a well can significantly increase the size and number of colloidal particles suspended in borehole water (Kearl and other, 1992; Puls and others, 1992), and purging a well can increase the radius of aquifer influenced by pumping which in turn can yield samples that are not representative of ambient ground water (Reilly and Gibs, 1993; Barcelona and others, 1994; Vroblesky, 2001b). Considerable resources also are required to properly collect, treat, and dispose of contaminated purge water. When collecting a representative ground-water sample for VOC analysis, it is clearly advantageous to minimize well purging as much as possible.

Recent investigations indicate that purging a well is not necessarily required to obtain a representative ground-water sample. Ground water can move through the screened portion of a borehole with little interaction or mixing with water in the overlying well casing (Robin and Gillham, 1987; Kearl and others, 1992; Powell and Puls, 1993; and Vroblesky and Hyde, 1997). The studies suggested that flow across the screened interval of the tested wells generally was horizontal and laminar and representative of ambient ground water. Visual support of this hypothesis was provided using a downhole colloidal borescope to document advection of suspended sediment across the borehole (Kearl and others, 1992). Thus, in a well with horizontal laminar flow across the screened interval, a sampling device in the screened interval could be used to collect a representative sample while minimizing disturbance of the remaining borehole water.

Methods have been developed to minimize well purging while obtaining representative ground-water samples. Micro-purging and low-flow sampling with dedicated pumps are methods that minimally disturb the borehole water column by pumping at a rate slow enough to minimize drawdown in the borehole (Barcelona and others, 1994; Shanklin and others, 1995). Another sampling method involves isolating a short-screened interval with an inflatable packer, and then purging and sampling the isolated interval (Kamlinsky and Wylie, 1995). Both of these methods reduce but do not eliminate the amount of purge water.

Diffusion samplers have the potential to completely eliminate well purging while obtaining representative ground-water samples (Kaplan and others, 1991; Powell and Puls, 1993; Vroblesky and Hyde, 1997; Vroblesky and Peters, 2000; and Vroblesky and Petkewich, 2000). Diffusion samplers rely on the diffusion of borehole solutes across various membranes into cells or bags filled with distilled water that are suspended in the borehole. The multi-layer passive sampler uses dialysis cells (Kaplan and others, 1991), while other methods use simpler polyethylene bags (Vroblesky and Hyde, 1997; A.W. Alexander and T.L. Lammons , Bunnell-Lammons Engineering, Inc., written commun., August 1998). Field investigations of the latter method showed a close match between VOC concentrations in samples collected with diffusion samplers and VOC concentrations in samples collected using traditional purging and sampling methods (Vroblesky and Hyde, 1997; A.W. Alexander and T.L. Lammons, Bunnell-Lammons Engineering, Inc., written commun., August 1998; Vroblesky and Peters, 2000; and Vroblesky and Petkewich, 2000). Vroblesky (2001a) prepared a protocol for the use of low-density, water-filled polyethylene diffusion samplers for VOCs in wells.

In addition to minimizing well purging, there is often a need to obtain more information on the vertical distribution of VOCs in an aquifer from established monitoring wells. At sites characterized before the early 1990s, ground-water contamination commonly was monitored using wells with long screens that spanned more than one discrete zone of head or transmissivity. The advantage of using long-screened wells is to optimize the probability of intercepting contamination within the screened interval. The disadvantages are that samples provide little information about the vertical distribution of VOCs across the screened interval, and samples commonly represent a mixture of clean and contaminated waters that reflect neither the highest nor lowest contaminant concentrations (Reilly and Gibs, 1993). Again, the micro-purge and the inflatable packer sampling methods can be applied at different depths in a single long-screen well to provide data on the vertical distribution of VOCs, but the passive sampler methodology could potentially provide that information at a lower cost and with no well purging.

Description of Study Area

This study was conducted in April 1999, at Area 6, Naval Air Station Whidbey, on Whidbey Island, Washington in the northern part of Puget Sound (fig. 1). The study area includes a capped 40-acre landfill that was used for the deposition of hazardous and municipal waste. The ground water beneath the study area is contaminated with volatile organic compounds (VOCs), primarily 1,1,1-trichloroethane (TCA), trichloroethene (TCE), *cis*-1, 2-dichloroethene (*cis*-DCE), 1,1-dichloroethane (DCA), 1,1-dichloroethene (DCE), and vinyl chloride. The approximate extent of contamination beneath Area 6 is shown in figure 2.

All wells sampled were screened within the shallow aquifer at Area 6. The shallow aquifer beneath Area 6 is contained within the Vashon glacial advance outwash sediments. The saturated portion of the aquifer is composed of a fine to medium sand that gradually becomes finer and siltier with depth. Thin layers of gravel are present in the unit (Dinicola and others, 2000).

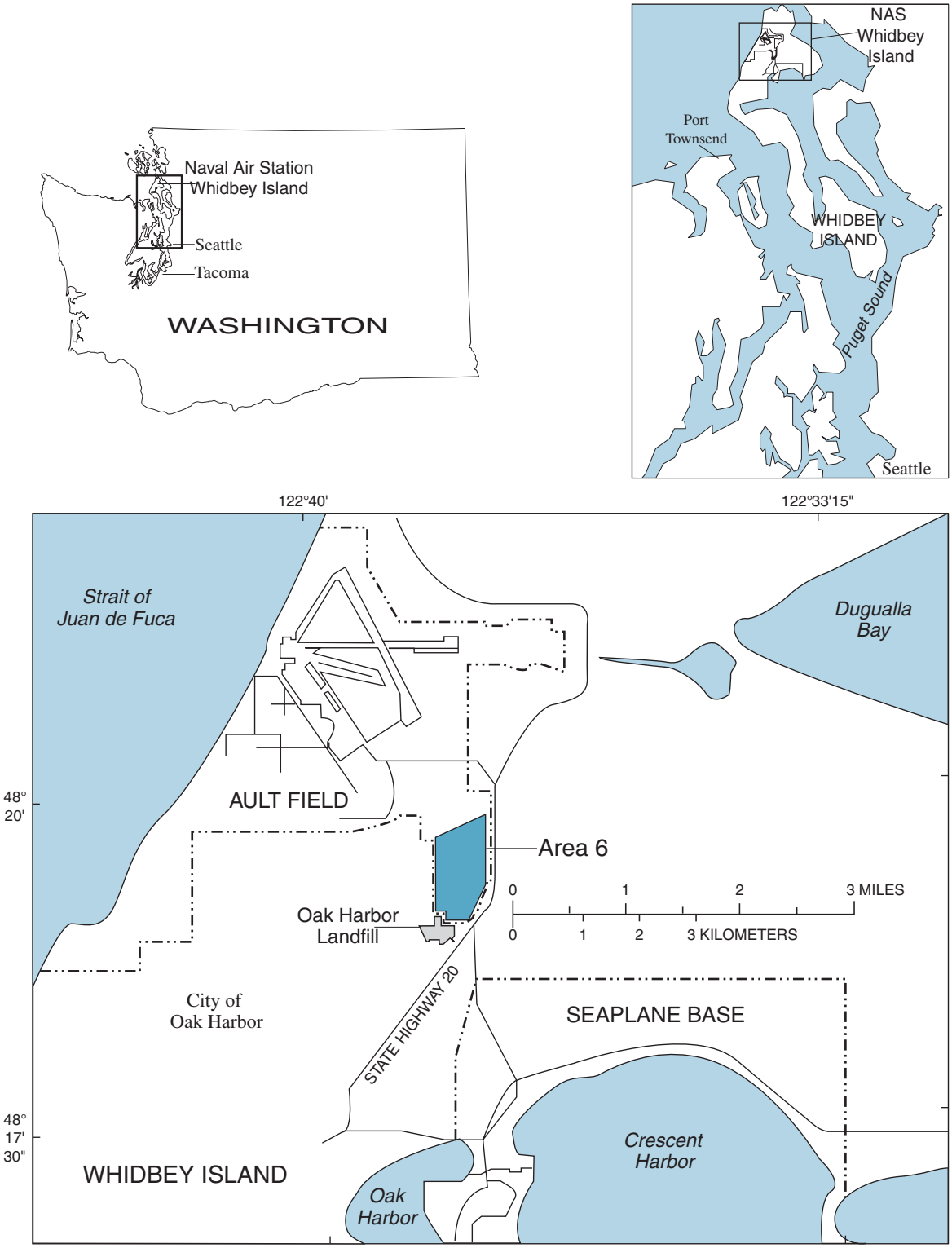


Figure 1. Location of the Area 6 study area, Naval Air Station Whidbey Island, Washington. Modified from URS Consultants, 1993a.

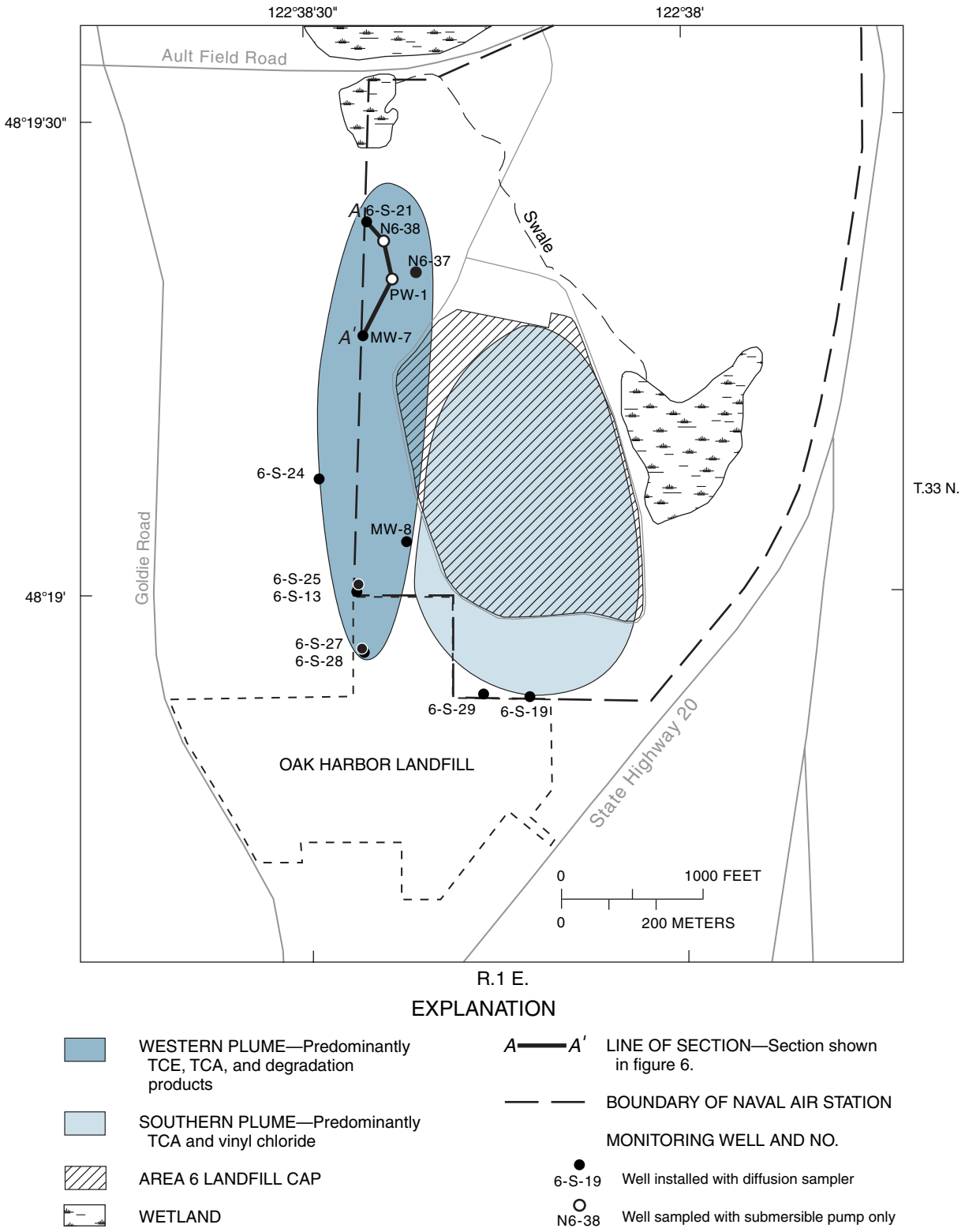


Figure 2. Location of wells selected for diffusion sampler installation, source areas, approximate locations of contaminant plumes, and features in Area 6, Naval Air Station Whidbey Island, Washington

STUDY DESIGN

Well Selection

Eleven wells were selected for installation of diffusion samplers based on the results of previous sampling. Diffusion samplers were installed in wells with historical high as well as low VOC concentrations. Some wells with longer screened intervals also were selected to evaluate if more information on the vertical distribution of VOC contamination could be obtained using multiple diffusion samplers. The depths, altitudes, and water-level data for these selected wells are shown in table 1. The location of the 11 wells installed with diffusion samplers as well as source areas, contaminant plumes, and features in Area 6 are shown in figure 2. The areas delineating the contaminant plumes in figure 2 are defined by wells not shown on the figure and are discussed in more detail in Dinicola and others (2000).

Sampler Assembly, Installation, and Recovery

The samplers were constructed by USGS personnel in Tacoma, Washington based on guidelines developed by D.A. Vroblesky and T.R. Campbell (U.S. Geological Survey, written commun, January 1999). Since this investigation, a users' guide has been published for the installment, recovery, data interpretation, and quality control and assurance of polyethylene based passive diffusion bag samplers (Vroblesky, 2001a). There were no substantial differences in the installation and recovery aspects between the draft and published protocols.

Table 1. Depths, altitudes, and water-level data for selected wells at Area 6, Naval Air Station Whidbey Island, Washington

[**USGS station identification No.**: Unique number based on the latitude and longitude of the site. First six digits are latitude, next eight digits are longitude, and final two digits are a sequence number to uniquely identify a site. USGS, U.S. Geological Survey; –, not determined]

Well No. (fig. 2)	USGS station identification No.	Altitude of the top of well (feet above mean sea level)	Reported total well depth (feet below land surface)	Depth of screened interval (feet)	Water-level altitude, April 1999 (feet above mean sea level)
6-S-13	481901122382601	197.82	156.5	145–155	78.55
6-S-19	481854122380901	219.37	164.5	143.5–163.5	76.18
6-S-21	481924122382602	157.74	104.5	63.5–103.5	89.15
6-S-24	481901122383002	192.56	116.5	105–115.5	81.93
6-S-25	481900122382602	197.92	126	115–125	78.64
6-S-27	481856122382601	198.58	130	120–130	78.22
6-S-28	481856122382501	198.6	155	145–155	78.2
6-S-29	181854122381401	213.14	164	144-164	76.63
MW-7	481917122382601	199.46	149	118.4–148.4	86.13
MW-8	481904122382201	205.9	162	122–162	80.28
N6-37	481921122382201	172.25	96	85.5–95.5	87.98
N6-38	–	163.85	98	79.5–89.5	88.88
PW-1	–	170.81	118.5	87.5–117.5	–

A sampler was constructed by cutting an 18-inch length of 2-inch wide lay-flat polyethylene tubing and heat sealing one end. The lay-flat tubing was placed inside mesh tubing to help prevent the filled bag from rupturing. The lay-flat tubing was then filled with about 300 milliliters of de-ionized water and the open end was sealed while ensuring no air bubbles remained inside. An assembled sampler contained enough water for obtaining environmental and duplicate samples. The samplers were constructed about 3 days prior to installation and were temporarily stored within a plastic-lined cooler.

Well depth was measured before installing a sampler down a well. This provided information as to whether sediment had accumulated at the bottom of the well. The distance was calculated from the bottom of the well to where the sampler would be placed. The sampler was placed in the vertical midpoint of the screen for 10 feet or shorter well screens. Multiple samplers were installed at midpoints for every 10 feet within the screened interval for 20 feet or longer screens. Sampler equilibration times vary, and a minimum of 14 days is suggested (Vroblesky, 2001a). Samplers were allowed to equilibrate for 20 days prior to removal.

The sampler was laid on clean plastic upon removal from the well. A corner was cut and the water gently poured into 40-mL septa vials that contained the preservative hydrochloric acid. The vials were filled without headspace, capped, placed on ice, and sent overnight mail to Quanterra Inc. Laboratory in Denver, Colorado. For multiple samplers in a well, the upper most sampler (shallowest) was cut open and water transferred first; and the deepest sampler was processed last.

Within a few days after removing the diffusion samplers, a second set of VOC samples were collected using a submersible pump using low-flow sampling methods. Samples were collected by Navy contractors who conduct the regular monitoring at the site. A submersible pump was lowered into the well about 10 feet into the water column. The well was purged of at least three casing volumes of water, and ground-water-quality parameters, including pH, temperature, specific conductance, and turbidity were measured after every well volume. After three well volumes had been purged and water-quality parameters stabilized to within 10 percent, the pump flow rate was reduced and VOC samples were collected by pouring ground water directly from the pump discharge line into 40-mL septa vials containing hydrochloric acid. The sample vials were placed in a cooler with ice and delivered to the laboratory the next morning. The submersible pump VOC concentrations are listed in tables 2 and 3. The sample depth associated with the submersible pump samples shown in the tables are estimated depths, based on the documented procedures used by the Navy contractors.

Table 2. Concentrations of selected chlorinated volatile organic compounds from environmental and quality-control samples collected with diffusion samplers and submersible pumps from selected wells at Area 6, Naval Air Station Whidbey Island, Washington

[**Sampling Method**: **DS**, diffusion sample; **SUB**, submersible pump sample. **Chemical abbreviations:** TCE, Trichloroethene; TCA 1,1,1-Trichloroethane; *cis*-DCE, *cis*-1,2-dichloroethene; DCE, 1,1-dichloroethene; DCA, 1,1-dichloroethane. <, not detected at the given concentration; e, detected concentration is less than the reporting limit and is an estimated concentration; **bold** indicates detected concentrations; *italics* indicates a replicate sample]

Well No. (sample depth, in feet)	Date	Sampling method	TCE (μg/L)	TCA (μg/L)	*cis*-DCE (μg/L)	DCE (μg/L)	DCA (μg/L)	Vinyl chloride (μg/L)
Wells with 10-foot screened intervals								
6-S-13 (152.6)	04-14-99	DS	<1.0	**36**	<1.0	**5.8**	**65**	<1.0
6-S-13 (129)	04-22-99	SUB	<0.20	**51**	<0.20	**5.5**	**110**	<1.0
6-S-24 (115)	04-14-99	DS	<1.0	**10**	<1.0	<1.0	<1.0	<1.0
6-S-24 (115) Replicate	*04-14-99*	*DS*	*<1.0*	***9.5***	*<1.0*	***0.76e***	*<1.0*	*<1.0*
6-S-24 (115)	04-22-99	SUB	**0.31**	**9.7**	<0.20	**0.30**	<0.20	<1.0
6-S-25 (124.3)	04-14-99	DS	<20	**1,800**	<20	**51**	<20	<20
6-S-25 (124.3) Replicate	*04-14-99*	*DS*	*<20*	***1,800***	*<20*	***52***	*<20*	*<20*
6-S-25 (124)	04-23-99	SUB	**10**	**1,800**	1.6	**57**	1.1	<1.0
6-S-27 (124.5)	04-14-99	DS	<1.0	**7.7**	<1.0	**1.8**	<1.0	<1.0
6-S-27 (130)	04-20-99	SUB	<0.20	**2.3**	<0.20	<0.20	<0.20	<1.0
6-S-28 (150.5)	04-14-99	DS	<1.0	**1.1**	<1.0	<1.0	<1.0	<1.0
6-S-28 (130)	04-20-99	SUB	<0.20	<0.50	<0.20	<0.20	<0.20	<1.0
N6-37 (91.4)	04-14-99	DS	**24**	**4.2**	<1.0	**0.87e**	<1.0	<1.0
N6-37 (94)	04-22-99	SUB	**39**	**14**	**2.1**	**1.1**	<0.20	<1.0
Wells with 20- to 40-foot screened intervals								
6-S-19 (151.1)	04-14-99	DS	<1.0	**11**	<1.0	**0.77e**	<1.0	2.3
6-S-19 (161.1)	04-14-99	DS	<1.0	<1.0	<1.0	<1.0	<1.0	2.9
6-S-19 (153)	04-22-99	SUB	<0.20	**6.9**	<0.20	<0.20	<0.20	**1.8**
6-S-19 (153) Replicate	04-22-99	SUB	<0.20	**7.1**	<0.20	<0.20	<0.20	**1.9**
6-S-21 (73.2)	04-14-99	DS	<2.0	**240**	<2.0	**42**	<2.0	<2.0
6-S-21 (83.2)	04-14-99	DS	<1.0	**15**	<1.0	5.7	<1.0	<1.0
6-S-21 (93.2)	04-14-99	DS	<1.0	**0.87e**	<1.0	<1.0	<1.0	<1.0
6-S-21 (103.2)	04-14-99	DS	<1.0	**2.8**	<1.0	<1.0	<1.0	<1.0
6-S-21 (78)	04-22-99	SUB	<0.20	**120**	<0.20	**11**	<0.20	<1.0
6-S-29 (151.5)	04-14-99	DS	<1.0	**7.2**	<1.0	**0.80e**	**5.4**	**3.6**
6-S-29 (161.5)	04-14-99	DS	<1.0	<1.0	<1.0	<1.0	<1.0	**1.5**
6-S-29 (146)	04-21-99	SUB	<0.20	**7.4**	<0.20	**0.39**	**3.5**	**5.9**
MW-7 (125)	04-14-99	DS	**810**	**450**	**130**	**84**	**3.3e**	<5.0
MW-7 (135)	04-14-99	DS	**940**	**420**	**110**	**83**	<10	<10
MW-7 (145)	04-14-99	DS	**0.76e**	<1.0	<1.0	<1.0	**0.66e**	<1.0
MW-7 (123)	04-22-99	SUB	**390**	**480**	**120**	**78**	**55**	<10
MW-8 (128.5)	04-14-99	DS	<1.0	**6.0**	<1.0	<1.0	**3.8**	**1.9**
MW-8 (138.5)	04-14-99	DS	<1.0	**5.9**	<1.0	<1.0	**3.0**	**2.1**
MW-8 (148.5)	04-14-99	DS	<1.0	**6.0**	<1.0	<1.0	**2.8**	**1.4**
MW-8 (158.5)	04-14-99	DS	<1.0	**5.3**	<1.0	<1.0	**2.6**	**1.6**
MW-8 (135)	04-14-99	SUB	<0.20	**2.5**	<0.20	<0.20	**2.3**	**1.6**
DI-B (source blank)	03-24-99	DS	<0.50	<0.50	<0.50	<0.50	<0.50	<1.0
FB (field blank)	04-14-99	DS	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
TRIP (trip blank)	04-14-99	DS	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
SOURCE B (source blank)	04-19-99	SUB	<0.20	<0.50	<0.20	<0.20	<0.20	<1.0
TB (trip blank)	04-19-99	SUB	<0.20	<0.50	<0.20	<0.20	<0.20	<1.0

Table 3. Concentrations of all chlorinated volatile organic compounds from environmental and quality-control samples collected with diffusion samplers and submersible pumps from selected wells at Area 6, Naval Air Station Whidbey Island, Washington

[**Sampling Method**: **DS**, diffusion sample; **SUB**, submersible pump sample. **Chemical abbreviations:** TCE, Trichloroethene; TCA 1,1,1-Trichloroethane; *cis*-DCE, *cis*-1,2-dichloroethene; DCE, 1,1-dichloroethene; DCA, 1,1-dichloroethane. <, not detected at the given concentration; e, detected concentration is less than the reporting limit and is an estimated concentration; **bold** indicates detected concentrations; *italics* indicates replicate sample]

Well No. (sample depth, in feet)	Date	Sampling method	Bromo-dichloro-methane (μg/L)	Bromo-form (μg/L)	Bromo-methane (μg/L)	Carbon tetra-chloride (μg/L)	Chloro-benzene (μg/L)	Dibromo-chloro-methane (μg/L)	Chloro-ethane (μg/L)
Wells with 10-foot screened intervals									
6-S-13 (152.6)	04-14-99	DS	<1.0	<5.0	<5.0	<1.0	<2.0	<1.0	**8.5**
6-S-13 (129)	04-22-99	SUB	<0.20	<0.50	<2.0	<0.20	<0.50	<0.20	**17**
6-S-24 (115)	04-14-99	DS	<1.0	<5.0	<5.0	<1.0	<2.0	<1.0	<5.0
6-S-24 (115) Replicate	*04-14-99*	*DS*	*<1.0*	*<5.0*	*<5.0*	*<1.0*	*<2.0*	*<1.0*	*<5.0*
6-S-24 (115)	04-22-99	SUB	<0.20	<0.50	<2.0	<0.20	<0.50	<0.20	<2.0
6-S-25 (124.3)	04-14-99	DS	<20	<100	<100	<20	<40	<20	<100
6-S-25 (124.3) Replicate	*04-14-99*	*DS*	*<20*	*<100*	*<100*	*<20*	*<40*	*<20*	*<100*
6-S-25 (124)	04-23-99	SUB	<0.20	<0.50	<2.0	**1.8**	<0.50	<0.20	<2.0
6-S-27 (124.5)	04-14-99	DS	<1.0	<5.0	<5.0	<1.0	<2.0	<1.0	<5.0
6-S-27 (130)	04-20-99	SUB	<0.20	<0.50	<2.0	<0.20	<0.50	<0.20	<2.0
6-S-28 (150.5)	04-14-99	DS	<1.0	<5.0	<5.0	<1.0	<2.0	<1.0	1.5e
6-S-28 (130)	04-20-99	SUB	<0.20	<0.50	<2.0	<0.20	<0.50	<0.20	<2.0
N6-37 (91.4)	04-14-99	DS	<1.0	<5.0	<5.0	<1.0	<2.0	<1.0	<5.0
N6-37 (94)	04-22-99	SUB	<0.20	<0.50	<2.0	<0.20	<0.50	<0.20	<2.0
N6-38	04-22-99	SUB	<1.0	<2.5	<10	<1.0	<2.5	<1.0	<10
Wells with 20- to 40-foot screened intervals									
6-S-19 (151.1)	04-14-99	DS	<1.0	<5.0	<5.0	<1.0	<2.0	<1.0	**28**
6-S-19 (161.1)	04-14-99	DS	<1.0	<5.0	<5.0	<1.0	<2.0	<1.0	**4.6e**
6-S-19 (153)	04-22-99	SUB	<0.20	<0.50	<2.0	<0.20	<0.50	<0.20	<2.0
6-S-19 (153) Replicate	*04-22-99*	*SUB*	*<0.20*	*<0.50*	*<2.0*	*<0.20*	*<0.50*	*<0.20*	*<2.0*
6-S-21 (73.2)	04-14-99	DS	<2.0	<10	<10	<2.0	<4.0	<2.0	<10
6-S-21 (83.2)	04-14-99	DS	<1.0	<5.0	<5.0	<1.0	<2.0	<1.0	<5.0
6-S-21 (93.2)	04-14-99	DS	<1.0	<5.0	<5.0	<1.0	<2.0	<1.0	<5.0
6-S-21 (103.2)	04-14-99	DS	<1.0	<5.0	<5.0	<1.0	<2.0	<1.0	<5.0
6-S-21 (78)	04-22-99	SUB	<0.20	<0.50	<2.0	<0.20	<0.50	<0.20	<2.0
6-S-29 (151.5)	04-14-99	DS	<1.0	<5.0	<5.0	<1.0	<2.0	<1.0	**28**
6-S-29 (161.5)	04-14-99	DS	<1.0	<5.0	<5.0	<1.0	<2.0	<1.0	**7.8**
6-S-29 (146)	04-21-99	SUB	<0.20	<0.50	<2.0	<0.20	<0.50	<0.20	<2.0
MW-7 (125)	04-14-99	DS	<5.0	<25	<25	<5.0	<10	<5.0	<25
MW-7 (135)	04-14-99	DS	<10	<50	<50	<10	<20	<10	<50
MW-7 (145)	04-14-99	DS	<1.0	<5.0	<5.0	<1.0	<2.0	<1.0	<5.0
MW-7 (123)	04-22-99	SUB	<2.0	<0.50	<20	<2.0	<5.0	<2.0	<2.0
MW-8 (128.5)	04-14-99	DS	<1.0	<5.0	<5.0	<1.0	<2.0	<1.0	**19**
MW-8 (138.5)	04-14-99	DS	<1.0	<5.0	<5.0	<1.0	<2.0	<1.0	**22**
MW-8 (148.5)	04-14-99	DS	<1.0	<5.0	<5.0	<1.0	<2.0	<1.0	**21**
MW-8 (158.5)	04-14-99	DS	<1.0	<5.0	<5.0	<1.0	<2.0	<1.0	**20**
MW-8 (135)	04-14-99	SUB	<0.20	<0.50	<2.0	<0.20	<0.50	<0.20	<2.0
PW-1	04-19-99	SUB	<0.20	<0.50	<2.0	<0.20	<0.50	<0.20	<2.0
DI-B (source blank)	03-24-99	DS	<1.0	<5.0	<5.0	<0.50	<2.0	<1.0	<5.0
FB (field blank)	04-14-99	DS	<1.0	<5.0	<5.0	<1.0	<2.0	<1.0	<5.0
TRIP (trip blank)	04-14-99	DS	<1.0	<5.0	<5.0	<1.0	<2.0	<1.0	<5.0
SOURCE B (source blank)	04-19-99	SUB	<0.20	<0.50	<2.0	<0.20	<0.50	<0.20	<2.0
TB (trip blank)	04-19-99	SUB	<0.20	<0.50	<2.0	<0.20	<0.50	<0.20	<2.0

Table 3. Concentrations of all chlorinated volatile organic compounds from environmental and quality-control samples collected with diffusion samplers and submersible pumps from selected wells at Area 6, Naval Air Station Whidbey Island, Washington—*Continued*

Well No. (sample depth. in feet)	Date	Sampling method	Chloro-form (μg/L)	Chloro-methane (μg/L)	1,2-Di-chloro-benzene (μg/L)	1,3-Di-chloro-benzene (μg/L)	1,4-Di-chloro-benzene (μg/L)	DCA (μg/L)	1,2-Di-chloro-ethane (μg/L)
Wells with 10-foot screened intervals									
6-S-13 (152.6)	04-14-99	DS	<1.0	<5.0	<2.0	<2.0	**0.66e**	**65**	<1.0
6-S-13 (129)	04-22-99	SUB	<0.20	<1.0	<0.50	<0.50	<0.50	**110**	<0.20
6-S-24 (115)	04-14-99	DS	<1.0	<5.0	<2.0	<2.0	<2.0	<1.0	<1.0
6-S-24 (115) Replicate	*04-14-99*	*DS*	*<1.0*	*<5.0*	*<2.0*	*<2.0*	*<2.0*	*<1.0*	*<1.0*
6-S-24 (115)	04-22-99	SUB	<0.20	<1.0	<0.50	<0.50	<0.50	<0.20	<0.20
6-S-25 (124.3)	04-14-99	DS	<20	<100	<40	<40	<40	<20	<20
6-S-25 (124.3) Replicate	*04-14-99*	*DS*	*<20*	*<100*	*<40*	*<40*	*<40*	*<20*	*<20*
6-S-25 (124)	04-23-99	SUB	<0.20	<1.0	<0.50	<0.50	<0.50	**1.1**	<0.20
6-S-27 (124.5)	04-14-99	DS	<1.0	<5.0	<2.0	<2.0	<2.0	<1.0	<1.0
6-S-27 (130)	04-20-99	SUB	**0.87**	<1.0	<0.50	<0.50	<0.50	<0.20	<0.20
6-S-28 (150.5)	04-14-99	DS	<1.0	<5.0	<2.0	<2.0	<2.0	<1.0	<1.0
6-S-28 (130)	04-20-99	SUB	<0.20	<1.0	<0.50	<0.50	<0.50	<0.20	<0.20
N6-37 (91.4)	04-14-99	DS	<1.0	<5.0	<2.0	<2.0	<2.0	<1.0	<1.0
N6-37 (94)	04-22-99	SUB	<0.20	<1.0	<0.50	<0.50	<0.50	<0.20	<0.20
N6-38 (85)	04-22-99	SUB	<1.0	<5.0	<2.5	<2.5	<2.5	<1.0	<1.0
Wells with 20- to 40-foot screened intervals									
6-S-19 (151.1)	04-14-99	DS	<1.0	**2.3e**	<2.0	<2.0	<2.0	<1.0	<1.0
6-S-19 (161.1)	04-14-99	DS	<1.0	<5.0	<2.0	<2.0	**0.70e**	<1.0	<1.0
6-S-19 (153)	04-22-99	SUB	<0.20	<1.0	<0.50	<0.50	<0.50	<0.20	<0.20
6-S-19 (153) Replicate	*04-22-99*	*SUB*	*<0.20*	*<1.0*	*<0.50*	*<0.50*	*<0.50*	*<0.20*	*<0.20*
6-S-21 (73.2)	04-14-99	DS	<2.0	<10	<4.0	<4.0	<4.0	<2.0	<2.0
6-S-21 (83.2)	04-14-99	DS	<1.0	<5.0	<2.0	<2.0	<2.0	<1.0	<1.0
6-S-21 (93.2)	04-14-99	DS	<1.0	<5.0	<2.0	<2.0	**0.67e**	<1.0	<1.0
6-S-21 (103.2)	04-14-99	DS	<1.0	<5.0	<2.0	<2.0	**1.0e**	<1.0	<1.0
6-S-21 (78)	04-22-99	SUB	<0.20	<1.0	<0.50	<0.50	<0.50	<0.20	<0.20
6-S-29 (151.5)	04-14-99	DS	<1.0	**3.1e**	<2.0	<2.0	<2.0	**5.4**	<1.0
6-S-29 (161.5)	04-14-99	DS	<1.0	**2.5e**	<2.0	<2.0	**0.85e**	<1.0	<1.0
6-S-29 (146)	04-21-99	SUB	<0.20	<1.0	<0.50	<0.50	<0.50	**3.5**	<0.20
MW-7 (125)	04-14-99	DS	3.7e	<25	<10	<10	<10	**3.3e**	<5.0
MW-7 (135)	04-14-99	DS	<10	<50	<20	<20	<20	<10	<10
MW-7 (145)	04-14-99	DS	<1.0	<5.0	<2.0	<2.0	**0.79e**	**0.66e**	<1.0
MW-7 (123)	04-22-99	SUB	<2.0	<10	<5.0	<5.0	<5.0	**55**	<2.0
MW-8 (128.5)	04-14-99	DS	<1.0	<5.0	<2.0	<2.0	<2.0	**3.8**	<1.0
MW-8 (138.5)	04-14-99	DS	<1.0	<5.0	<2.0	<2.0	**0.45e**	**3.0**	<1.0
MW-8 (148.5)	04-14-99	DS	<1.0	<5.0	<2.0	<2.0	<2.0	**2.8**	<1.0
MW-8 (158.5)	04-14-99	DS	<1.0	<5.0	<2.0	<2.0	**0.81e**	**2.6**	<1.0
MW-8 (135)	04-14-99	SUB	<0.20	<1.0	<0.50	<0.50	<0.50	**2.3**	<0.20
PW-1	04-19-99	SUB	<0.20	**0.55**	<0.50	<0.50	<0.50	**4.3**	1.1
DI-B (source blank)	03-24-99	DS	<0.50	**4.4e**	<2.0	<2.0	<2.0	<0.50	<1.0
FB (field blank)	04-14-99	DS	<5.0	<5.0	<2.0	<2.0	<2.0	<1.0	<1.0
TRIP (trip blank)	04-14-99	DS	<5.0	<5.0	<2.0	<2.0	<2.0	<1.0	<1.0
SOURCE B (source blank)	04-19-99	SUB	<1.0	<1.0	<0.50	<0.50	<0.50	<0.20	<0.20
TB (trip blank)	04-19-99	SUB	<1.0	<1.0	<0.50	<0.50	<0.50	<0.20	<0.20

Table 3. Concentrations of all chlorinated volatile organic compounds from environmental and quality-control samples collected with diffusion samplers and submersible pumps from selected wells at Area 6, Naval Air Station Whidbey Island, Washington—*Continued*

Well No. (sample depth, in feet)	Date	Sampling method	DCE (μg/L)	*cis*-DCE (μg/L	*trans*-1,2-Dichloro-ethene (μg/L)	1,2-Di-chloro-propane (μg/L)	*cis*-1,3-Dichloro-propene (μg/L)	*trans*-1,3-dichloro-propene (μg/L)	Trichloro-fluoro-methane (μg/L)
Wells with 10-foot screened intervals									
6-S-13 (152.6)	04-14-99	DS	**5.8**	<1.0	<1.0	<1.0	<2.0	<1.0	<5.0
6-S-13 (129)	04-22-99	SUB	**5.5**	<0.20	<0.20	<0.20	<0.20	<0.20	<0.50
6-S-24 (115)	04-14-99	DS	<1.0	<1.0	<1.0	<1.0	<2.0	<1.0	<5.0
6-S-24 (115) Replicate	*04-14-99*	*DS*	***0.76e***	*<1.0*	*<1.0*	*<1.0*	*<2.0*	*<1.0*	*<5.0*
6-S-24 (115)	04-22-99	SUB	**0.30**	<0.20	<0.20	<0.20	<0.20	<0.20	<0.50
6-S-25 (124.3)	04-14-99	DS	**51**	<20	<20	<20	<40	<20	<100
6-S-25 (124.3) Replicate	*04-14-99*	*DS*	***52***	*<20*	*<20*	*<20*	*<40*	*<20*	*<100*
6-S-25 (124)	04-23-99	SUB	**57**	**1.6**	<0.20	<0.20	<0.20	<0.20	<0.50
6-S-27 (124.5)	04-14-99	DS	**1.8**	<1.0	<1.0	<1.0	<2.0	<1.0	<5.0
6-S-27 (130)	04-20-99	SUB	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.50
6-S-28 (150.5)	04-14-99	DS	<1.0	<1.0	<1.0	<1.0	<2.0	<1.0	1.5e
6-S-28 (130)	04-20-99	SUB	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.50
N6-37 (91.4)	04-14-99	DS	**0.87e**	<1.0	<1.0	<1.0	<2.0	<1.0	<5.0
N6-37 (94)	04-22-99	SUB	**1.1**	**2.1**	<0.20	<0.20	<0.20	<0.20	<0.50
N6-38 (85)	04-22-99	SUB	**38**	<1.0	<1.0	<1.0	<1.0	<1.0	<2.5
Wells with 20- to 40-foot screened intervals									
6-S-19 (151.1)	04-14-99	DS	*0.77e*	<1.0	<1.0	<1.0	<2.0	<1.0	**5.8**
6-S-19 (161.1)	04-14-99	DS	<1.0	<1.0	<1.0	<1.0	<2.0	<1.0	**1.8e**
6-S-19 (153)	04-22-99	SUB	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	**5.4**
6-S-19 (153) Replicate	*04-22-99*	*SUB*	*<0.20*	*<0.20*	*<0.20*	*<0.20*	*<0.20*	*<0.20*	***5.4***
6-S-21 (73.2)	04-14-99	DS	**42**	<2.0	<2.0	<2.0	<4.0	<2.0	<10
6-S-21 (83.2)	04-14-99	DS	**5.7**	<1.0	<1.0	<1.0	<2.0	<1.0	<5.0
6-S-21 (93.2)	04-14-99	DS	<1.0	<1.0	<1.0	<1.0	<2.0	<1.0	<5.0
6-S-21 (103.2)	04-14-99	DS	<1.0	<1.0	<1.0	<1.0	<2.0	<1.0	<5.0
6-S-21 (78)	04-22-99	SUB	**11**	<0.20	<0.20	<0.20	<0.20	<0.20	<0.50
6-S-29 (151.5)	04-14-99	DS	**0.80e**	<1.0	<1.0	<1.0	<2.0	<1.0	4.3e
6-S-29 (161.5)	04-14-99	DS	<1.0	<1.0	<1.0	<1.0	<2.0	<1.0	<5.0
6-S-29 (146)	04-21-99	SUB	**0.39**	<0.20	<0.20	<0.20	<0.20	<0.20	4.8
MW-7 (125)	04-14-99	DS	**84**	**130**	<5.0	<5.0	<10	<5.0	<25
MW-7 (135)	04-14-99	DS	**83**	**110**	<10	<10	<20	<10	<50
MW-7 (145)	04-14-99	DS	<1.0	<1.0	<1.0	<1.0	<2.0	<1.0	<5.0
MW-7 (123)	04-22-99	SUB	**78**	**120**	<2.0	<2.0	<2.0	<2.0	<5.0
MW-8 (128.5)	04-14-99	DS	<1.0	<1.0	<1.0	<1.0	<2.0	<1.0	**12**
MW-8 (138.5)	04-14-99	DS	<1.0	<1.0	<1.0	<1.0	<2.0	<1.0	**14**
MW-8 (148.5)	04-14-99	DS	<1.0	<1.0	<1.0	<1.0	<2.0	<1.0	**13**
MW-8 (158.5)	04-14-99	DS	<1.0	<1.0	<1.0	<1.0	<2.0	<1.0	**9.6**
MW-8 (135)	04-14-99	SUB	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	**4.8**
PW-1	04-19-99	SUB	**10**	**64**	<0.20	<0.20	<0.20	<0.20	<0.50
DI-B (source blank)	03-24-99	DS	<1.0	<1.0	<1.0	<1.0	<2.0	<1.0	<5.0
FB (field blank)	04-14-99	DS	<1.0	<1.0	<1.0	<1.0	<2.0	<1.0	<5.0
TRIP (trip blank)	04-14-99	DS	<1.0	<1.0	<1.0	<1.0	<2.0	<1.0	<5.0
SOURCE B (source blank)	04-19-99	SUB	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.50
TB (trip blank)	04-19-99	SUB	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.50

Table 3. Concentrations of all chlorinated volatile organic compounds from environmental and quality-control samples collected with diffusion samplers and submersible pumps from selected wells at Area 6, Naval Air Station Whidbey Island, Washington—*Continued*

Well No. (sample depth, in feet)	Date	Sampling method	Methylene chloride (µg/L)	1,1,2,2-Tetrachloethene (µg/L)	Tetrachloroethene (µg/L)	TCA (µg/L)	1,1,2-Trichloroethane (µg/L)	TCE (µg/L)	Vinyl chloride (µg/L)
Wells with 10-foot screened intervals									
6-S-13 (152.6)	04-14-99	DS	**0.53e**	<1.0	<1.0	**36**	<1.0	<1.0	<1.0
6-S-13 (129)	04-22-99	SUB	<5.0	<0.20	<0.20	**51**	<0.20	<0.20	<1.0
6-S-24 (115)	04-14-99	DS	<5.0	<1.0	<1.0	**10**	<1.0	<1.0	<1.0
6-S-24 (115) Replicate	*04-14-99*	*DS*	*<5.0*	*<1.0*	*<1.0*	***9.5***	*<1.0*	*<1.0*	*<1.0*
6-S-24 (115)	04-22-99	SUB	<5.0	<0.20	<0.20	**9.7**	<0.20	**0.31**	<1.0
6-S-25 (124.3)	04-14-99	DS	<100	<20	<20	**1,800**	<20	<20	<20
6-S-25 (124.3) Replicate	*04-14-99*	*DS*	*<100*	*<20*	*<20*	***1,800***	*<20*	*<20*	*<20*
6-S-25 (124)	04-23-99	SUB	<5.0	<0.20	<0.20	**1,800**	<0.20	10	<1.0
6-S-27 (124.5)	04-14-99	DS	<5.0	<1.0	<1.0	**7.7**	<1.0	<1.0	<1.0
6-S-27 (130)	04-20-99	SUB	<5.0	<0.20	<0.20	**2.3**	<0.20	<0.20	<1.0
6-S-28 (150.5)	04-14-99	DS	<5.0	<1.0	<1.0	**1.1**	<1.0	<1.0	<1.0
6-S-28 (130)	04-20-99	SUB	<5.0	<0.20	<0.20	<0.50	<0.20	<0.20	<1.0
N6-37 (91.4)	04-14-99	DS	<5.0	<1.0	<1.0	**4.2**	<1.0	**24**	<1.0
N6-37 (94)	04-22-99	SUB	<5.0	<0.20	<0.20	**14**	<0.20	**39**	<1.0
N6-38	04-22-99	SUB	<25	<1.0	<1.0	**260**	<1.0	**18**	<5.0
Wells with 20- to 40-foot screened intervals									
6-S-19 (151.1)	04-14-99	DS	<5.0	<1.0	<1.0	**11**	<1.0	<1.0	**2.3**
6-S-19 (161.1)	04-14-99	DS	<5.0	<1.0	<1.0	<1.0	<1.0	<1.0	**2.9**
6-S-19 (153)	04-22-99	SUB	<5.0	<0.20	<0.20	**6.9**	<0.20	<0.20	**1.8**
6-S-19 (153) Replicate	*04-22-99*	*SUB*	*<5.0*	*<0.20*	*<0.20*	***7.1***	*<0.20*	*<0.20*	***1.9***
6-S-21 (73.2)	04-14-99	DS	**0.75e**	<2.0	<2.0	**240**	<2.0	<2.0	<2.0
6-S-21 (83.2)	04-14-99	DS	**0.43e**	<1.0	<1.0	**15**	<1.0	<1.0	<1.0
6-S-21 (93.2)	04-14-99	DS	<5.0	<1.0	<1.0	**0.87e**	<1.0	<1.0	<1.0
6-S-21 (103.2)	04-14-99	DS	<5.0	<1.0	<1.0	**2.8**	<1.0	<1.0	<1.0
6-S-21 (78)	04-22-99	SUB	<5.0	<0.20	<0.20	**120**	<0.20	<0.20	<1.0
6-S-29 (151.5)	04-14-99	DS	**0.41e**	<1.0	<1.0	**7.2**	<1.0	<1.0	**3.6**
6-S-29 (161.5)	04-14-99	DS	<5.0	<1.0	<1.0	<1.0	<1.0	<1.0	**1.5**
6-S-29 (146)	04-21-99	SUB	<5.0	<0.20	<0.20	**7.4**	<0.20	<0.20	**5.9**
MW-7 (125)	04-14-99	DS	**5.4e**	<5.0	**5.3**	**450**	<5.0	**810**	<5.0
MW-7 (135)	04-14-99	DS	<50	<10	<10	**420**	<10	**940**	<10
MW-7 (145)	04-14-99	DS	<5.0	<1.0	<1.0	<1.0	<1.0	**0.76e**	<1.0
MW-7 (123)	04-22-99	SUB	<50	<2.0	<2.0	**480**	**2.3**	**390**	<10
MW-8 (128.5)	04-14-99	DS	**0.88e**	<1.0	<1.0	**6.0**	<1.0	<1.0	**1.9**
MW-8 (138.5)	04-14-99	DS	**0.78e**	<1.0	<1.0	**5.9**	<1.0	<1.0	**2.1**
MW-8 (148.5)	04-14-99	DS	**0.39e**	<1.0	<1.0	**6.0**	<1.0	<1.0	**1.4**
MW-8 (158.5)	04-14-99	DS	<5.0	<1.0	<1.0	**5.3**	<1.0	<1.0	**1.6**
MW-8 (135)	04-14-99	SUB	<5.0	<0.20	<0.20	**2.5**	<0.20	<0.20	**1.6**
PW-1	04-19-99	SUB	<5.0	<0.20	<0.20	**200**	**0.74**	**148**	<1.0
DI-B (source blank)	03-24-99	DS	<5.0	<1.0	<0.50	<0.50	<1.0	<0.50	<1.0
FB (field blank)	04-14-99	DS	<5.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
TRIP (trip blank)	04-14-99	DS	**0.87e**	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
SOURCE B (source blank)	04-19-99	SUB	<5.0	<0.20	<0.20	<0.20	<0.20	<0.20	<1.0
TB (trip blank)	04-19-99	SUB	<5.0	<0.20	<0.20	<0.20	<0.20	<0.20	<1.0

ANALYTICAL METHODS

Both sample sets were sent to commercial laboratories for analysis using U.S. Environmental Protection Agency (EPA) method 601. Although the same EPA analytical methods were performed on both sample sets, the submersible pump samples had lower detection limits because they were sent to a different laboratory for analysis. Due to the high VOC concentrations at the site, samples required dilution at both laboratories for quantification. The laboratory that performed the analyses on the samples collected with the diffusion sampler diluted samples to obtain quantification for one analyte and quantified the remainder of the analytes of interest in the same diluted sample. The laboratory that performed the analyses on the pumped samples only quantified high concentration analytes in diluted samples, and quantified other analytes in undiluted samples from the same well.

Quality-Control Samples

When using a new sampling method, such as diffusion sampling, it is necessary to know if quality assurance and control results are within acceptable ranges and how they compare with the quality assurance and control results of low-flow sampling using a submersible pump. Quality-control samples submitted to the laboratories included field blanks, trip blanks, and source blanks to measure possible contamination and bias; as well as replicate samples to measure variability. Concentrations of the six compounds of primary interest (TCE, TCA, *cis*-DCE, DCE, DCA, and vinyl chloride) in environmental and quality-control samples collected with the diffusion samplers and the submersible pump are shown in table 2. Concentrations of all analytes in the analysis are shown in table 3.

A total of five blanks, two trip blanks, a field-trip blank, and two source blanks were collected from both sampling methods. Trip blanks are used to determine whether external VOCs are contaminating the sample due to handling and/or analytical processes not associated with field processing. Trip blanks for both sampling methods were water-filled vials supplied by the laboratory that were stored and transported with other bottles used for collecting the environmental samples and were then submitted for analysis with the environmental samples. A field blank was collected from a diffusion sampler that was stored and transported with the field diffusion samplers from the time of sampler construction to the time of sampler recovery. A field blank is a blank solution that is subject to all aspects of the sample collection, field processing, preservations, transportation, and laboratory handling. The water from the field blank was poured from the diffusion sampler into 40-mL vials at the time of sampler recovery and submitted for analysis with the environmental samples. Source blanks were collected from both sampling methods and are aliquots of blank water that are analyzed to determine the presence of background VOCs. Concentrations of the compounds of interest were not detected in any blank samples for both sampling methods.

Replicate samples provide information needed to estimate the variability of concentrations determined from the sample-processing and analytical method, and to evaluate the consistency of quantifying target VOCs. A replicate sample for diffusion samplers consisted of two separate sets of VOC vials filled from the same diffusion sampler. Two sets of diffusion sampler replicate samples were collected, and concentration differences in those samples ranged from 0 to 5 percent as measured by relative percentage of difference. Concentration differences for the pump replicate sample ranged from 0 to 5.4 percent as measured by relative percentage of difference. The data set was not modified based on these results. The results of the quality-control data from the diffusion samplers were acceptable and the relative percentages of differences using the diffusion sampler are comparable to those using the submersible pump.

COMPARISON OF PASSIVE DIFFUSION BAG SAMPLERS AND SUBMERSIBLE PUMP SAMPLING METHODS FOR MONITORING VOLATILE ORGANIC COMPOUNDS IN SHORT- AND LONG-SCREENED WELLS

VOC concentrations in water samples collected from the 10-foot screened wells with diffusion samplers generally were similar to concentrations in water samples collected with the submersible pump, which was consistent with previous study results (Vroblesky and Hyde, 1997; Vroblesky and Peters, 2000; Vroblesky and Petkewich, 2000; Vroblesky and others, 2000). Most differences in concentrations between the two sampling methods can likely be attributed to the mixing of chemically stratified water in the well. Diffusion samplers also indicated vertical stratification of VOC contamination in wells with long-screened intervals.

Short-Screened Wells

Six of the 11 wells selected for diffusion sampler installation were wells with 10-foot screened intervals (table 1). VOC concentrations of the primary compounds of interest (TCE, TCA, *cis*-DCE, DCE, DCA and vinyl chloride) in samples collected using the diffusion samplers and a submersible pump are shown in table 2.

VOC concentrations in ground-water samples collected using the diffusion sampler and a submersible pump were comparable for the wells with 10-foot screened intervals (table 2). VOC concentrations of the compounds of interest from ground-water samples collected with a submersible pump compared to concentrations from samples collected with the diffusion samplers are shown in figure 3. The mean absolute difference of detected concentrations between the two sampling methods was only 7.7 µg/L with a bias of 6.5 µg/L.

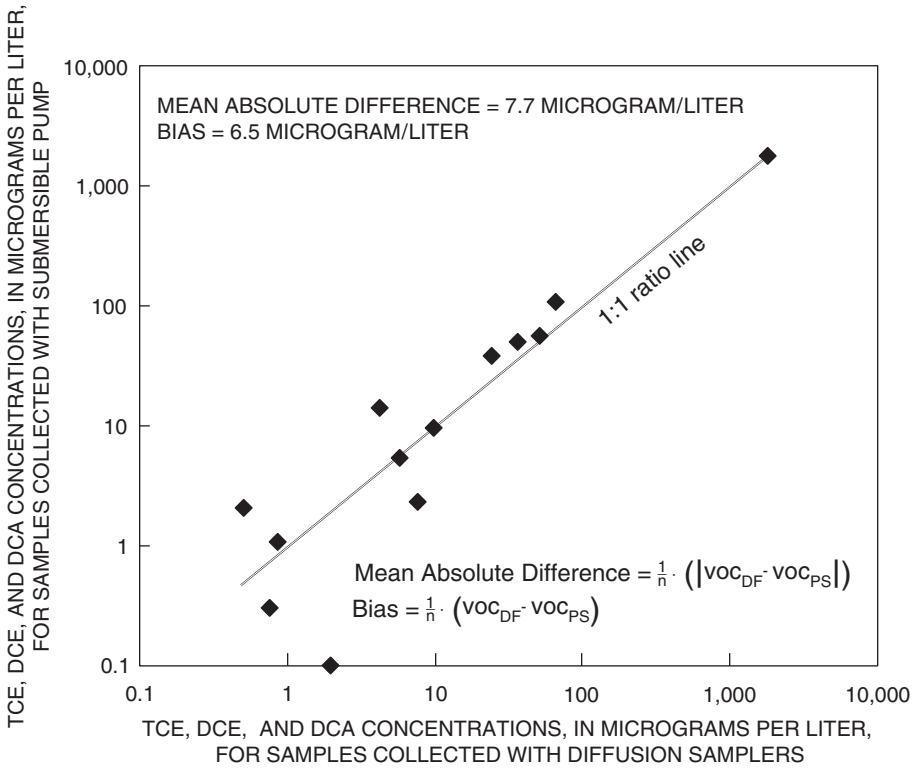


Figure 3. Comparison of selected volatile organic compound concentrations from ground-water samples collected with diffusion samplers and a submersible pump for six wells with 10-foot screened intervals in Area 6, Naval Air Station Whidbey Island, Washington.

A Rank-Sum Test (Wilcoxon rank sum) was used to determine if there were significant differences between the two data sets. The null hypothesis for this test is that the probability of a x value (diffusion sampler) being higher than any given y value (submersible pump) is one-half. That is, if both groups of data are from the same population, an observation from either group could be expected to be higher than that from the other about one-half of the time. A high p value of 0.94 was obtained from the test therefore the above null hypothesis applies. The diffusion samplers generally provided results similar to pumped samples in wells with short-screened intervals (10 feet or less), which is consistent with previous study results (Vorblesky and Hyde, 1997; A.W. Alexander and T.L. Lammons, Bunnell-Lammons Engineering, Inc., written commun., August 1998; Vroblesky and Peters, 2000; and Vroblesky and Petkewich, 2000).

However, TCA and DCA concentrations in the water sample collected with the submersible pump from well 6-S-13 were considerably higher than the TCA and DCA concentrations in water samples collected with the diffusion sampler as were TCE, TCA and *cis*-DCE concentrations in water samples from well N6-37. A possible explanation for the differences is that purging induced flow from a more contaminated zone of the aquifer into the well bore; whereas, the diffusion samplers do not affect the well bore. Alternatively, the well may be characterized by contaminant stratification. Vroblesky and Peters (2001) found *cis*-DCE concentration changes in wells of 2,500 μg/L over a vertical distance of 3.4 feet, and TCE concentration changes of 7,300 to 17,500 μg/L over a vertical distance of 5 feet. Down-hole flow-meter testing and multiple diffusion samplers would be needed to further explore the differences.

Long-Screened Wells

Multiple diffusion samplers were installed in 5 of the 11 wells at 20- to 40-foot screen intervals (table 2). Multiple diffusion samplers were installed in these wells to obtain a better understanding of the vertical distribution of VOC contamination at the study site. As long as there is laminar flow across the screened interval in the wells, diffusion samplers can quantify vertical stratification of VOC contaminants (Kearl and others, 1992; Reilly and LeBlanc, 1998).

Concentrations of TCA and chloroethane in water samples collected with the diffusion samplers and a submersible pump from wells 6-S-19 and 6-S-29 with 20-foot screened intervals are shown in figure 4. Two diffusion samplers were installed in both of these wells at different depths within the screened interval. Concentrations of TCA and chloroethane were consistently high in water samples collected with the diffusion samplers toward the top of the aquifer. TCA concentrations in water samples from well 6-S-29 were 7.2 μg/L in the sample collected with the shallow diffusion sampler (installed at 151.5 feet); <1.0 μg/L in the sample collected with the diffusion sampler installed 10 feet deeper (161.5 feet); and 7.4 μg/L in the sample collected with the submersible pump at a depth of about 146 feet. Chloroethane concentrations ranged from 28 μg/L in the water sample collected with the shallow diffusion sampler to 7.8 μg/L in the water sample collected with the deeper diffusion sampler.

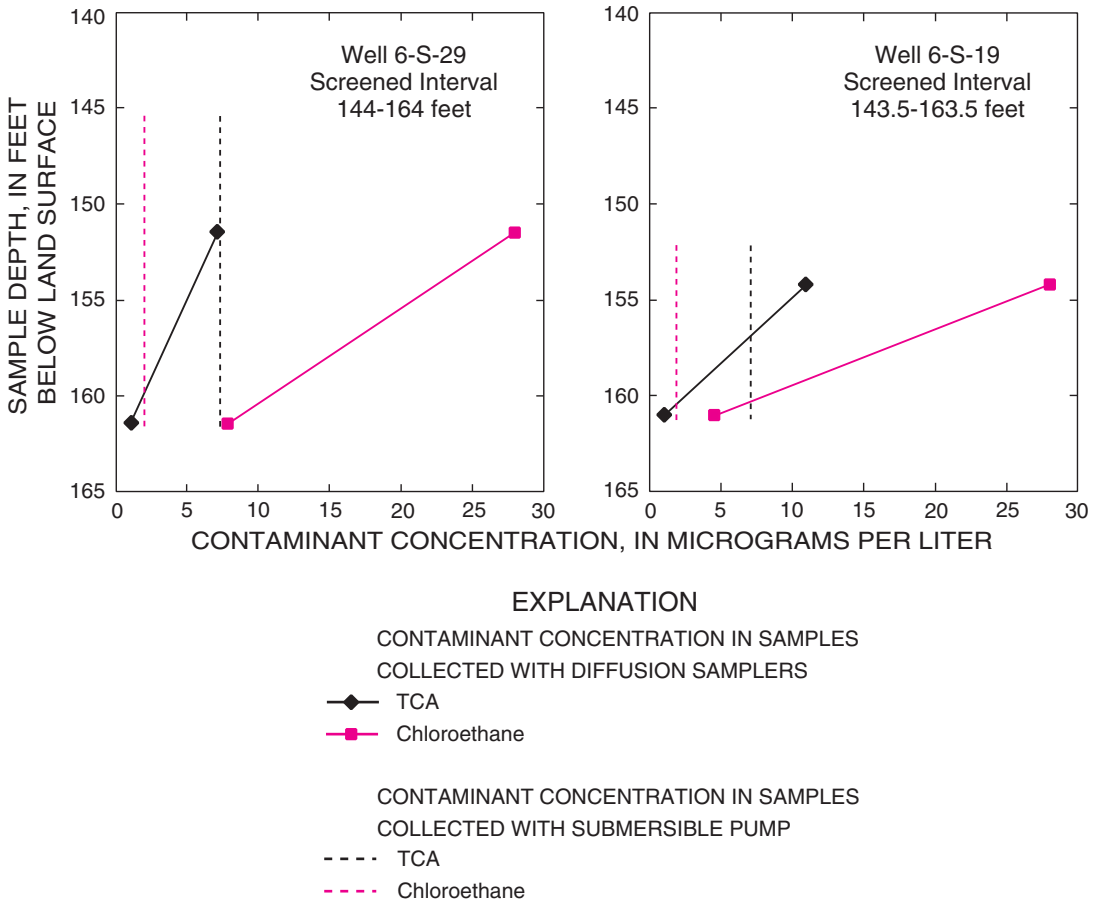
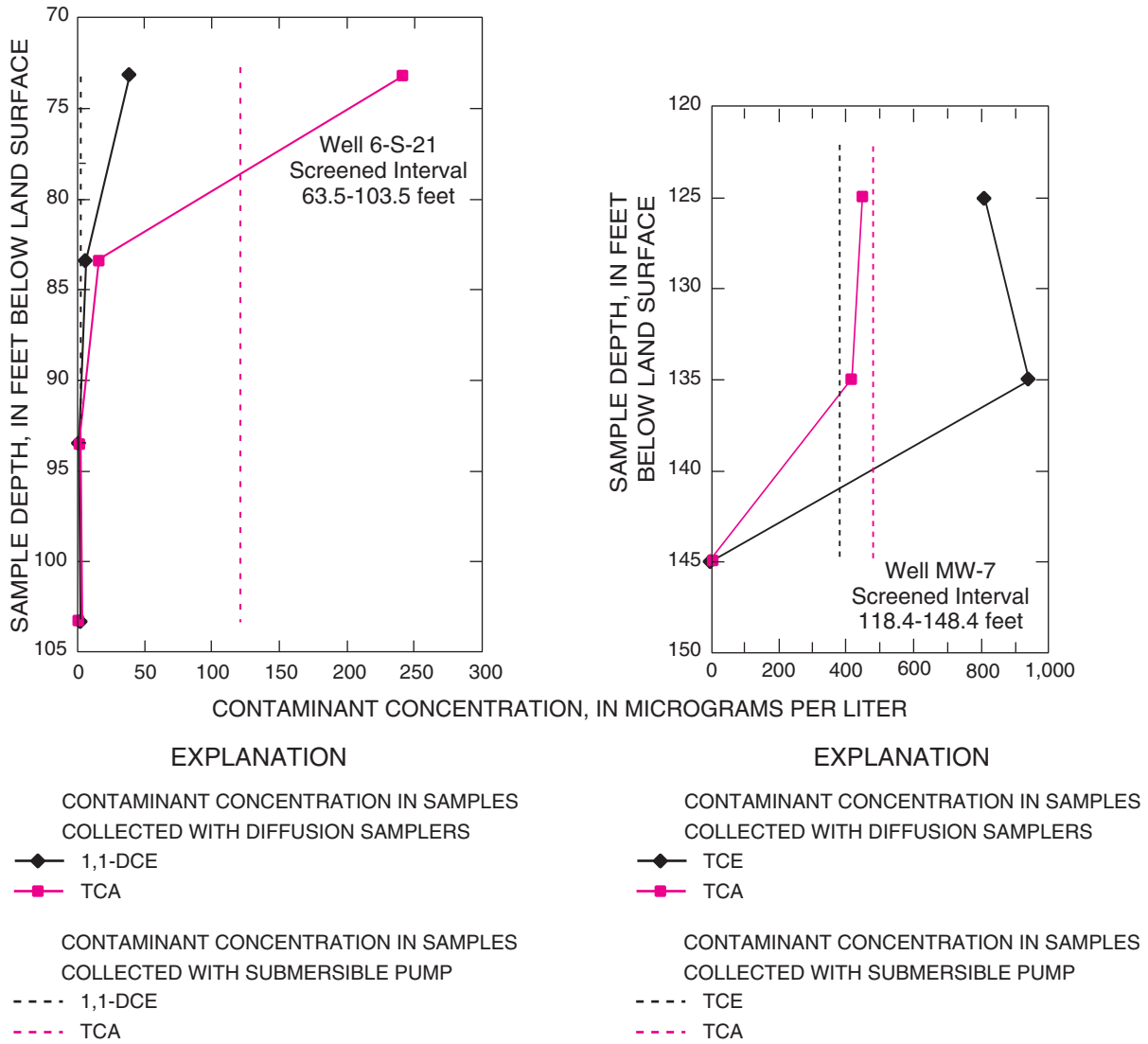


Figure 4. Comparison of TCA and chloroethane concentrations from ground-water samples collected with diffusion samplers and a submersible pump for wells with 20-foot screened intervals in Area 6, Naval Air Station Whidbey Island, Washington.

The results are similar for well 6-S-19, with the samples collected with the diffusion samplers showing high concentrations of TCA and chloroethane near the top of the aquifer. The TCA concentration from the sample collected with the submersible pump showed considerably less contamination and appears to represent a mixture of water from the shallower and deeper part of the screened interval. TCA and chloroethane concentrations within the screened interval were generally underestimated in samples collected with the submersible pump and did not show a vertical distribution of contamination like the samples collected with the diffusion samplers.

The vertical distribution of contamination in wells 6-S-21 and MW-7 with screened-intervals of 40 and 30 feet are shown in figure 5. Four diffusion samplers were installed in well 6-S-21 at 73.2, 83.2, 93.2, and 103.2 feet. The TCA concentrations ranged from 240 µg/L in the shallowest sample to 2.8 µg/L in the deepest and DCE concentrations ranged from 42 to <1.0 µg/L. The TCA concentration in the corresponding sample collected with the submersible pump was 120 µg/L and the DCE concentration was 11 µg/L. Three diffusion samplers were installed in the screened interval at 125, 135, and 145 feet in well MW-7. TCE concentrations in samples collected with the



EXPLANATION

CONTAMINANT CONCENTRATION IN SAMPLES COLLECTED WITH DIFFUSION SAMPLERS
- 1,1-DCE
- TCA

CONTAMINANT CONCENTRATION IN SAMPLES COLLECTED WITH SUBMERSIBLE PUMP
- 1,1-DCE
- TCA

EXPLANATION

CONTAMINANT CONCENTRATION IN SAMPLES COLLECTED WITH DIFFUSION SAMPLERS
- TCE
- TCA

CONTAMINANT CONCENTRATION IN SAMPLES COLLECTED WITH SUBMERSIBLE PUMP
- TCE
- TCA

Figure 5. Comparison of selected volatile organic compound concentrations from ground-water samples collected with diffusion samplers and a submersible pump for wells with greater than 20-foot screened intervals in Area 6, Naval Air Station Whidbey Island, Washington.

diffusion samplers were 810 μg/L from the shallowest sample and 0.76 μg/L from the deepest sample and TCE concentrations ranged from 450 to <1.0 μg/L. TCE and TCA concentrations were 390 and 480 μg/L in the corresponding sample collected with the submersible pump. Concentrations of DCE, TCE, and TCA from the water samples collected with the submersible pump from these two wells appear to represent an integrated sample of water from the entire screened interval.

For comparison to the diffusion sampler results, an inflatable straddle-packer was placed down well MW-7 in June 1998 to preferentially sample an 18-inch interval of the long screen. Samples were collected with a submersible pump from three depth intervals - 123, 126, and 136 feet. The results of the straddle-packer data are shown in table 4. The packer results, like the diffusion samplers, and unlike the samples collected with the submersible pump indicate vertical stratification of contamination. Although the packer was used to preferentially sample the screen at certain intervals, the wells were purged and sampled with a pump allowing water to move freely toward the pump through the sand or gravel screen pack through zones not adjacent to the packed interval, resulting in a sample that represents an integration of different water types from outside the borehole (Vorbelsky and Hyde, 1997). Although the packer results showed a better vertical resolution than the single submersible pump sample, the packer would not be as effective as the diffusion samplers in discriminating the vertical distribution of contaminants because it does not actually isolate a horizon. Whereas, the concentrations in water samples collected using diffusion samplers represent the immediate vicinity of the sampler.

Table 4. Concentrations of selected chlorinated volatile organic compounds in water collected from isolated intervals using a straddle packer in well MW-7 at Area 6, Naval Air Station Whidbey Island, Washington

[**Chemical Abbreviations**: TCE, trichloroethene; TCA, 1.1.1-trichloroethane; *cis*-DCE, *cis*-1,1-dichloroethene; DCE, 1,1-dichloroethene; DCA, 1,1-dichloroethane. μg/L, micrograms per liter; <, not detected at the given concentration; e, detected concentration is less than the reporting limit and is an estimate concentration]

Well No. (sample depth, in feet)	TCE (μg/L)	TCA (μg/L)	*cis*-DCE (μg/L)	DCE (μg/L)	DCA (μg/L)	Vinyl chloride (μg/L)
MW-7 (123)	1,000	820	160	36	4.5	<25
MW-7 (126)	570	420	170	38	5.1e	<25
MW-7 (136)	650	440	120	57	140	<25

The analysis of VOC concentrations in water samples collected with diffusion samplers generally provides a better understanding of the vertical distribution of contaminants in the aquifer. Figure 6 is a generalized cross section that illustrates the differences in vertical distribution of TCA in the aquifer that could be inferred from the VOC data collected with the diffusion samplers and submersible pump. The single concentrations in samples collected with the submersible pump infer that the concentration is distributed across the entire screened interval, which spans 40 feet for well 6-S-21 and 30 feet for well MW-7. Whereas, a different distribution of contamination is inferred based on multiple concentrations in samples collected from the diffusion samplers.

In contrast to results from other wells, analysis of VOC concentrations in samples collected with the diffusion samplers for well MW-8 (a 40-foot screen well) did not show a clear vertical distinction of VOC contamination (see figure 7 and table 2). The results may be indicative of vertical flow within the screened interval where contaminants are entering the well near the top or bottom of the screen, flowing vertically with in the screen under a hydraulic gradient and exiting the well at the opposite end. Concentration changes are not apparent because the measurements are at different points along the pipe flow. In a 40-foot screen, it is almost certain that there is vertical flow in the well because of the large potential to connect zones of differing hydraulic head. A down-hole flow meter could be used in this well to indicate the primary source water zones. If the zone of low hydraulic head from the well is within the contaminated horizon then water samples from the diffusion samplers as well as the submersible pump would be inadequate because the contaminated horizon does not contribute water to the well under static conditions, therefore contamination concentrations in the water samples would be underestimated or not detected (Reilly and Leblanc, 1998; Vroblesky, 2001). Instead, water from other horizons with higher hydraulic head will flow into the contaminated horizon by way of the well screen. Although pumping draws inflow from the contaminated zone, most of that inflow will represent the residual water from other horizons.

Sampling Technique Cost Comparisons

The materials cost for the construction of a diffusion sampler were about $2 per sampler. Materials included nylon parachute cord, polyethylene tubing, mesh tubing, and stainless steel weights. A reusable heat sealer was purchased at cost of $80; the item is a one-time purchase needed to construct the diffusion sampler. For this study site, construction required one person 4 hours for 24 samplers, and a two-person crew 8 hours for installation and another 4 hours for retrieval of the samplers. About six wells (12 samplers) were sampled per-person day, and the total purge water collected for disposal was a little over 1 gallon.

In comparison, the ability to collect a sample using a submersible pump requires a much larger one-time purchase of a submersible pump (about $5,000) and a generator, which can be either rented or purchased. At this study site, an average of 2.5 wells were sampled per person-day and the total purge water collected for disposal was about 200 gallons. The use of diffusion samplers is clearly more cost effective. If diffusion samplers were to be used again at this site, the re-installation of the samplers would be faster because the desired placement of samplers is known.

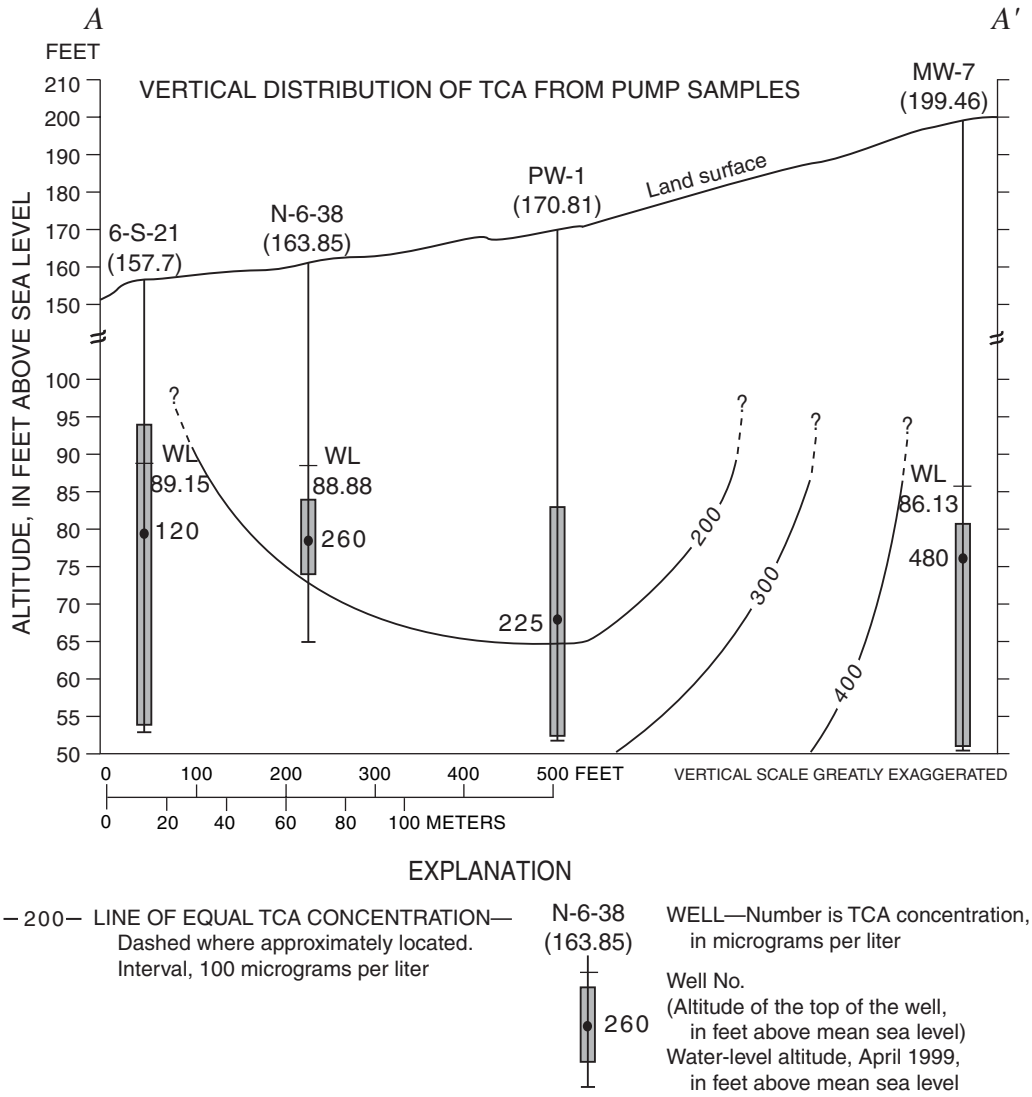


Figure 6. Vertical distribution of TCA concentrations in ground-water samples collected with the diffusion samplers and submersible pump.

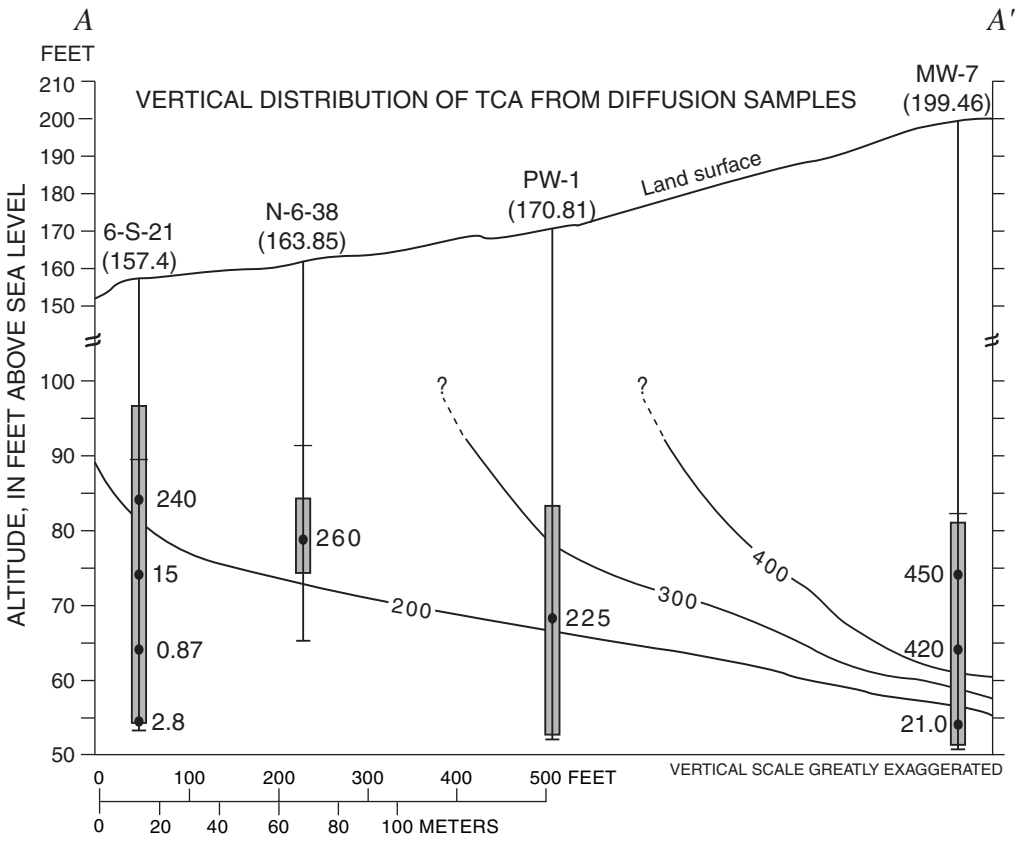


Figure 6.—*Continued.*

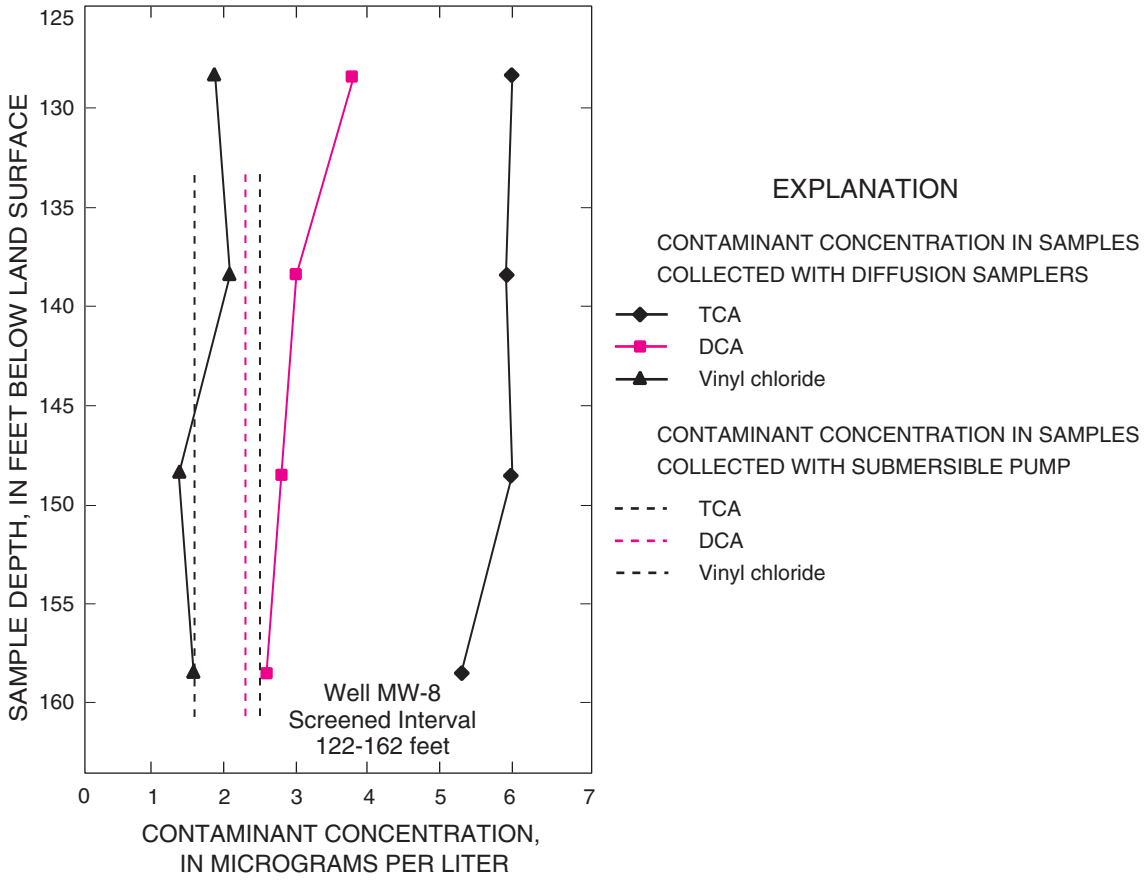


Figure 7. Comparison of selected volatile organic compounds from ground-water samples collected with diffusion samplers and a submersible pump for well MW-8, with a 40-foot screened interval that is not indicative of laminar flow across the screened interval in Area 6, Naval Air Station Whidbey Island, Washington.

SUMMARY

Ground-water samples were collected in April 1999 at Naval Air Station Whidbey Island, Washington, with passive diffusion samplers and a submersible pump to compare concentrations of volatile organic compounds (VOCs) in water samples collected using the two sampling methods. Single diffusion samplers were installed in six wells with 10-foot screened intervals, and multiple diffusion samplers were installed in five wells with 20- to 40-foot screened intervals. The samplers were recovered after 20 days, and the wells were then sampled using a submersible pump.

For the 10-foot screened wells, contaminant concentrations in samples collected using the passive diffusion samplers closely matched contaminant concentrations using the submersible pump. The mean absolute difference of detected concentrations was 7.7 μg/L. For the long-screen wells (screen length greater than 10 feet), the analysis of VOC concentrations in samples collected with multiple diffusion samplers indicated vertical concentration variations within the screened interval, whereas the analysis of VOC concentrations in samples collected with the conventional submersible pump indicated mixing during pumping. VOC data collected using diffusion samplers also indicated that contaminant stratification was present in some wells. TCA concentrations in one well ranged from 240 to 15 μg/L over a vertical distance of about 10 feet. In this and other wells where concentration stratification was observed, the concentration in the samples collected with the submersible pump appears to represent a mixing of waters with differing concentrations, whereas the concentrations in samples collected with the diffusion samplers represent localized concentrations. However, where vertical flow may be apparent within the screened interval such as the data indicate from well MW-8, a borehole flow meter should be used to determine what horizon borehole water is coming from, and to determine if samples collected with diffusion samplers as well as samples collected with submersible pumps would be representative of contaminant concentrations in the aquifer.

An advantage of the diffusion sampling method over the traditional submersible pump method includes less overall time and money for collection of samples and minimal wastewater. In addition, diffusion samplers have an advantage over the pump method in evaluating the stratification of VOCs in wells because diffusion samplers can collect multiple samples with little added time over the time needed for collection of one sample. Overall, the data indicate that the use of diffusion samplers provided an effective less expensive alternative sampling method to the purge-and-sample approach used at this site.

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USGS

Huffman

Comparison of Methods for Monitoring Volatile Organic Compounds in Ground Water, Area 6, Naval Air Station Whidbey Island, WA

WRIR 02-4203