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Interpretation of Borehole Geophysical Logs, Aquifer-Isolation Tests, and Water-Quality Data for Sites 1, 3, and 5 at Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania: 2005

Scientific Investigations Report 2006–5243

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

Cover. View of straddle-packer assembly being lowered in a well at the Willow Grove Naval Air Station/Joint Reserve Base.

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DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
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Conversion Factors and Datum

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
milliliter (mL)	.06102	cubic inch (in^3)
	Flow rate	
Liter (L)	0.2642	gallon (gal)
cubic foot per second (ft^3/s)	0.02832	cubic meters per second (m^3/s)

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

$$°F = (1.8 \times °C) + 32$$

Interpretation of Borehole Geophysical Logs, Aquifer-Isolation Tests, and Water-Quality Data for Sites 1, 3, and 5 at the Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania: 2005

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Abstract

Borehole geophysical logging, heatpulse-flowmeter measurements, borehole television surveys, and aquifer-isolation tests were conducted in 2005 at the Willow Grove Naval Air Station/Joint Reserve Base (NAS/JRB) in Horsham Township, Montgomery County, Pa. This study was done by the U.S. Geological Survey (USGS) in cooperation with the U.S. Navy in support of hydrogeological investigations to address ground-water contamination. Data collected for this study are valuable for understanding ground-water flow in the Stockton Formation at the local and regional scale. The Willow Grove NAS/JRB is underlain by the Stockton Formation, which consists of sedimentary rocks of Triassic age. The rocks of the Stockton Formation form a complex, heterogeneous aquifer with partially connected zones of high permeability. Borehole geophysical logs, heatpulse-flowmeter measurements, and borehole television surveys made in seven boreholes ranging from 70 to 350 ft deep were used to identify potential water-producing fractures and fracture zones and to select intervals for aquifer-isolation tests. An upward vertical hydraulic gradient was measured in one borehole, a downward vertical hydraulic gradient was measured in four boreholes, both an upward and a downward vertical hydraulic gradient were measured in one borehole, and no flow was measurable in one borehole. The aquifer-isolation tests isolated 30 discrete fractures in the seven boreholes for collection of depth-discrete hydraulic and water-quality data. Of the 30 fractures identified as potentially water producing, 26 fractures (87 percent) produced more than 1 gallon per minute of water. The specific capacity of the isolated intervals producing more than 1 gallon per minute ranged from 0.02 to 5.2 gallons per minute per foot. There was no relation between specific capacity and depth of the fracture. Samples for analysis for volatile organic compounds were collected from each isolated zone. Tetrachloroethylene (PCE) was the most prevalent compound at Site 1; concentrations were as great as 62 µg/L (micrograms per liter). 1,1-dichloroethane was the most prevalent compound at Site 3; concentrations were as great as 9.3 µg/L. Toluene was the most prevalent compound at Site 5; concentrations were as great as 77 µg/L. For five out of the six wells (83 percent) sampled for field determinations of water-quality constituents, the interval with the lowest dissolved oxygen concentration had the highest total VOC concentration.

Introduction

The Willow Grove Naval Air Station/Joint Reserve Base (NAS/JRB) is in Horsham Township, Montgomery County, Pa. (fig. 1). In addition to its primary use as a reserve Naval air station, this 1,000-acre facility also supports Marine, Army, and Air Force activities. Areas with possible contamination at the Willow Grove NAS/JRB (fig. 1), also referred to as “the base” in this report, were identified by the U.S. Navy as part of a preliminary assessment program (Halliburton NUS Environmental Corporation, 1993). A hydrogeological investigation is being conducted by the U.S. Navy to address ground-water contamination at these sites.

In support of this investigation, the U.S. Geological Survey (USGS) conducted borehole geophysical logging and aquifer-isolation (packer) tests in seven boreholes to characterize the geophysical and hydraulic properties and to characterize the water quality of water-producing fractures. This work is a continuation of previous work by the USGS (Conger, 1997, 1999; Sloto, 2002; Sloto and others, 2001, 2002). Some data used for this study and presented in this report were provided by TetraTech NUS, Inc., and ECOR Solutions, Inc., and are reproduced herein with permission.

Purpose and Scope

For this study, borehole geophysical logs, heatpulse-flowmeter measurements, and borehole television surveys made in seven boreholes ranging from 70 to 350 ft deep were used to identify potential water-producing fractures and fracture zones and to select intervals for aquifer-isolation tests. The aquifer-isolation tests isolated 30 discrete fractures in the seven boreholes for collection of depth-discrete hydraulic and water-quality data. Samples for analysis for volatile organic compounds were collected from each isolated zone.This report presents an interpretation of borehole geophysical logs, heatpulse-flowmeter measurements, borehole television surveys, and aquifer-iso-

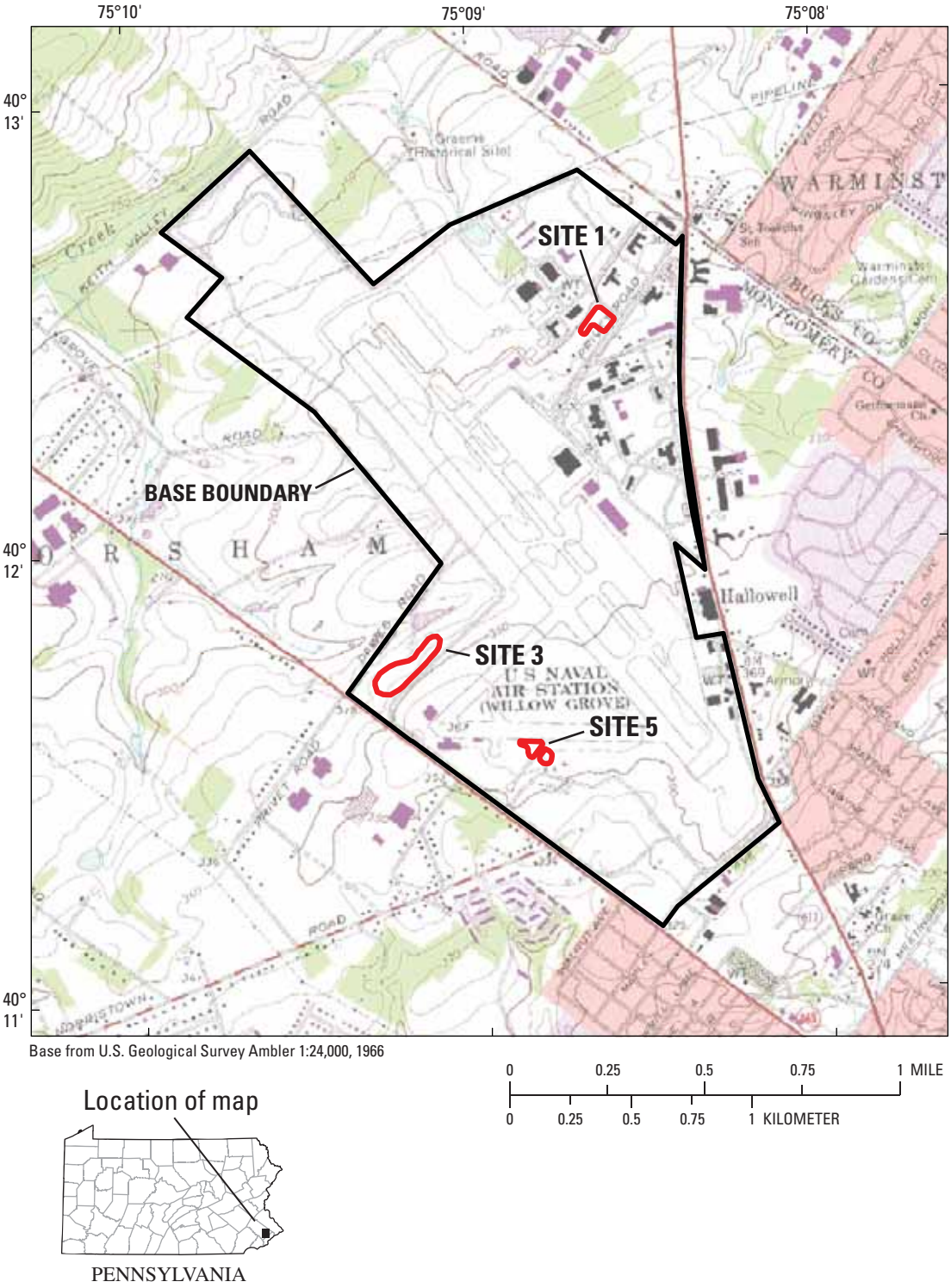

Figure 1. Location of the Willow Grove Naval Air Station/Joint Reserve Base and sites of possible groundwater contamination, Horsham Township, Montgomery County, Pennsylvania.

lation tests conducted in the seven boreholes. The report also presents water-quality data collected during the aquifer-isolation tests.

Hydrogeologic Setting

The Willow Grove NAS/JRB is in the Gettysburg-Newark Lowlands Section of the Piedmont Physiographic Province. The site and surrounding area are underlain by the Stockton Formation, which consists of sedimentary rocks of Triassic age. The Stockton Formation is subdivided into three units known as the lower arkose, middle arkose, and upper shale members (Rima and others, 1962). The middle arkose member crops out at the Willow Grove NAS/JRB, where it consists of fine- to medium-grained arkosic sandstone interbedded with red siltstone and mudstone. Quartz and feldspar are the dominant minerals. The Stockton Formation is about 6,000 ft thick at the Bucks-Montgomery County border (Rima and others, 1962). Bedding in the Stockton Formation at the base strikes N. 76° E. and dips about 7° NW. (Brown and Root Environmental, Inc., 1998). Vertical fractures are common.

The rocks of the Stockton Formation form a complex, heterogeneous aquifer with partially connected zones of high permeability. The aquifer is composed of a series of gently dipping lithologic units with different hydraulic properties. Permeability commonly differs from one lithologic unit to another.

Ground water in the unweathered part of the Stockton Formation primarily flows through a network of interconnecting secondary openings—bedding-plane fractures and joints. Primary porosity that originally may have been present has been almost eliminated by compaction and cementation. Ground water in the weathered zone of the bedrock moves through intergranular openings formed as a result of weathering. In some places, permeability of the weathered zone may be poor because of a high percentage of clay derived from weathering of mudstone and siltstone.

Boreholes may penetrate several major water-producing zones with different hydraulic properties. Each water-producing zone usually has a different hydraulic head (water level). The head in a deep, open-hole borehole is the composite of the heads in the water-producing zones penetrated. This can cause heads in some boreholes to be different than heads in adjacent boreholes of different depths. Where differences in head exist between water-producing zones, water flows in the direction of decreasing head. Boreholes that connect several water-producing zones may act as conduits for the transport of contaminants (Sloto and others, 1996).

Ground water at the base originates from local infiltration of precipitation and inflow of ground water from upgradient areas. Ground-water levels fluctuate with seasonal variations in recharge and are affected by pumping of wells. Water in the shallow part of the aquifer generally is under unconfined (water-table) conditions; ground water in the deeper part of the aquifer may be confined or partially confined. Local artesian (confined) conditions are common.

Well-Identification System

Two well-identification numbering systems are used in this report to maintain consistency with previous studies. Navy well-identification numbers are used for wells at the Willow Grove NAS/JRB. Navy well-identification numbers for monitor wells consist of a site-designation number, the letters MW, a sequentially assigned well-cluster number, and a depth-interval letter (S for shallow, I for intermediate, and D for deep). Well 05MW12S would indicate a shallow monitor well in cluster 12 at Site 5. Navy well-identification numbers also begin with the prefix SW. The USGS well-identification number consists of a county-abbreviation prefix followed by a sequentially assigned number. The prefix MG denotes a well in Montgomery County. A cross-reference between site and USGS well-identification numbers is given in table 1. Locations of the wells are shown on figures 2 and 3.

Table 1. Record of selected wells, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[—, no data]

U.S. Navy well-identification number	U.S. Geological Survey well-identification number	Depth drilled (feet)	Screened or open interval (feet below land surface)
01MW09	MG-2143	150	120-130
01MW10I	MG-2144	350	148-158
01MW10D	MG-2141	—	300-320
03MW08S	MG-2145	222	38-68
03MW08I	MG-2142	—-	127-142
05MW12S	MG-2136	70	50-70
05MW13I	MG-2137	181	127-142
05MW14S	MG-2140	148	38-55
05MW14I	MG-2138	—	128-148
05MW15I	MG-2139	150	140-150
SW-1	MG-209	389	50-389
SW-2	MG-210	340	43-340

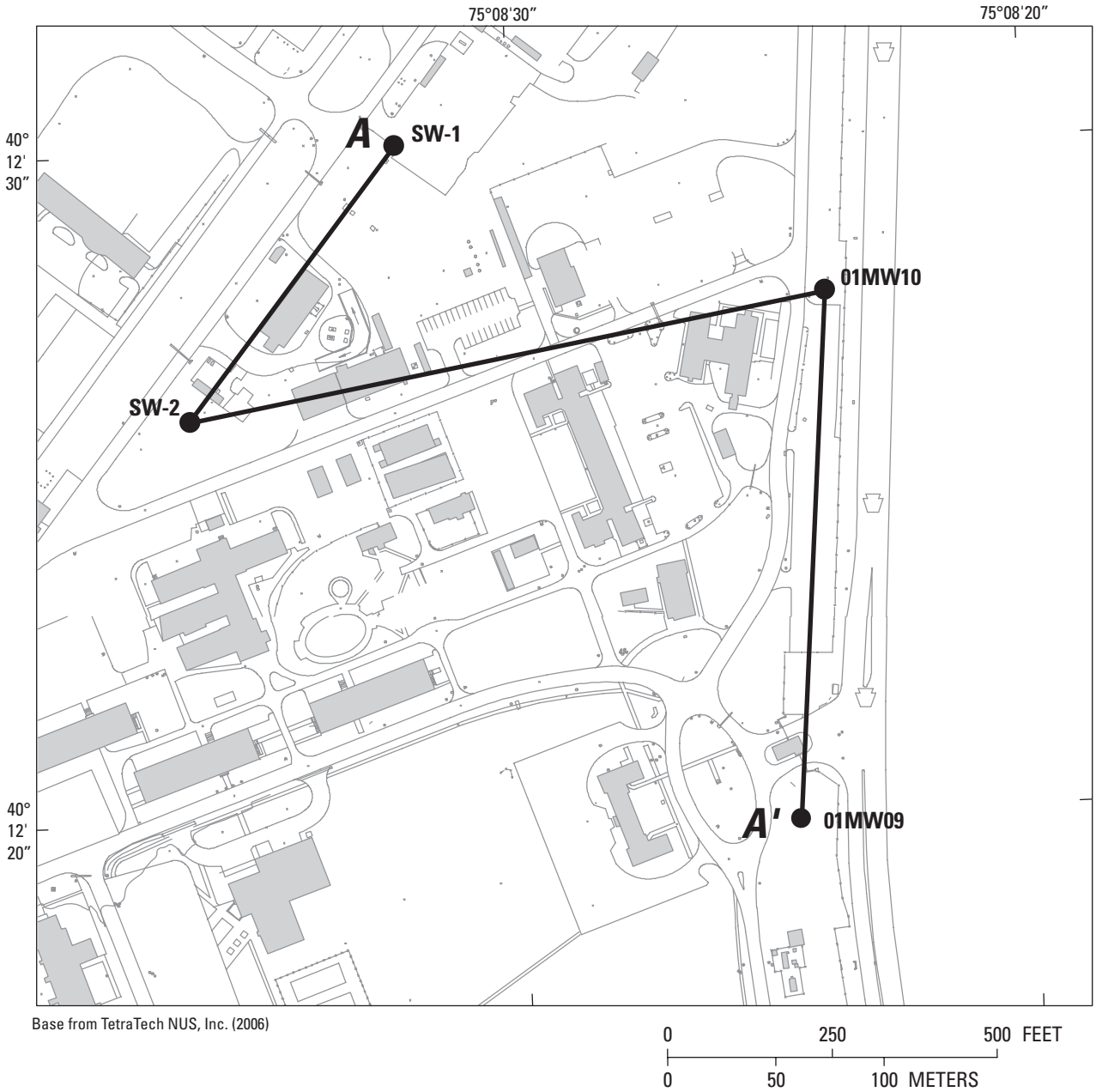

Figure 2. Locations of base supply wells (SW) and selected monitor wells (MW) at Site 1, Willow Grove Naval Air Station/ Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

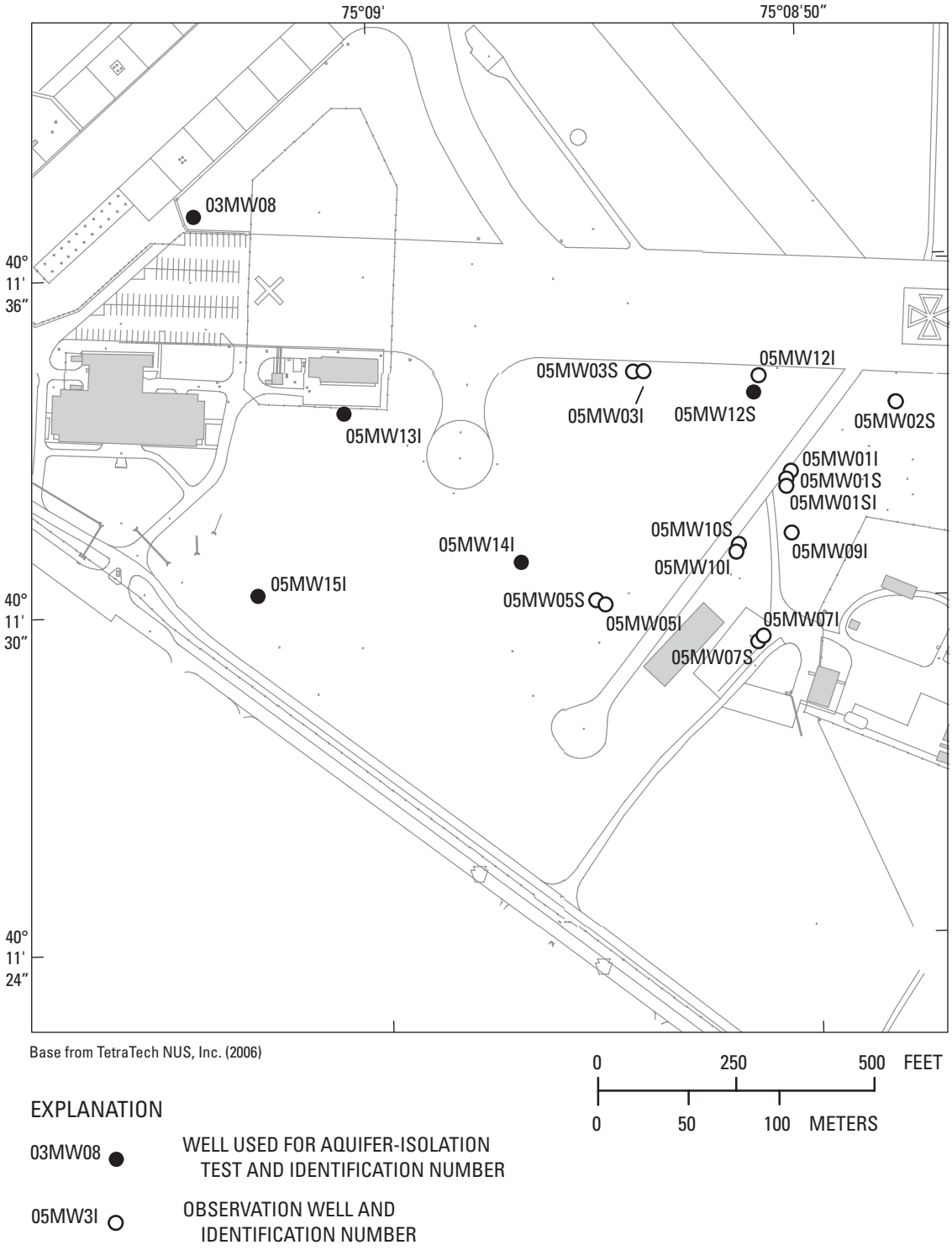

Figure 3. Locations of selected monitor wells at Sites 3 and 5, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Methods of Investigation

This study included collection of borehole geophysical logs, heatpulse-flowmeter measurements, borehole television surveys, aquifer-isolation tests, and collection of water-quality samples. They are described in the following sections.

Borehole Geophysical Logs

Caliper, natural-gamma, single-point-resistance, fluid-resistivity, and fluid-temperature borehole geophysical logs were collected in the boreholes listed in table 1. The logs were used to locate water-producing fractures, to determine the rate and direction of vertical movement of water in the borehole, and to determine intervals to be isolated by straddle packers for the aquifer-isolation tests.

Caliper logs provide a continuous record of average borehole diameter, which is related to fractures, lithology, and drilling technique. Caliper logs were used to identify fractures and possible water-producing openings. Correlation of caliper logs with fluid-resistivity and fluid-temperature logs was used to identify water-producing and water-receiving fractures or zones. The term fracture used in association with the caliper-log interpretations might identify a change in borehole diameter that may not necessarily indicate a bedding-plane separation, lithologic contact, or water-producing or water-receiving zone, but may simply indicate an enlargement of the borehole.

Natural-gamma logs, also called gamma-ray logs, record the natural-gamma radiation emitted from rocks penetrated by the borehole. Uranium-238, thorium-232, and the progeny of their decay series and potassium-40 are the most common emitters of natural-gamma radiation. These radioactive elements are concentrated in clays by adsorption, precipitation, and ion exchange. Fine-grained sediments, such as mudstone or siltstone, usually emit more gamma radiation than sandstone. Geophysical logging with a gamma probe can be conducted in the water-filled, dry, cased, or uncased parts of the borehole (Keys, 1990). However, casing reduces the gamma response. The gamma logs were used to correlate lithologic units between boreholes.

Single-point-resistance logs record the electrical resistance between the borehole and an electrical ground at land surface. In general, resistance increases with grain size and decreases with borehole diameter, density of water-producing fractures, and increasing dissolved-solids concentration of borehole water (Keys, 1990). A water-filled borehole is required for single-point-resistance logs, and they are run only for the saturated part of the formation below the casing. A single-point-resistance log is used to correlate lithology between boreholes and may help identify water-producing fractures or zones.

Fluid-temperature logs provide a continuous record of the vertical water-temperature variation in the borehole. Fluid-temperature logs were used to identify water-producing and water-receiving zones and to determine intervals of vertical borehole flow. Water-producing and water-receiving zones usually are identified by sharp changes in temperature, and intervals of vertical borehole flow are identified by little or no temperature gradient.

Fluid-resistivity logs measure the electrical resistance of the water in the borehole. Resistivity is the reciprocal of fluid conductivity, and fluid-resistivity logs reflect changes in the dissolved-solids concentration of the borehole water. Fluid-resistivity logs are used to identify water-producing and water-receiving zones and to determine intervals of vertical borehole flow. Water-producing and water-receiving zones usually are identified by sharp changes in resistivity. Intervals of vertical borehole flow usually are identified by a low-resistivity gradient between a water-producing and a water-receiving zone.

Heatpulse-Flowmeter Measurements

The direction and rate of borehole-fluid movement were measured with a high-resolution heatpulse flowmeter. The heatpulse flowmeter operates by diverting nearly all flow to the center of the tool where a heating grid slightly heats a thin zone of water. If vertical borehole flow is occurring, the water moves up or down the borehole to one of two sensitive thermistors (heat sensors). When a peak temperature is recorded by one of the thermistors, a measurement of direction and rate is calculated by the computer collecting the logging data. The range of flow measurement is about 0.01 to 1.5 gal/min in a 2- to 10-in. diameter borehole. Heatpulse-flowmeter measurements may be affected by poor seal integrity between the borehole and the flowmeter. If the seal between the borehole and the heatpulse flowmeter is not complete, some water can bypass the flowmeter, resulting in flow measurements that are less than the actual rate. The quantity of water bypassing the tool is a function of borehole size and shape and degree of fracturing. For some boreholes, the rate of borehole flow was greater than the upper limit of flow measurable by the heatpulse flowmeter, and a smaller diameter diverter was used to allow some of the flow to bypass the tool. Although the heatpulse flowmeter is a calibrated tool, the data primarily are used as a relative indicator of water-producing zones.

Borehole Television Surveys

Borehole television surveys were conducted by lowering a waterproof video camera down the borehole and recording the image on video tape. The depth indicated on the video image may not correspond exactly to the geophysical logs because of slippage of the video cable. The borehole television surveys were used to characterize water-producing fractures and to locate smooth sections of borehole to set packers.

Aquifer-Isolation Tests

Because most ground-water flow and contaminant movement at the Willow Grove NAS/JRB occurs in distinct water-

producing fractures rather than through primary openings in the bedrock, it is important to define the hydraulic and chemical characteristics of important, discrete water-producing fractures. This characterization only can be performed by isolating each water-producing fracture with straddle packers so that its properties can be separated from the other water-producing fractures in the borehole. These tests are called aquifer-isolation tests and commonly are referred to as packer tests.

The straddle-packer assembly consisted of two inflatable rubber bladders (packers) about 4 ft long set on 2-in.-diameter lift pipe with a pump set between the packers. The distance from the center of the upper packer to the center of the lower packer varied. Packer settings given in this report are from the bottom of the top packer to the top of the bottom packer. Isolated intervals are numbered in order from the bottom to the top of the borehole.

Several aquifer-isolation tests were conducted in each borehole. Intervals selected for aquifer-isolation tests were based on the borehole geophysical logs and borehole television surveys. The packer assembly was lowered to the selected depth in the borehole, and the packers were inflated against the borehole wall, isolating the selected interval. Exact depths to set packers were based on the location of smooth sections of borehole wall determined from the caliper logs and borehole television surveys. For the test of most intervals, both packers were inflated (fig. 4B). For the test of the lowermost isolated interval in most boreholes, only the upper packer was inflated (fig. 4A). For the test of the uppermost isolated interval in most boreholes, only the lower packer was inflated (fig. 4C). Inflation of both packers created three intervals—an upper interval above the upper packer, the isolated interval between the packers, and a lower interval below the lower packer. Pressure in the packers was monitored continuously so that the packers always remained at maximum inflation. After the packers were inflated, water levels in each interval usually were allowed to stabilize before pumping began. Because of interference caused by the pumping of the supply wells, water levels may not have stabilized completely before the start of the test. Water levels were recorded above, below, and in the isolated interval.

During aquifer-isolation tests, measurements of water levels were made in each interval by calibrated pressure transducers and were recorded by a digital data logger. Water levels initially were determined by electric measuring tapes; these water levels were used to calibrate the transducers. The transducers were set in measurement tubes open to the monitored intervals. The accuracy of the transducer in the isolated interval was ± 0.06 ft. The accuracy of the transducers used in the intervals above and below the isolated interval was ± 0.03 ft. Land surface is used as a reference for all water-level measurements in this report. Calibrated, in-line flowmeters were used to measure discharge. The water was treated by a granulated active carbon filtration system before discharge.

The specific capacity of each isolated interval was calculated by dividing the pumping rate by the drawdown. Water samples were collected prior to the end of each test by opening a sampling port in the discharge line before the flowmeter and the activated carbon treatment system. This caused the pumping rate to increase and the water level to decline. The specific capacity was determined using the drawdown just prior to sampling. Specific capacity is affected by the pumping rate and the length of pumping. In general, a higher pumping rate and(or) a longer pumping duration will result in a lower specific capacity.

Water-Quality Samples

Field determination of water-quality constituents (dissolved oxygen, pH, specific conductance, and temperature) were made by the USGS. Water samples were collected for laboratory analysis for volatile organic compounds (VOCs) (table 2) by TetraTech NUS, Inc., or ECOR Solutions, Inc. Samples were collected near the end of each aquifer-isolation test from a sampling port placed in the discharge line before the flowmeter and active carbon filtration system. Samples for VOC analysis were collected in 40-milliliter septum bottles, placed on ice, and shipped overnight to a contract laboratory.

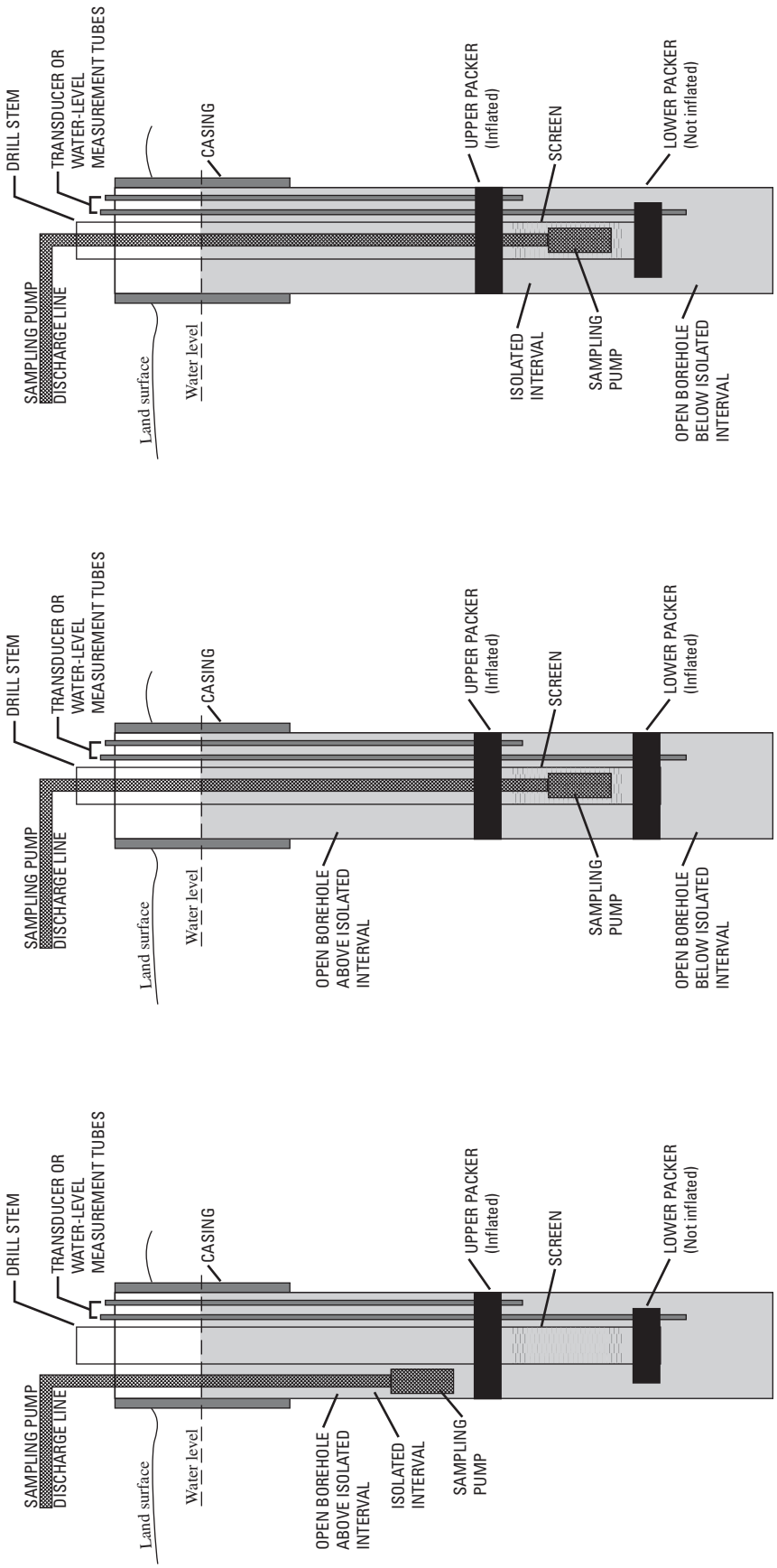

Figure 4. Generalized sketch of straddle-packer assembly and sampling pump in a borehole.

Table 2. Volatile organic compounds analyzed in ground-water samples, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Chemical Abstract Service registry number	Compound	Detection limit (micrograms per liter)
75-71-8	Dichlorodifluoromethane	1.0
74-87-3	Chloromethane	1.0
75-01-4	Vinyl chloride	1.0
74-83-9	Bromomethane	1.0
75-00-3	Chloroethane	1.0
75-69-4	Trichlorofluoromethane	1.0
76-13-1	1,1,2-Trichlorotrifluoroethane (1,1,2-Trichloro-1,2,2-trifluoroethane)	1.0
75-35-4	1,1-Dichloroethene	1.0
67-64-1	Acetone	5.0
75-15-0	Carbon disulfide	1.0
1634-04-4	Methyl tert-butyl ether	1.0
79-20-9	Methyl acetate	1.0
75-09-2	Methylene chloride	1.0
156-60-5	trans-1,2-Dichloroethene	1.0
75-34-3	1,1-Dichloroethane	1.0
110-82-7	Cyclohexane	1.0
78-93-3	2-Butanone	5.0
56-23-5	Carbon tetrachloride	1.0
156-59-2	cis-1,2-Dichloroethene	1.0
67-66-3	Chloroform	1.0
71-55-6	1,1,1-Trichloroethane	1.0
108-87-2	Methylcyclohexane	1.0
71-43-2	Benzene	1.0
107-06-2	1,2-Dichloroethane	1.0
79-01-6	Trichloroethene	1.0
78-87-5	1,2-Dichloropropane	1.0
75-27-4	Bromodichloromethane	1.0
108-10-1	4-Methyl-2-pentanone	5.0
108-88-3	Toluene	1.0
10061-02-6	trans-1,3-Dichloropropene	1.0
10061-01-5	cis-1,3-Dichloropropene	1.0
79-00-5	1,1,2-Trichloroethane	1.0
591-78-6	2-Hexanone	5.0
124-48-1	Dibromochloromethane	1.0
106-93-4	1,2-Dibromoethane	1.0
127-18-4	Tetrachloroethene	1.0
108-90-7	Chlorobenzene	1.0
100-41-4	Ethylbenzene	1.0
126777-61-2	m- and p-Xylenes[1]	1.0
95-47-6	o-Xylene[1]	1.0
1330-20-7	Total xylenes	3.0
100-42-5	Styrene	1.0
75-25-2	Bromoform	1.0
98-82-8	Isopropylbenzene	1.0
79-34-5	1,1,2,2-Tetrachloroethane	1.0
541-73-1	1,3-Dichlorobenzene	1.0
106-46-7	1,4-Dichlorobenzene	1.0
95-50-1	1,2-Dichlorobenzene	1.0
96-12-8	1,2-Dibromo-3-chloropropane	1.0
120-82-1	1,2,4-Trichlorobenzene	1.0
123-91-1	1,4-Dioxane[1]	1.0

[1]Analyzed by TetraTech NUS, Inc., only.

Interpretation of Borehole Geophysical Logs, Aquifer-Isolation Tests, and Water-Quality Data at Site 1

Water levels in the vicinity of Site 1 (figs. 1 and 2) are strongly influenced by the pumping cycle of wells SW-1 and SW-2 (fig. 2), which pump in tandem. Water levels in wells 01MW09 and 01MW10 are never static. The water levels are always rising or falling in response to the pumping cycles in wells SW-1 and SW-2 (fig. 5). During the aquifer-isolation tests, the water-level cycle in well 01MW09 had a range of approximately 0.6 ft, and the water-level cycle in well 01MW10 had a range of approximately 4.7 ft. The peaks in water level in well 01MW09 occurred about 25 minutes later than the peaks in well 01MW10. Constantly rising and falling water levels can make interpretation of borehole geophysical logs and aquifer-isolation-test data difficult.

Correlation of Borehole Geophysical Logs

Lithologic units penetrated by wells SW-1 and SW-2 were correlated by Sloto and others (2002, p. 54). This correlation was extended to wells 01MW09 and 01MW10 (fig. 6). Fractures in lithologic units in wells SW-1 and SW-2 with the greatest concentrations of tetrachloroethylene (PCE) are also penetrated by wells 01MW09 and 01MW10. The highest concentration of PCE measured in well SW-1 was from lithologic unit H (39 µg/L) and lithologic unit G (34 µg/L). These units are penetrated by wells 01MW09 and 01MW10 (fig. 6).

Well 01MW09 (MG-2143)

Well 01MW09 was drilled about 1,240 ft southeast of well SW-1 and 1,140 ft southeast of well SW-2 (fig. 2). Projecting the location of well 01MW09 in the direction of dip places it about 1,165 ft updip of well SW-1.

Interpretation of Borehole Geophysical Logs

A suite of borehole geophysical logs (fig. 7) was collected in well 01MW09 (fig. 2) by the USGS on November 8, 2005. A gamma log is not available. The caliper log shows the well is 150 ft deep, cased to 29 ft bls (below land surface), and major fractures are at 43, 59-66, 75, and 125 ft bls. The fluid-temperature log shows sharp breaks in slope at about 60 and 129 ft bls. The fluid-resistivity log shows sharp breaks in slope at about 60 and 118 ft bls. The fluid-temperature and fluid-resistivity logs

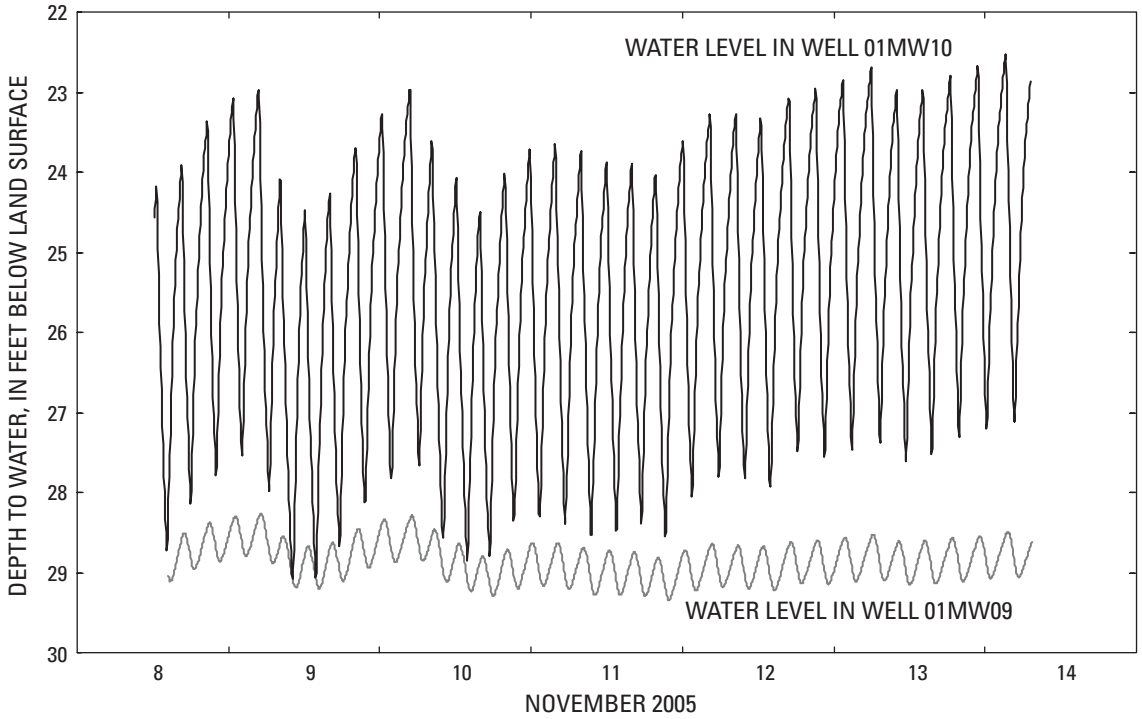

Figure 5. Hydrographs from wells 01MW09 (MG-2143) and 01MW10 (MG-2141), Willow Grove Naval Air Station/ Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania, November 8-14, 2005.

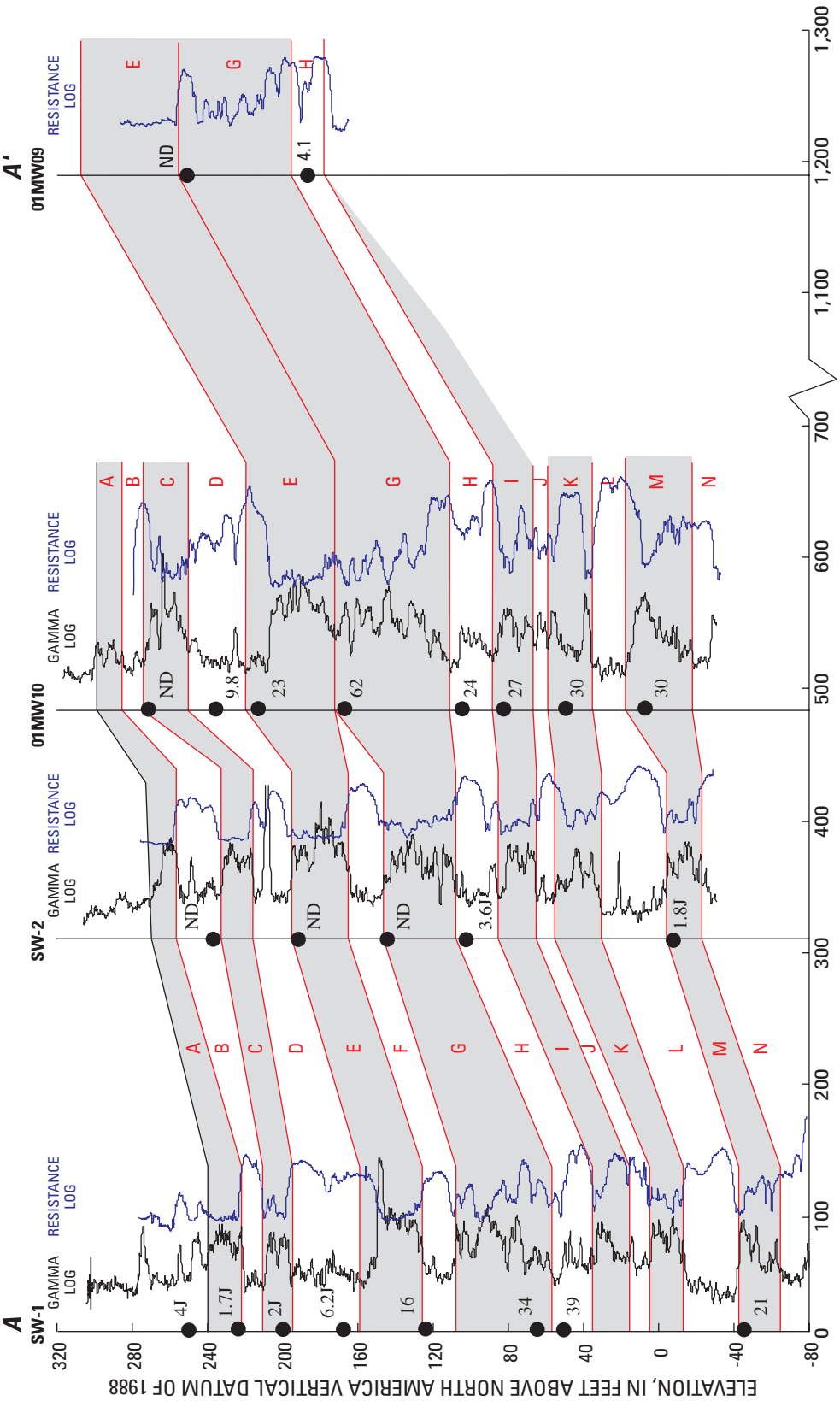

Figure 6. Correlation of natural-gamma logs, single-point-resistance logs, and tetrachloroethylene concentrations from wells SW-1 (MG-209), SW-2 (MG-210), 01MW09 (MG-2140), and 01MW10 (MG-2141), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania. Line of section shown on figure 2. Letters designating lithologic units are from Sloto (2002, p. 54).

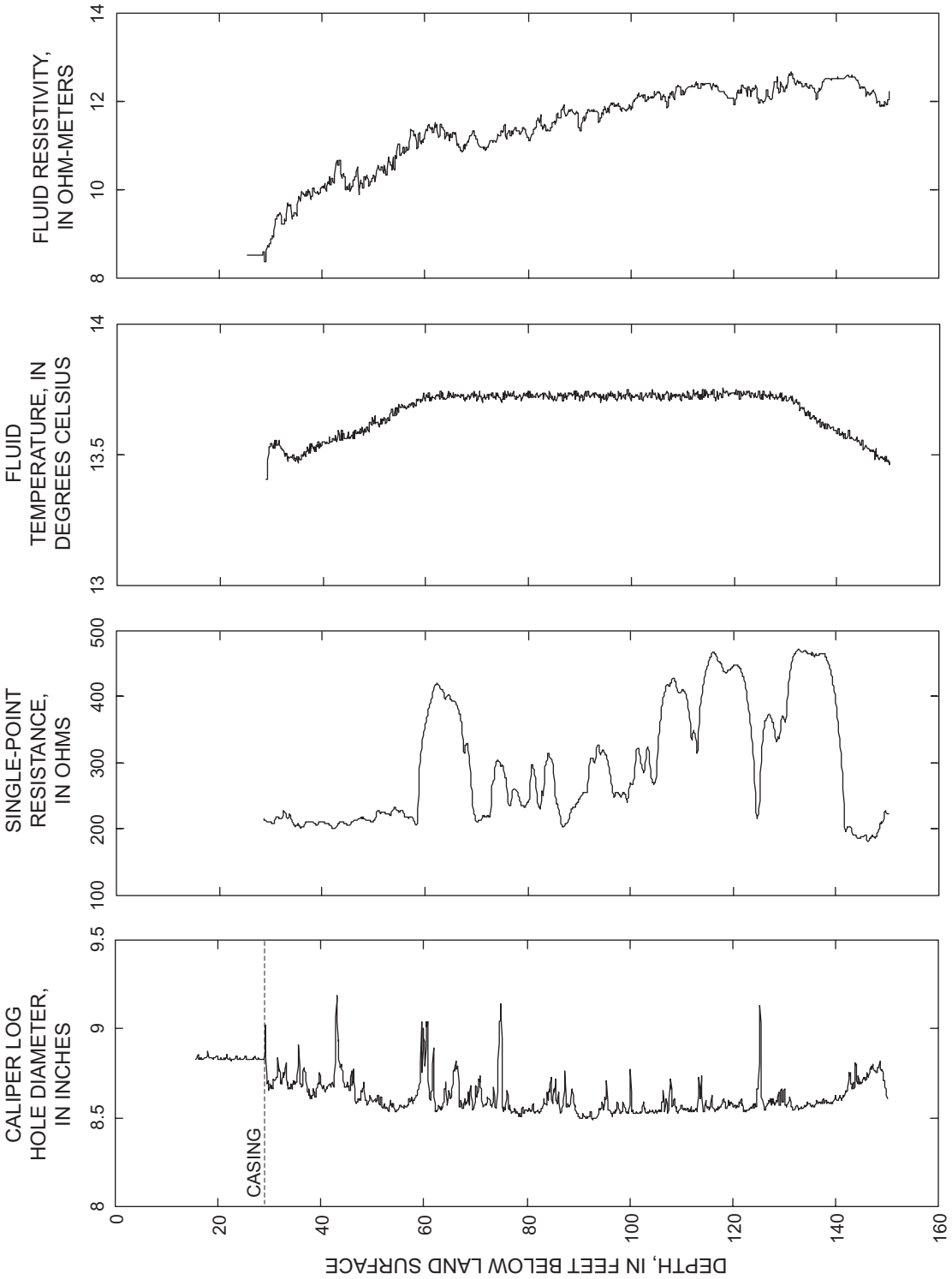

Figure 7. Borehole geophysical logs for well 01MW09 (MG-2143), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania, November 8, 2005.

indicate borehole flow and possible water-producing zones at about 60 and 125 ft bls.

Heatpulse-flowmeter measurements were made under nonpumping conditions (table 3). However, the water level in well 01MW09 was not static at the time the measurements were made. The geophysical logs and heatpulse-flowmeter measurements indicate water entered the borehole at a rate of about 1.1 gal/min through a large vertical fracture at 59-66 ft bls and flowed upward and downward. Water flowing upward exited the borehole through fractures above 44 ft bls. Water flowing downward exited through a horizontal fracture at 125 ft bls (fig. 8). Well 01MW09 was screened later from 120 to 130 ft bls to monitor the principle water-producing fracture at 125 ft bls.

Table 3. Heatpulse-flowmeter measurements made in well 01MW09 (MG-2143), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania, November 8, 2005.

Depth (feet below land surface)	Flow (gallons per minute)	Flow direction
38.2	0.07	Up
54.0	.05	Up
70.1	1.1	Down
80.1	1.2	Down
92.1	1.2	Down
120.2	1.2	Down

Interpretation of Aquifer-Isolation Tests

On the basis of the borehole geophysical logs, heatpulse-flowmeter measurements, and the borehole television survey, three intervals were selected for aquifer-isolation tests in well 01MW09 (table 4). A straddle-packer assembly was used to isolate discrete fractures to determine depth-discrete specific-capacity values and to obtain depth-discrete water samples. For the test of intervals 1 and 2, the distance between the bottom of the upper packer and the top of the lower packer was 11 ft, and both packers were inflated. For the test of interval 3, only the upper packer was inflated.

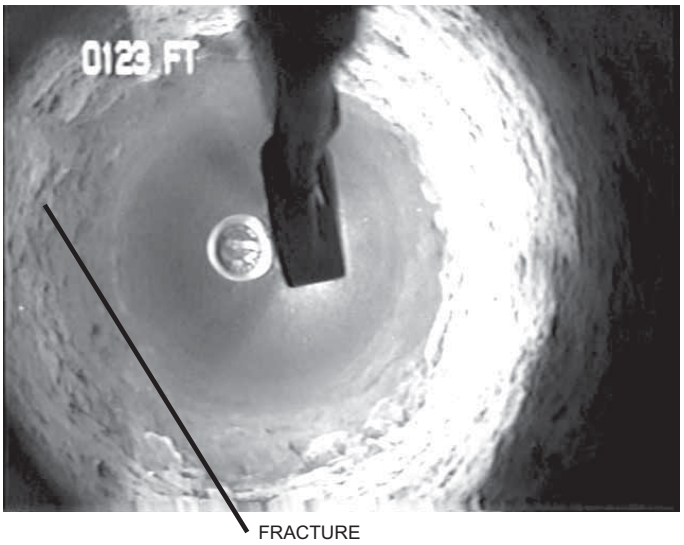

Figure 8. Image from borehole television survey showing horizontal fracture at 125 feet below land surface in well 01MW09 (MG-2143), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania, November 8, 2005.

Table 4. Intervals isolated during aquifer-isolation tests conducted in well 01MW09 (MG-2143), November 14-15, 2005, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[ft, feet; ft bls, feet below land surface; gal/min, gallons per minute; (gal/min)/ft, gallon per minute per foot of drawdown; —, no data]

Interval	Depth of isolated fracture (ft bls)	Bottom of upper packer (ft bls)	Top of lower packer (ft bls)	Average pumping rate (gal/min)	Drawdown (ft)	Specific capacity [(gal/min)/ft]
3	43	[1]50	Not inflated	—	—	—
2	59-62	57	68	2.1	4.80	0.44
1	125	120.5	131.5	1.3	60.07	.02

[1]Top of upper packer.

Interval 1 (120.5-131.5 Feet Below Land Surface)

For the aquifer-isolation test of interval 1, the bottom of the upper packer and the top of the lower packer were set at 120.5 and 131.5 ft bls, respectively, to isolate the fracture zone at 125 ft bls. Before packer inflation, the depth to water in the open borehole was 28.73 ft bls. Pumping began 71 minutes after the start of packer inflation. Just prior to the start of pumping, the depth to water in the isolated interval decreased 13.05 ft, the depth to water in the interval below the packers decreased 1.54 ft, and the depth to water in the interval above the packers increased 0.38 ft. This is consistent with the heat-pulse-flowmeter measurements, which showed downward flow to the fracture at 125 ft bls. The average pumping rate of interval 1 was 1.3 gal/min. Drawdown was 60.07 ft in the isolated interval (fig. 9). The specific capacity of interval 1 was 0.02 (gal/min)/ft.

Interval 2 (57-68 Feet Below Land Surface)

For the aquifer-isolation test of interval 2, the bottom of the upper packer and the top of the lower packer were set at 57 and 68 ft bls, respectively, to isolate the fracture zone at 59-62 ft bls. The average pumping rate of interval 2 was 2.1 gal/min. Drawdown was 4.80 ft in the isolated interval. The specific capacity of interval 2 was 0.44 (gal/min)/ft. The hydrographs for the isolated interval and interval below the packers (fig. 10) indicate no hydraulic connection between the two intervals. The water level in the interval above the packers continued to recover from pumping interval 2 and did not show a hydraulic connection between that interval and wells SW-1 and SW-2.

Interval 3 (29-50 Feet Below Land Surface)

The testing of intervals 2 and 3 was conducted with the packers set at the same depth. Interval 3 was tested before interval 2. For the aquifer-isolation test of interval 3, only the upper packer was inflated, isolating the interval between the top of the upper packer at 50 ft bls and the bottom of casing at 29 ft bls. The pump was placed above the upper packer. Interval 3 was quickly pumped dry. The water level in interval 3 recovered very slowly, and no water sample was collected.

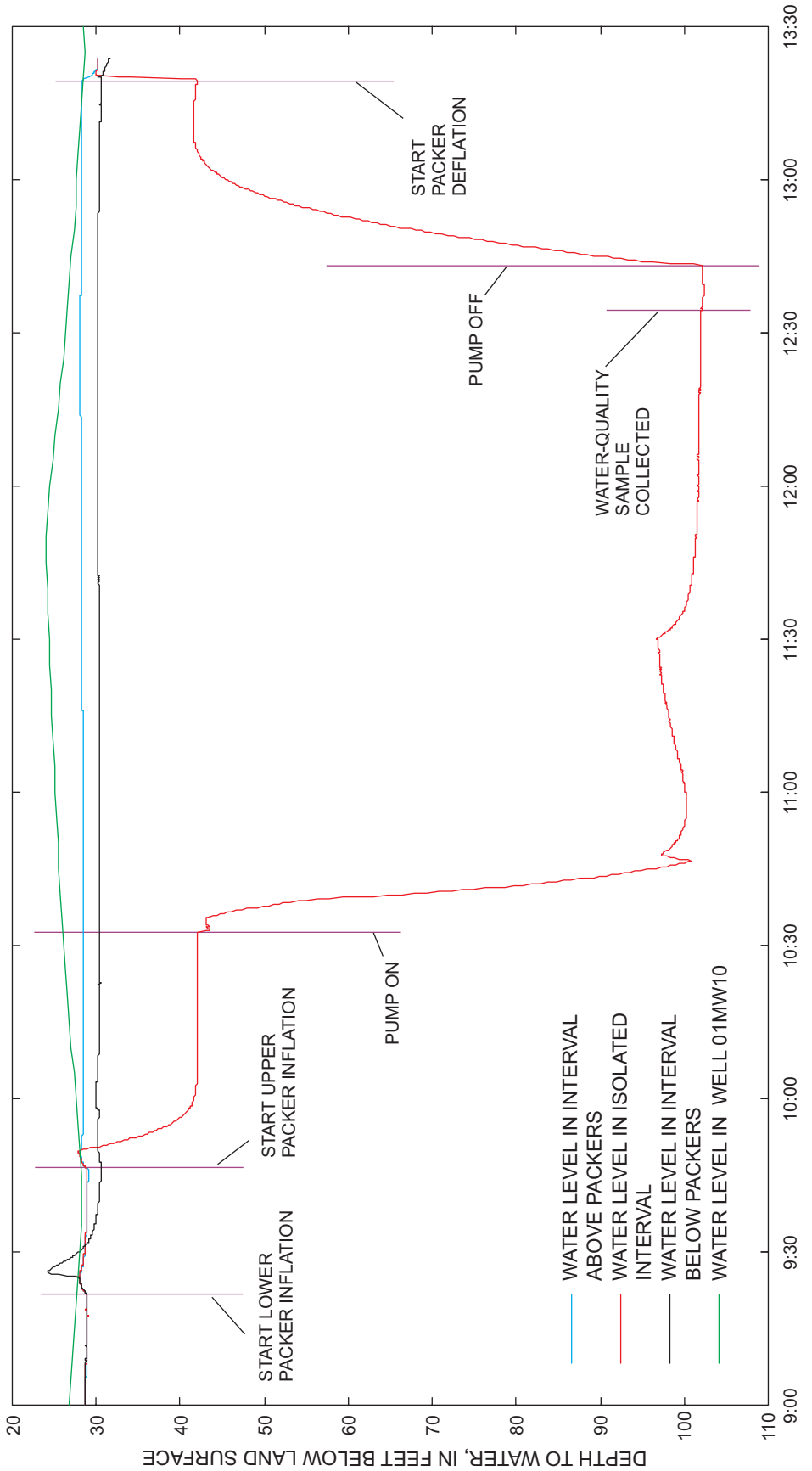

Figure 9. Hydrographs from aquifer-isolation test of interval 1 (120.5-131.5 feet below land surface) in well 01MW09 (MG-2143), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

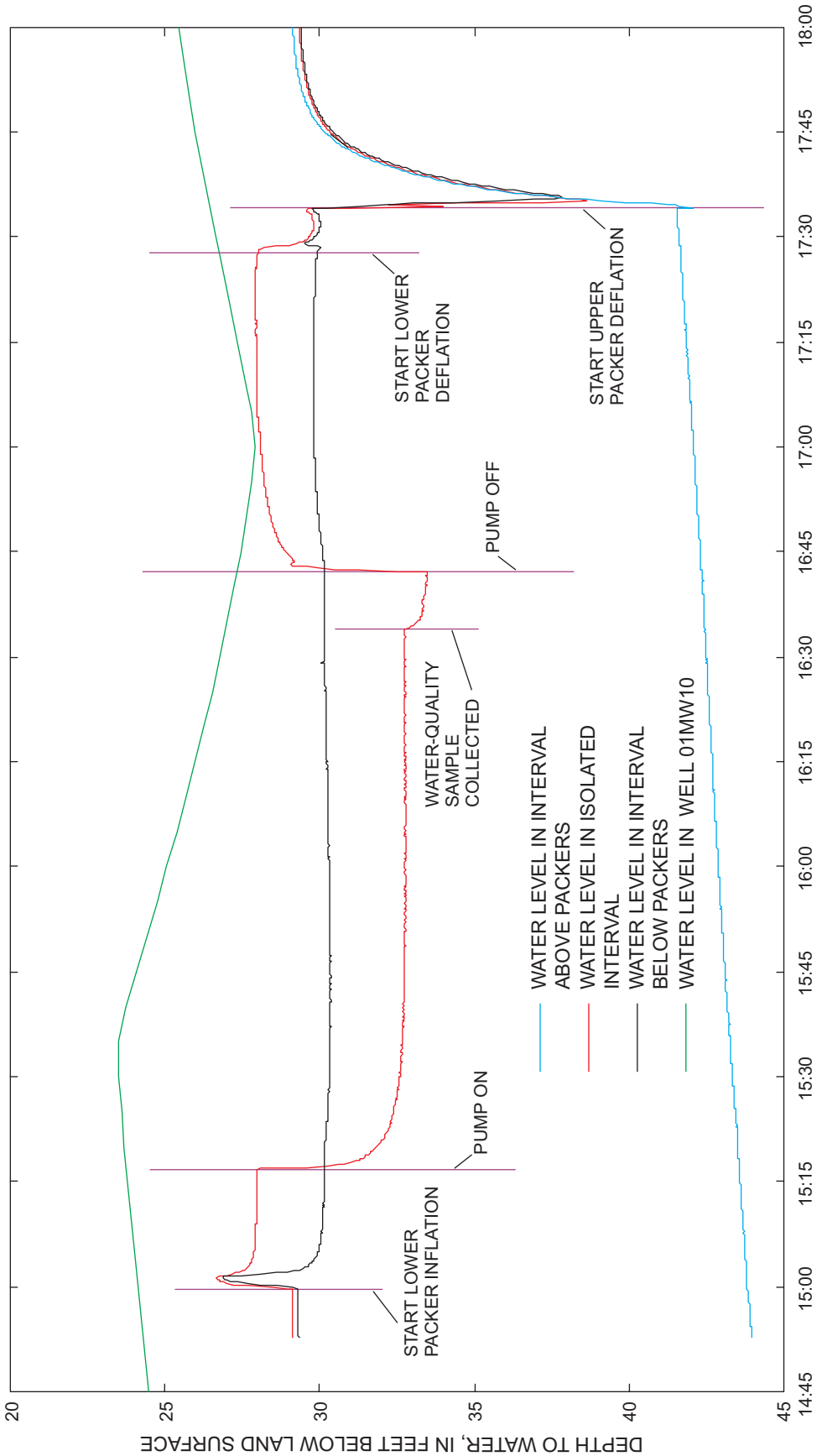

Figure 10. Hydrographs from aquifer-isolation test of interval 2 (57-68 feet below land surface) in well 01MW09 (MG-2143), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Vertical Distribution of Water-Quality Constituents

During the aquifer-isolation tests of intervals 1 and 2, water samples were collected by the USGS for field determinations and by ECOR Solutions, Inc., for analysis for VOCs. Analytical results were used to determine change in concentration with depth. VOCs detected in water samples are listed in table 5. Acetone and chloroform probably are laboratory contaminants. Concentrations of PCE (4.1 µg/L), trichlororethylene (TCE) (1.5 µg/L), and toluene (1.1 µg/L) above the laboratory reporting limit were detected only in the water sample from interval 1 (table 5). Interval 1 is in lithologic unit H (fig. 6), which had the greatest PCE concentration in well SW-1. Concentrations of dissolved oxygen and pH were higher in interval 1 than interval 2 (table 6).

Table 5. Concentrations of volatile organic compounds detected in water samples collected during aquifer-isolation tests in well 01MW09 (MG-2143), November 14-15, 2005, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[Laboratory results were provided by ECOR Solutions, Inc.; ft bls, feet below land surface; µg/L, micrograms per liter; ND, not detected, reporting limit is 5 µg/L for acetone and 1 µg/L for other constituents listed; J, estimated result less than reporting limit]

Interval	Depth of sample (ft bls)	Acetone (µg/L)	Chloroform (µg/L)	cis-1,2-dichloroethene (µg/L)	Tetrachloroethylene (µg/L)	Toluene (µg/L)	Trichloroethylene (µg/L)
2	57-68	6.2	2.4	ND	ND	ND	0.76 J
1	120.5-131.5	ND	3.4	0.71 J	4.1	1.1	1.5

Table 6. Selected water-quality constituents measured in the field in water samples collected during aquifer-isolation tests in well 01MW09 (MG-2143), November 14-15, 2005, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[ft bls, feet below land surface; mg/L, milligrams per liter; µS/cm at 25°C, microsiemens per centimeter at 25 degrees Celsius; C, Celsius; —, no data]

Interval	Depth of sample (ft bls)	Dissolved oxygen (mg/L)	pH (standard units)	Specific conductance (µS/cm at 25°C)	Temperature (degrees C)
2	57-68	1.5	6.5	514	13.9
1	120.5-131.5	3.3	7.9	—	16.9

Well 01MW10 (MG-2141)

Well 01MW10 was drilled about 695 ft southeast of well SW-1 and 990 ft northeast of well SW-2 (fig. 2). Projecting the location of well 01MW10 in the direction of dip places it about 485 ft updip of well SW-1.

Interpretation of Borehole Geophysical Logs

A suite of borehole geophysical logs (fig. 11) was collected in well 01MW10 by the USGS on November 4, 2005. The caliper log shows the well is 350 ft deep, cased to 39 ft bls, and major fractures are at 55-56, 71-86, 110, 215, 236, 266-272, and 310 ft bls. The fluid-temperature log shows sharp breaks in slope at about 80, 159, 181, and 312 ft bls. The fluid-resistivity log shows sharp breaks in slope at about 75, 181, and 240 ft bls. The fluid-temperature and fluid-resistivity logs together indicate borehole flow and possible water-producing zones at about 70-76, 159, 180, 234, and 310 ft bls. The borehole television survey identified water flowing into the borehole from a small vertical fracture at 153 ft bls.

Heatpulse-flowmeter measurements were made under nonpumping conditions (table 7). Because the rate of flow exceeded the upper measurable limit of the tool, smaller diameter diverters were used to allow some of the water to bypass the tool. Flow-rate measurements made with the 6- and 4-in. diverters are not accurate and are intended to show direction of flow only. The water level was rising during the first three measurements and was declining during the rest of the measurements. All measured flow was downward, except for the measurement made at 316.2 ft bls, which was upward. Water entered the borehole through fractures at 43, 55-56, 71-86, 110, 153, and 215 ft bls. Water exited the borehole through a horizontal fracture at 310 ft bls. Two screens were later set in well 01MW10, one at 148-158 ft bls to isolate the fracture at 153 ft bls (fig. 12A) and one at 300-320 ft bls to isolate the fracture at 310 ft bls (fig. 12B).

Table 7. Heatpulse-flowmeter measurements made in well 01MW10 (MG-2141), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania, November 4, 2005. Measurements are presented in the order in which they were made.

Depth (feet below land surface)	Flow (gallons per minute)	Flow direction	Water level (feet below land surface)
8-inch diverter			
46.0	0.35	Down	25.78
63.1	1.2	Down	25.60
6-inch diverter			
100.2	1.0	Down	25.00
4-inch diverter			
100.1	.34	Down	26.14
170.2	.38	Down	26.37
218.2	.25	Down	26.65
246.0	.26	Down	27.04
302.1	.06	Down	27.38
316.2	.06	Up	27.90
287.9	.09	Down	28.18
275.9	.11	Down	28.58
128.0	.66	Down	28.75
100.0	.62	Down	28.67

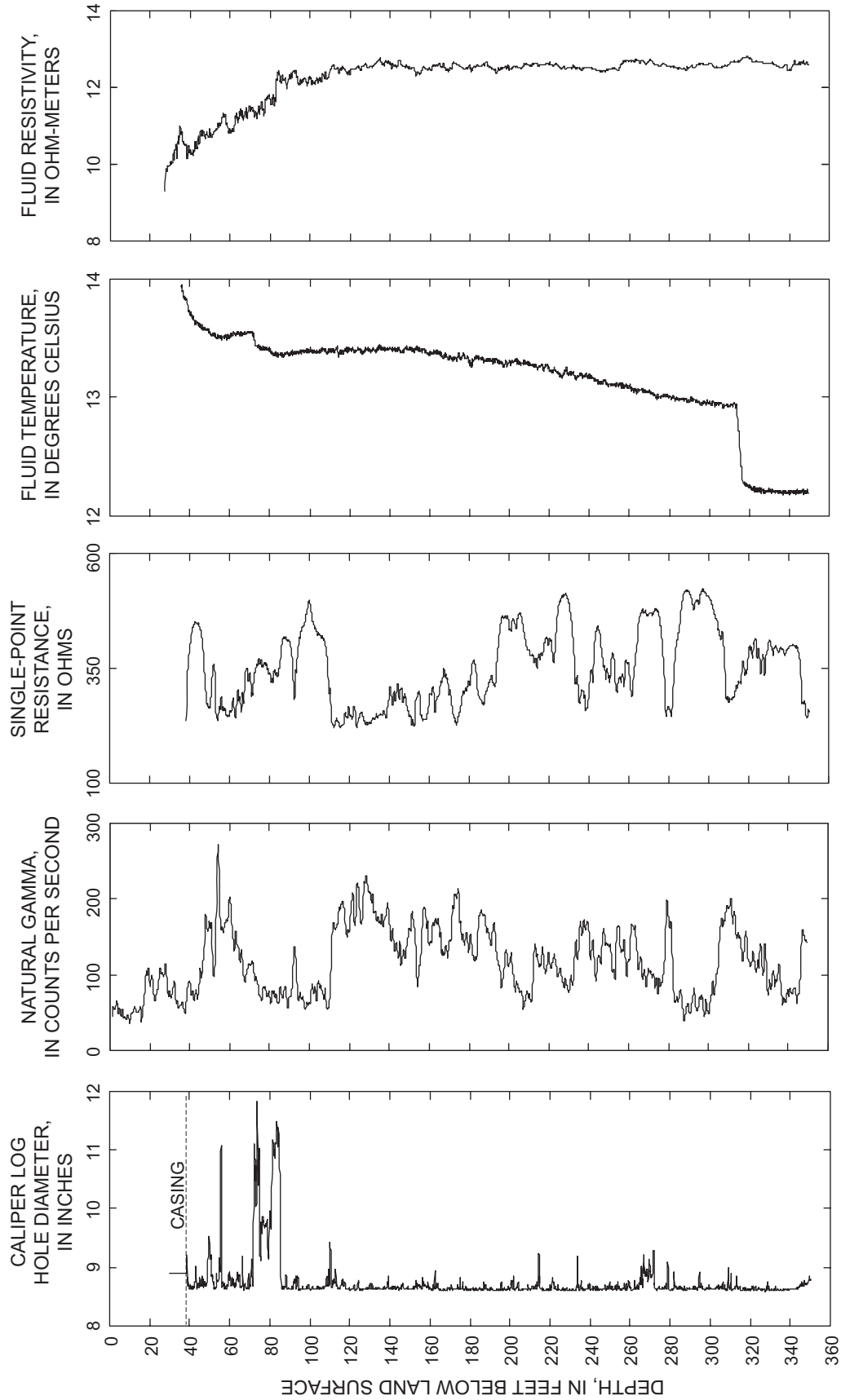

Figure 11. Borehole geophysical logs for well 01MW10 (MG-2141), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania, November 4, 2005.

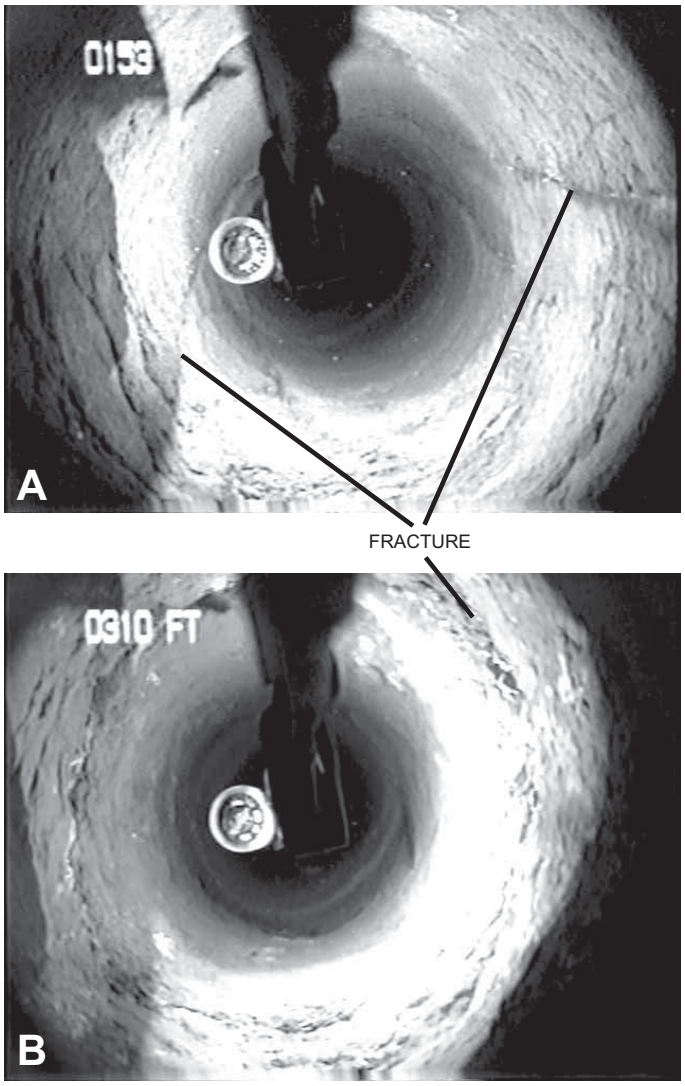

Figure 12. Images from borehole television survey showing (A) high-angle fracture at 153 feet below land surface and (B) horizontal fracture at 310 feet below land surface in well 01MW10 (MG-2141), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania, November 9, 2005.

Interpretation of Aquifer-Isolation Tests

On the basis of the borehole geophysical logs, heatpulse-flowmeter measurements, and the borehole television survey, eight intervals were selected for aquifer-isolation tests in well 01MW10 (table 8). A straddle-packer assembly was used to isolate discrete fractures to determine depth-discrete specific-capacity values and to obtain depth-discrete water samples. For the test of intervals 1 to 6, the distance between the bottom of the upper packer and the top of the lower packer was 11 ft, and both packers were inflated. For the test of interval 7, the distance between the bottom of the upper packer and the top of the lower packer was 23.2 ft, and both packers were inflated. For the test of interval 8, only the upper packer was inflated.

Interval 1 (305-316 Feet Below Land Surface)

For the aquifer-isolation test of interval 1, the bottom of the upper packer and the top of the lower packer were set at 305 and 316 ft bls, respectively, to isolate the fracture zone at 310 ft bls. Before packer inflation, the depth to water in the open borehole was 24.80 ft bls. After packer inflation, the depth to water in the isolated interval decreased 5.07 ft, the water level in the interval above the packers decreased 1.57 ft, and the water level in the interval below the packers decreased 1.79 ft. The water level in the isolated interval decreased 0.60 ft after the lower packer was inflated and decreased an additional 4.48 ft after the upper packer was inflated. This is consistent with the borehole geophysical logs, which indicated downward flow to the fracture at 310 ft bls. The water levels were still declining at the start of pumping of interval 1. Some of the decline was the response to the pumping of wells SW-1 and SW-2. The average pumping rate of interval 1 was 3.2 gal/min. Drawdown was 14.30 ft in the isolated interval, 4.23 ft in the interval below the packers, and 3.64 ft in the interval above the packers. The specific capacity of interval 1 was 0.22 (gal/min)/ft. The hydrographs for the interval above the packers, the isolated interval, and the interval below the packers (fig. 13) indicate a strong hydraulic connection between these intervals in well 01MW10 and between these intervals and wells SW-1 and SW-2.

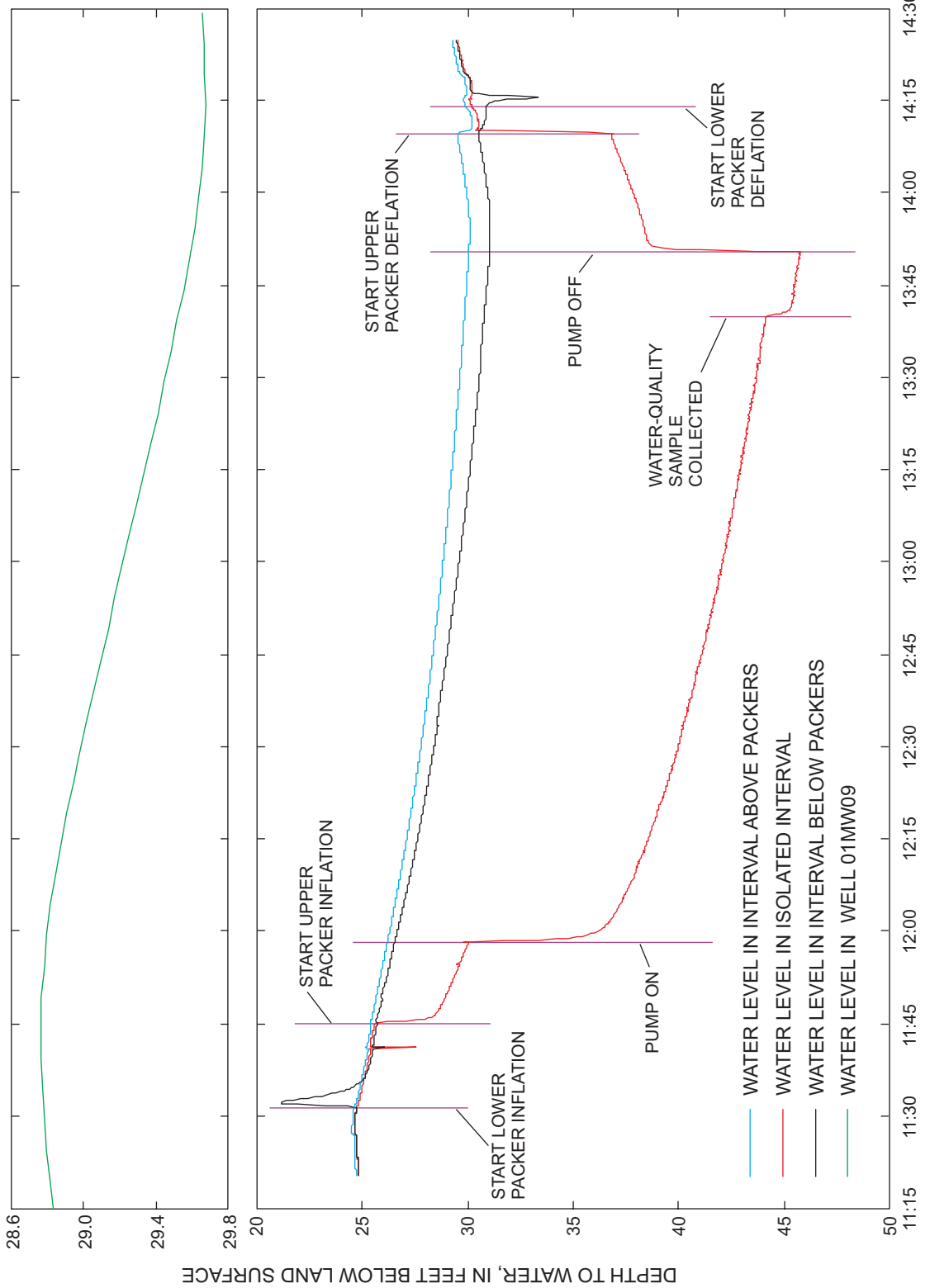

Figure 13. Hydrographs from aquifer-isolation test of interval 1 (305-316 feet below land surface) in well 01MW10 (MG-2141), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Table 8. Intervals isolated during aquifer-isolation tests conducted in well 01MW10 (MG-2141), November 15-21, 2005, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[ft, feet; ft bls, feet below land surface; gal/min, gallons per minute; (gal/min)/ft, gallons per minute per foot of drawdown; —, no data]

Interval	Depth of isolated fracture (ft bls)	Bottom of upper packer (ft bls)	Top of lower packer (ft bls)	Average pumping rate (gal/min)	Drawdown (ft)	Specific capacity [(gal/min)/ft]
8	43-56	[1]62.7	Not inflated	2.7	10.78	0.25
7	72-86	69.6	92.8	3.5	1.16	3.0
6	108-114	106	117	2.5	10.47	.24
5	153	148.7	159.7	1.2	23.54	.05
4	215	207	218	3.2	12.89	.25
3	233	230	241	—	—	—
2	266-272	263	274	3.9	10.35	.38
1	310	305	316	3.2	14.30	.22

[1]Top of upper packer.

Interval 2 (263-274 Feet Below Land Surface)

For the aquifer-isolation test of interval 2, the bottom of the upper packer and the top of the lower packer were set at 263 and 274 ft bls, respectively, to isolate the fracture zone at 266-272 ft bls. Before packer inflation, the water level in the borehole was declining (fig. 14). After inflation of the lower packer, the water level in the interval below the packers decreased 4.77 ft. After inflation of the upper packer, the water level in the isolated interval decreased 5.89 ft. This is consistent with the heatpulse-flowmeter measurements, which showed downward flow. Pumping of interval 2 began at an initial rate of 2.9 gal/min. After 2 minutes, the pumping rate was increased to 4 gal/min. The average pumping rate of interval 2 was 3.9 gal/min. The maximum drawdown in the isolated interval before the water level started to rise in response to the pumping of wells SW-1 and SW-2 was 10.35 ft. The estimated specific capacity of interval 2 using this maximum drawdown and the average pumping rate was 0.38 (gal/min)/ft. The hydrographs for the interval above the packers, the isolated interval, and the interval below the packers (fig. 14) indicate a strong hydraulic connection between these intervals in well 01MW10 and wells SW-1 and SW-2 and a weak hydraulic connection between the interval below the packers and the isolated interval.

Interval 3 (230-241 Feet Below Land Surface)

For the aquifer-isolation test of interval 3, the bottom of the upper packer and the top of the lower packer were set at 230 and 241 ft bls, respectively, to isolate the fracture at 233 ft bls. The isolated interval was rapidly dewatered. It was allowed to recover and then pumped again to obtain a water sample.

Interval 4 (207-218 Feet Below Land Surface)

For the aquifer-isolation test of interval 4, the bottom of the upper packer and the top of the lower packer were set at 207 and 218 ft bls, respectively, to isolate the fracture at 215 ft bls. Before packer inflation, the water level in the borehole was declining in response to pumping of wells SW-1 and SW-2. About the time the upper packer was inflated, the water level in the borehole began to rise in response to cessation of pumping of wells SW-1 and SW-2. After packer inflation, the depth to water in the isolated interval decreased 4.53 ft, the depth to water in the interval below the packers decreased 6.14 ft, and the depth to water in the interval above the packers increased 0.72 ft. This is consistent with the heatpulse-flowmeter measurements, which showed downward flow. Pumping of interval 4 began at an initial rate of 2.4 gal/min. After 1 minute, the pumping rate was increased to 3.4 gal/min. The average pumping rate of interval 4 was 3.2 gal/min. Water levels in all three intervals rose during the test in response to cessation of pumping of wells SW-1 and SW-2 (fig. 15). The estimated specific capacity of interval 4 using the maximum drawdown of 12.89 ft and the average pumping rate was 0.25 (gal/min)/ft. The hydrographs for the interval above the packers, the isolated interval, and the interval below the packers (fig. 15) indicate a strong hydraulic connection between these intervals in well 01MW10 and wells SW-1 and SW-2.

Interval 5 (148.7-159.7 Feet Below Land Surface)

For the aquifer-isolation test of interval 5, the bottom of the upper packer and the top of the lower packer were set at 148.7 and 159.7 ft bls, respectively, to isolate the fracture at 153 ft bls. After packer inflation, the depth to water in the isolated interval increased 7.6 ft, the depth to water in the interval below the packers decreased 4.26 ft, and the depth to water in the interval above the packers increased 2.58 ft. The water level was still rising in the isolated interval at the start of pumping of interval 5. This is consistent with the borehole television survey that showed water flowing into the borehole from this fracture. The average pumping rate of interval 5 was 1.2 gal/min. Water

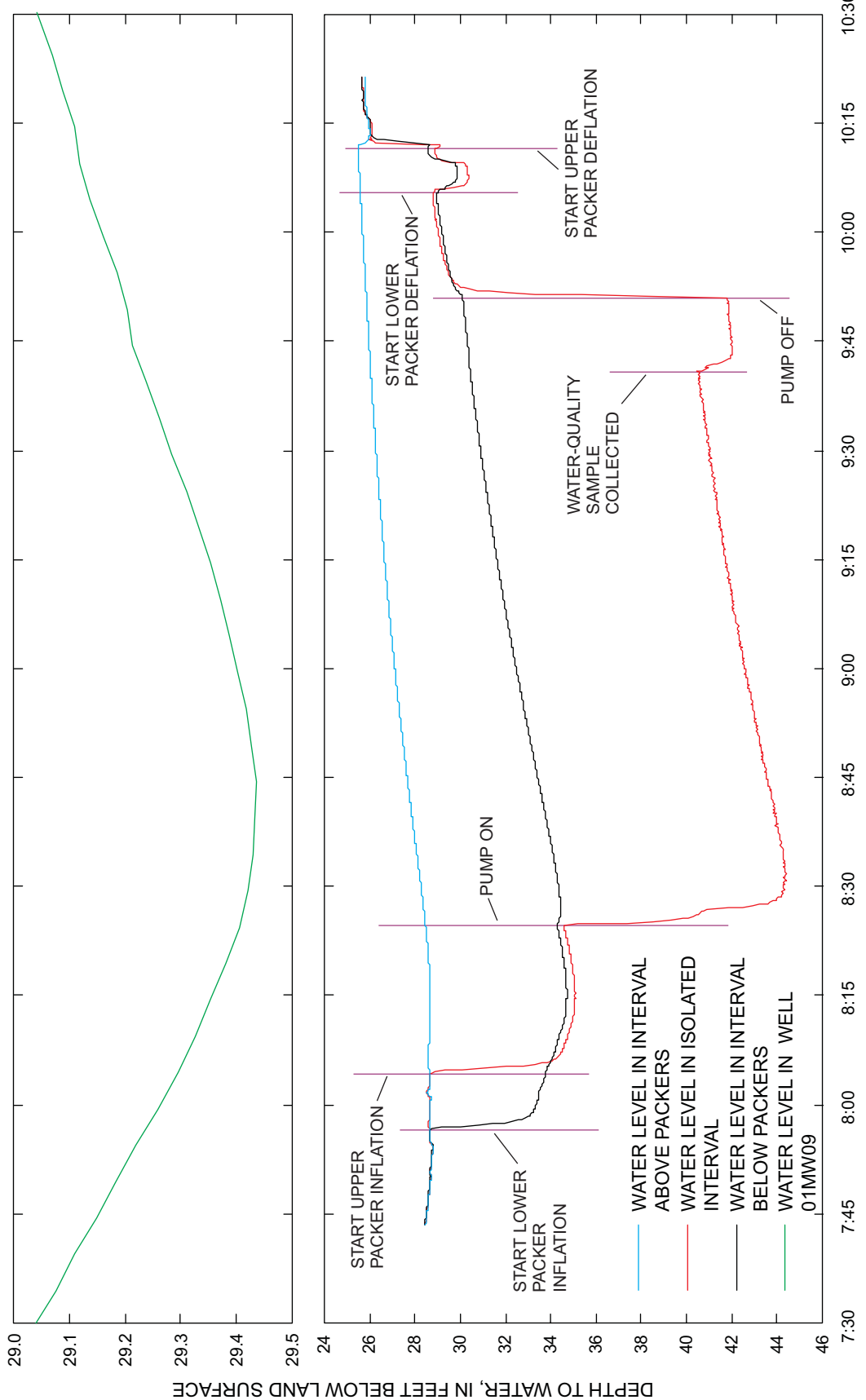

Figure 14. Hydrographs from aquifer-isolation test of interval 2 (263-274 feet below land surface) in well 01MW10 (MG-2141), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

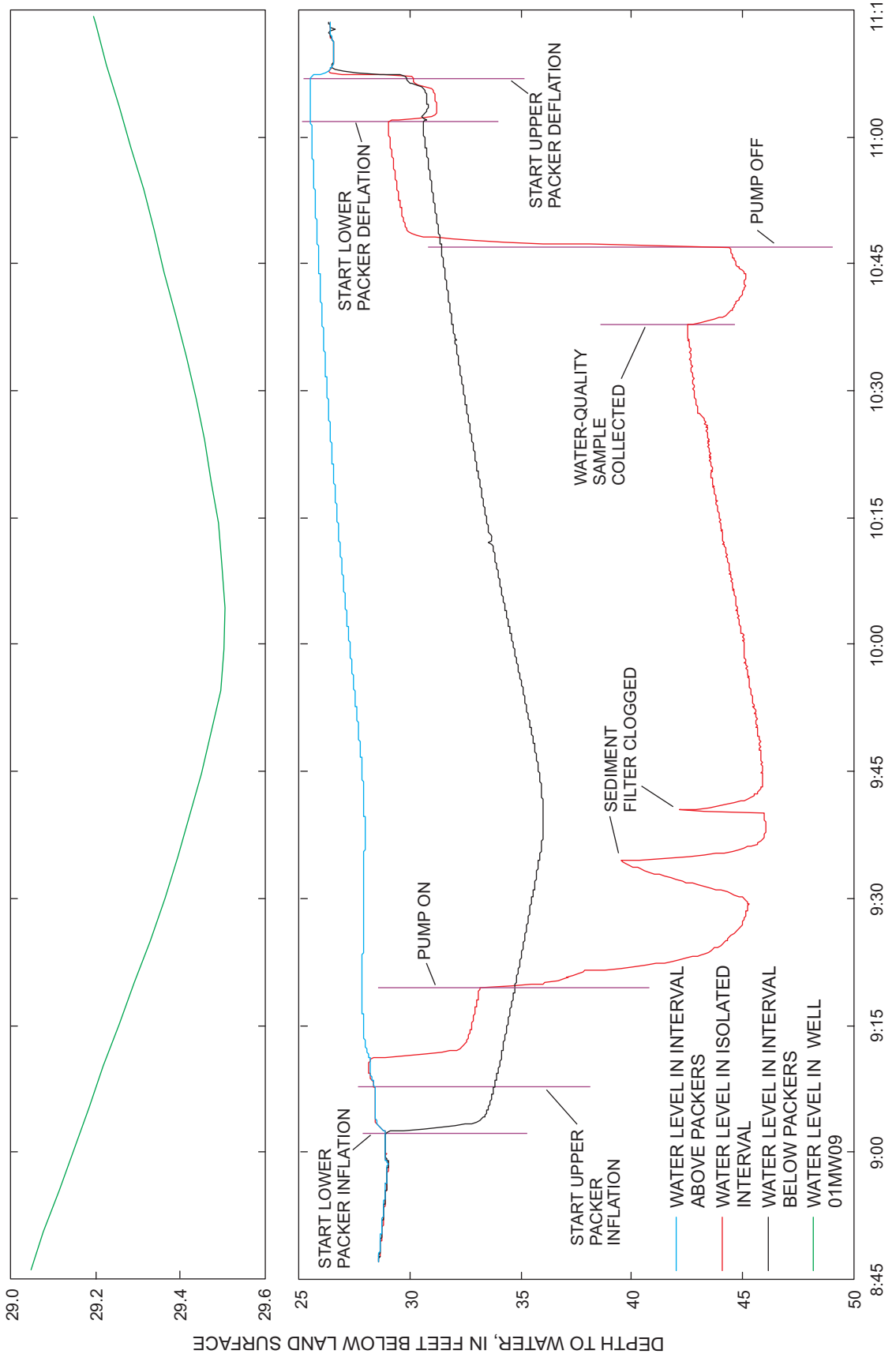

Figure 15. Hydrographs from aquifer-isolation test of interval 4 (207-218 feet below land surface) in well 01MW10 (MG-2141), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

levels rose during the test in response to cessation of pumping of wells SW-1 and SW-2 until 15:54 when water levels started to decline in response to pumping of wells SW-1 and SW-2 (fig. 16). Drawdown was 23.54 ft in the isolated interval. The estimated specific capacity was 0.05 (gal/min)/ft. The hydrographs for the interval above the packers, the isolated interval, and the interval below the packers (fig. 16) indicate a strong hydraulic connection between these intervals in well 01MW10 and wells SW-1 and SW-2.

Interval 6 (106-117 Feet Below Land Surface)

For the aquifer-isolation test of interval 6, the bottom of the upper packer and the top of the lower packer were set at 106 and 117 ft bls, respectively, to isolate the fracture zone at 108-114 ft bls. Water levels rose during the test in response to cessation of pumping of wells SW-1 and SW-2 until about 12:01 when the water levels started to decline in response to pumping of wells SW-1 and SW-2 (fig. 17). When the lower packer was inflated, the water level in the interval below the lower packer decreased 2.55 ft, and the water level above the lower packer increased. This is consistent with the heatpulse-flowmeter measurements, which showed downward flow. Pumping of interval 6 began at an initial rate of 1.5 gal/min. After 1 minute, the pumping rate was increased to 2.5 gal/min. The average pumping rate of interval 6 was 2.5 gal/min. Drawdown was 10.47 ft in the isolated interval. The estimated specific capacity was 0.24 (gal/min)/ft. The hydrographs for the interval above the packers, the isolated interval, and the interval below the packers (fig. 17) indicate a strong hydraulic connection between these intervals in well 01MW10 and wells SW-1 and SW-2 and a very slight hydraulic connection between the isolated interval and the interval above the packers.

Interval 7 (69.6-92.8 Feet Below Land Surface)

For the aquifer-isolation test of interval 7, the bottom of the upper packer and the top of the lower packer were set at 69.6 and 92.8 ft bls, respectively, to isolate the fracture zone at 72-86 ft bls. Water levels rose prior to the test and during the test in response to cessation of pumping of wells SW-1 and SW-2 until about 16:06 when the water levels started to decline in response to pumping of wells SW-1 and SW-2. When the lower packer was inflated, the water level in the interval below the lower packer decreased 1.84 ft, and the water level above the lower packer increased (fig. 18). When the upper packer was inflated, the water level above the upper packer rapidly rose until pumping of interval 7 began. Pumping of interval 7 began at an initial rate of 2.7 gal/min. After 2 minutes, the pumping rate was increased to 3.8 gal/min. The average pumping rate of interval 7 was 3.5 gal/min. The estimated specific capacity of interval 7 using the maximum drawdown of 1.16 ft and the average pumping rate was 3.0 (gal/min)/ft. Water levels in all intervals rose in response to cessation of pumping of wells SW-1 and SW-2 throughout most of the test, indicating a strong hydraulic connection to wells SW-1 and SW-2. The water level in the interval above the packers showed a response when the pump in the isolated zone was turned off, indicating a slight hydraulic connection between the isolated interval and the interval above the packers. The water level in the interval below the lower packer began to decline in response to the start of pumping of wells SW-1 and SW-2 and did not respond to the cessation of pumping in the isolated zone, indicating no hydraulic connection between the interval below the packers and the isolated interval.

Interval 8 (38-62.7 Feet Below Land Surface)

For the aquifer-isolation test of interval 8, only the upper packer was inflated. The top of the upper packer was set at 62.7 ft bls to isolate the interval between the bottom of the casing (38 ft bls) and 62.7 ft bls, which includes the fracture zone at 43-56 ft bls. Prior to packer inflation, the water level in the borehole was rising in response to cessation of pumping of wells SW-1 and SW-2 (fig. 19). When the packer was inflated, the water level in the isolated interval (the interval above the packer) increased 3.24 ft. The water level in the interval below the packer continued to rise throughout the test until about 11:49 when the water level began to decline in response to the pumping of wells SW-1 and SW-2. Pumping of interval 8 began at an initial rate of 2.1 gal/min. After 4 minutes, the pumping rate was increased to 2.8 gal/min. The average pumping rate of interval 8 was 2.7 gal/min. Drawdown was 10.78 ft in the isolated interval (fig. 19). The specific capacity of interval 8 was 0.25 (gal/min)/ft. The water level in the interval below the packer showed no response to pumping the isolated interval and showed a very strong hydraulic connection with wells SW-1 and SW-2.

Vertical Distribution of Water-Quality Constituents

During each aquifer-isolation test, water samples were collected by the USGS for field determinations of water-quality constituents and by ECOR Solutions, Inc., for analysis for VOCs. VOCs detected in water samples collected during aquifer-isolation tests are listed in table 9. Acetone and chloroform probably are laboratory contaminants. The concentration of toluene was less than 1 µg/L for all samples. The highest concentrations of PCE (62 µg/L), TCE (4.5 µg/L), and cis-1,2-dichloroethene (3.4 µg/L) were in water samples collected from interval 5. Interval 5 is in lithologic unit G (fig. 6). The PCE concentration of a sample from lithologic unit G in well SW-1 was 34 µg/L (fig. 6). Concentrations of VOCs from intervals 1 and 2 were similar. The second greatest concentrations of PCE were from intervals 1 and 2 (both 30 µg/L). Intervals 1 and 2 are in lithologic units K and L, respectively (fig. 6). The PCE concentration of a sample from lithologic unit M in well SW-1 was 21 µg/L (fig. 6). No VOCs were detected in the shallowest interval (interval 8). The water sample from interval 5 had the lowest temperature (13.0 °C) and concentration of dissolved oxygen (1.9 mg/L) and the highest concentration of VOCs, pH (7.2), and specific conductance (855 µS/cm) of the intervals sampled (table 10).

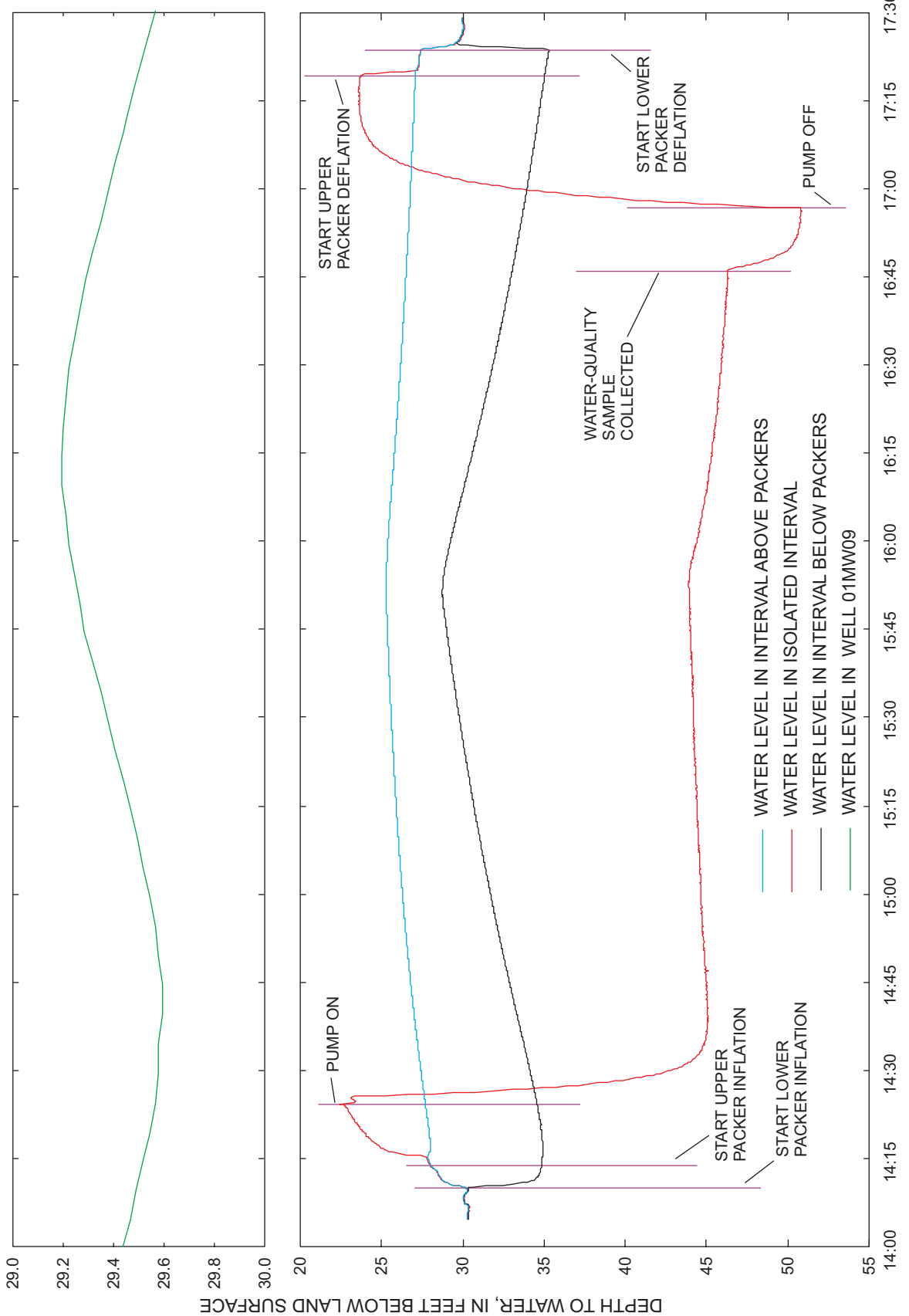

Figure 16. Hydrographs from aquifer-isolation test of interval 5 (148.7-159.7 feet below land surface) in well 01MW10 (MG-2141), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

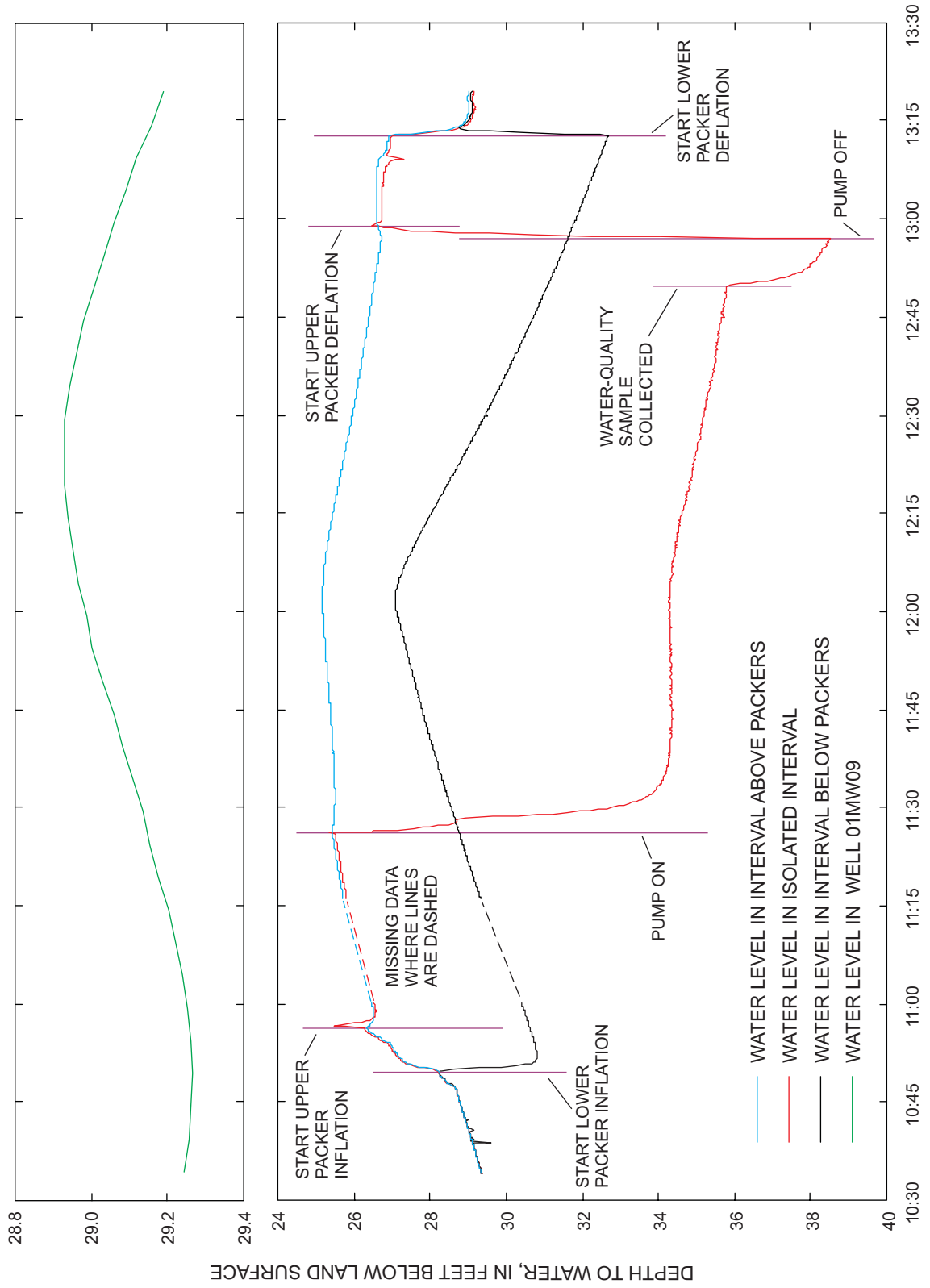

Figure 17. Hydrographs from aquifer-isolation test of interval 6 (106-117 feet below land surface) in well 01MW10 (MG-2141), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

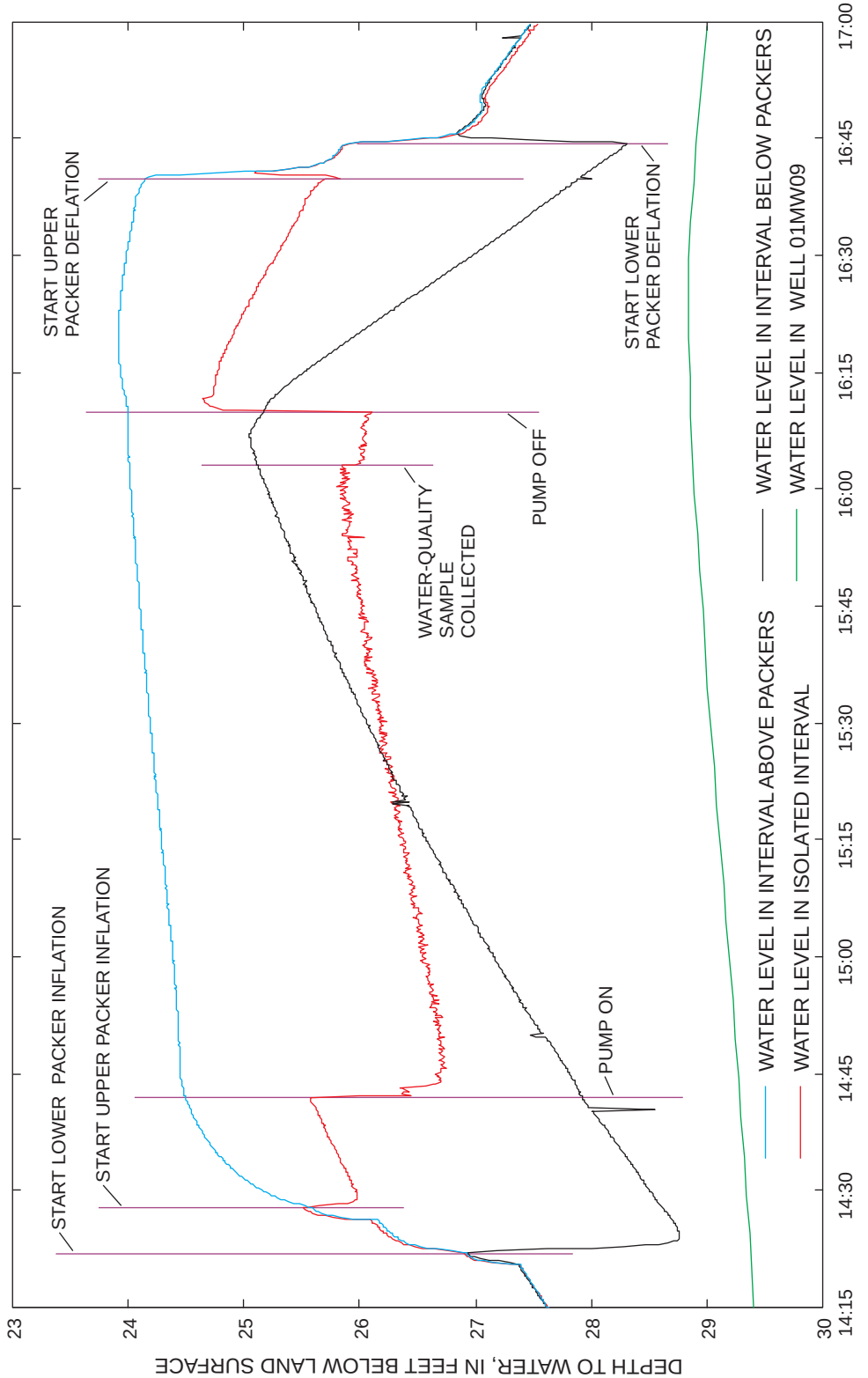

Figure 18. Hydrographs from aquifer-isolation test of interval 7 (69.6-92.9 feet below land surface) in well 01MW10 (MG-2141), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

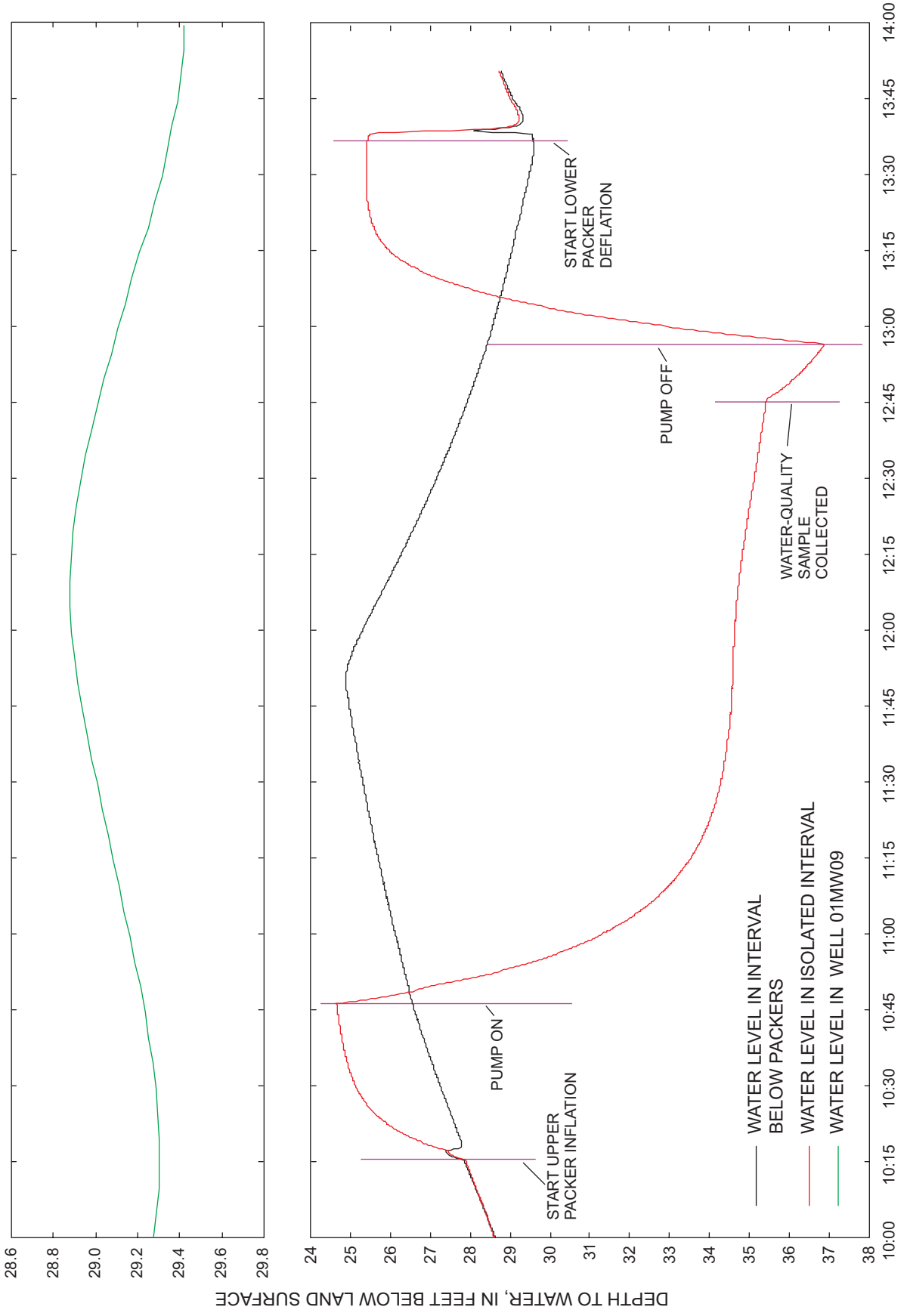

Figure 19. Hydrographs from aquifer-isolation test of interval 8 (38-62.7 feet below land surface) in well 01MW10 (MG-2141), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Table 9. Concentrations of volatile organic compounds detected in water samples collected during aquifer-isolation tests in well 01MW10 (MG-2141), November 15-21, 2005, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[Laboratory results were provided by ECOR Solutions, Inc.; ft bls, feet below land surface; µg/L, micrograms per liter; ND, not detected, reporting limit is 5 µg/L for acetone and 1 µg/L for other constituents listed; B, constituent detected in blank; J, estimated result less than reporting limit]

Interval	Depth of sample (ft bls)	Acetone (µg/L)	Chloroform (µg/L)	cis-1,2-dichloro-ethene (µg/L)	Tetrachloro-ethylene (µg/L)	Toluene (µg/L)	Trichloro-ethylene (µg/L)
8	38-62.7	ND	ND	ND	ND	0.98 BJ	ND
7	69.6-92.8	3.3 J	ND	ND	9.8	.66 BJ	0.94 J
6	106-117	9.0	ND	0.77 J	23	.67 BJ	2.3
5	148.7-159.7	ND	7.1	3.4	62	ND	4.5
4	207-218	2.9 J	.96 J	1.7	24	.43 J	2.8
3	230-241	2.8 J	1.1	2.0	27	.46 J	3.6
2	263-274	2.7 J	1.1	2.1	30	ND	3.3
1	305-316	3.1 J	1.0	2.0	30	ND	3.0

Table 10. Selected water-quality constituents measured in the field in water samples collected during aquifer-isolation tests in well 01MW10 (MG-2141), November 15-21, 2005, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[ft bls, feet below land surface; mg/L, milligrams per liter; µS/cm at 25°C, microsiemens per centimeter at 25 degrees Celsius; C, Celsius]

Interval	Depth of sample (ft bls)	Dissolved oxygen (mg/L)	pH (standard units)	Specific conductance (µS/cm at 25°C)	Temperature (degrees C)
8	38-62.7	6.2	6.1	673	14.7
7	69.6-92.8	6.8	6.5	629	14.4
6	106-117	5.7	7.1	598	13.6
5	148.7-159.7	1.9	7.2	855	13.0
4	207-218	5.1	6.8	690	13.6
3	230-241	4.8	7.1	761	14.1
2	263-274	5.2	7.1	767	13.7
1	305-316	5.1	7.1	776	13.8

Interpretation of Borehole Geophysical Logs, Aquifer-Isolation Tests, and Water-Quality Data at Site 3

Well 03MW08 (MG-2142)

Well 03MW08 is downgradient of Site 5 and upgradient of Site 3 (fig. 3). It is considered to be part of Site 3.

Interpretation of Borehole Geophysical Logs

A suite of borehole geophysical logs (fig. 20) was collected in well 03MW08 by the USGS on November 3, 2005. The caliper log shows the well is 222 ft deep, cased to 38 ft bls, and major fractures are at 49, 79, 121, 124, 138, 159, 169, and 191-193 ft bls. The fluid-temperature log shows a sharp break at about 170 ft bls. The fluid-resistivity log shows sharp breaks at about 80, 128, 143, and 190 ft bls.

Heatpulse-flowmeter measurements were made under nonpumping and pumping conditions (table 11). The geophysical logs and heatpulse-flowmeter measurements indicate water entered the borehole at a rate of 0.3 gal/min through the fracture zone above 70 ft bls and flowed downward. Additional water (0.3 gal/min) entered the borehole through a horizontal fracture at 80 ft bls and flowed downward. Water flowing downward exited the borehole through horizontal fractures at 121-124, 138, and below 164 ft bls (fig. 21). Well 03MW08 was screened later from 38-68 ft bls to monitor the water-producing fracture zone above 68 ft bls (fig. 21B) and from 163 to 173 ft bls to monitor the fracture at 169 ft bls (fig. 21A).

Table 11. Heatpulse-flowmeter measurements made in well 03MW08 (MG-2142), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania, November 3, 2005. Measurements are presented in the order in which they were made.

[—, no flow]

Depth (feet below land surface)	Flow (gallon per minute)	Flow direction
Nonpumping conditions		
55.2	0.19	Down
65.1	.23	Down
71.2	.29	Down
100.1	.59	Down
116.6	.60	Down
130.1	.53	Down
150.2	.35	Down
157.2	.34	Down
164.4	.36	Down
207.1	0	—
42.1	.34	Down
42.3	.26	Down
55.2	.26	Down
42.3	.26	Down
Pumping conditions		
54.9	.33	Up
65.1	.31	Up
71.0	.34	Up

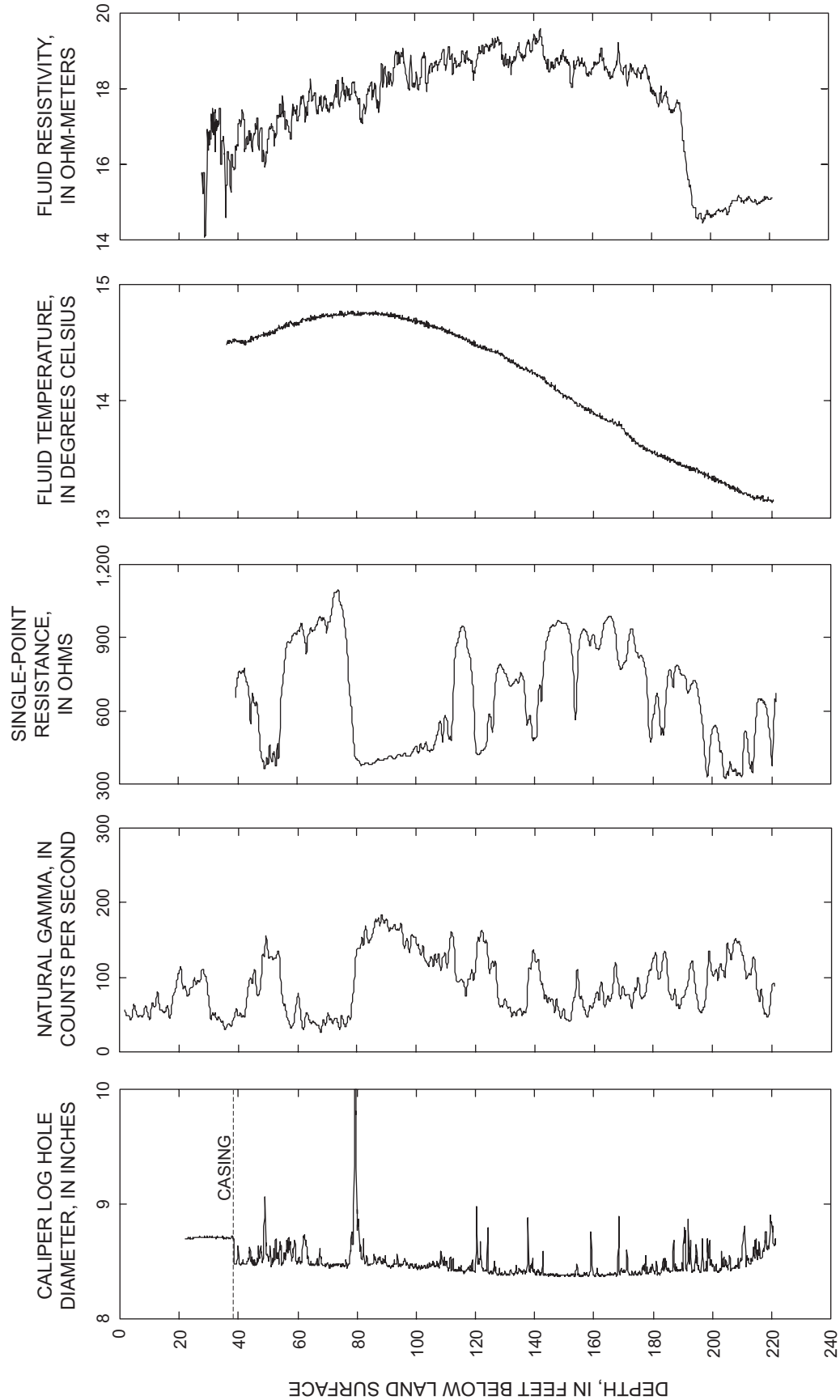

Figure 20. Borehole geophysical logs for well 03MW08 (MG-2142), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania, November 3, 2005.

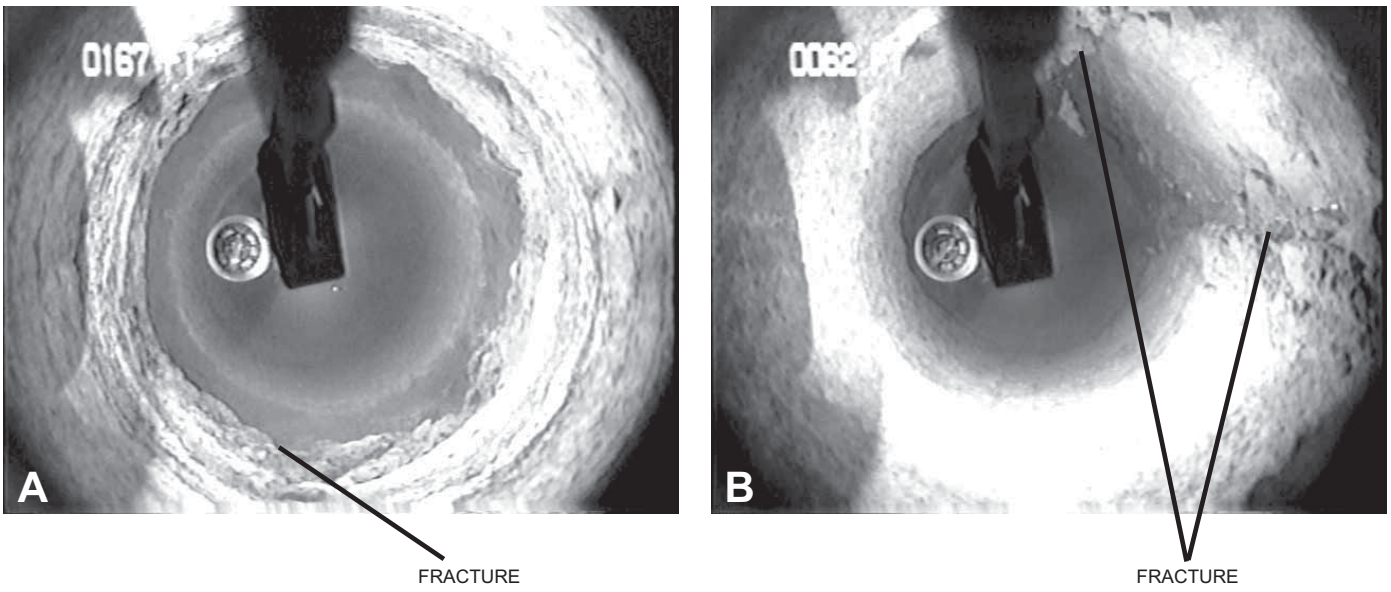

Figure 21. Images from borehole television survey showing (A) horizontal fracture at 169 feet below land surface and (B) vertical fracture at 64 feet below land surface in well 03MW08I (MG-2142), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania, November 8, 2005.

Interpretation of Aquifer-Isolation Tests

On the basis of the borehole geophysical logs, heatpulse-flowmeter measurements, and the borehole television survey, six intervals were selected for aquifer-isolation tests in well 03MW08 (table 12). A straddle-packer assembly was used to isolate discrete fractures to determine depth-discrete specific-capacity values and to obtain depth-discrete water samples. For the tests of intervals 2-5, the distance between the bottom of the upper packer and the top of the lower packer was 11 ft, and both packers were inflated. For the tests of intervals 1 and 6, only the upper packer was inflated. During the tests, the water level was measured in well 05MW13I, which is screened from 127 to 142 ft bls.

Table 12. Intervals isolated during aquifer-isolation tests conducted in well 03MW08 (MG-2142), November 22-28, 2005, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[ft, feet; ft bls, feet below land surface; gal/min, gallons per minute; (gal/min)/ft, gallons per minute per foot of drawdown]

Interval	Depth of isolated fracture (ft bls)	Bottom of upper packer (ft bls)	Top of lower packer (ft bls)	Average pumping rate (gal/min)	Drawdown (ft)	Specific capacity [(gal/min)/ft]
6	Above 68.5	[1]68.5	Not inflated	1.0	23.12	0.04
5	80	75.5	86.5	1.6	17.12	.09
4	124-125	124.5	135.5	2.4	6.36	.38
3	138	136.5	145.5	2.9	3.62	.80
2	169	162	173	4.0	2.60	1.5
1	Below 178.2	[2]178.2	Not inflated	5.3	28.95	.18

[1]Top of upper packer.

[2]Bottom of upper packer.

Interval 1 (178.2-222 Feet Below Land Surface)

For the aquifer-isolation test of interval 1, the bottom of the upper packer was set at 178.2 ft bls to isolate the lower section of the borehole. The packer was inflated on November 28 and left inflated overnight. On November 29, the depth to water above and below the packer was 26.60 ft bls, indicating no difference in hydraulic head between the two intervals. This is consistent with the heatpulse-flowmeter measurements, which showed no flow in this section of the borehole. The average pumping rate was 5.3 gal/min. Drawdown was 28.95 ft in the isolated interval and 0.64 ft in the interval above the packer. The specific capacity of interval 1 was 0.18 (gal/min)/ft. The hydrographs for the interval above the packer and the isolated interval (fig. 22) indicate a weak hydraulic connection between the intervals. The water level in well 05MW13I declined 0.31 ft in response to pumping interval 1, indicating a hydraulic connection between interval 1 and well 05MW13I.

Interval 2 (162-173 Feet Below Land Surface)

For the aquifer-isolation test of interval 2, the bottom of the upper packer and the top of the lower packer were set at 162 and 173 ft bls, respectively, to isolate the fracture zone at 169 ft bls. Before packer inflation, the depth to water in the open borehole was 26.64 ft bls. After packer inflation, the depth to water in the isolated interval was 26.64 ft bls (no change), the depth to water in the interval below the packers increased 0.07 ft, and the depth to water in the interval above the packers increased 0.05 ft. This is consistent with the heatpulse-flowmeter measurements, which showed downward flow to the fracture at 169 ft bls. Pumping began at an initial rate of 3.0 gal/min. After 2 minutes, the pumping rate was increased to 4.1 gal/min. The average pumping rate was 4.0 gal/min. Drawdown was 2.60 ft in the isolated interval, 0.57 ft in the interval below the packers, and 0.50 ft in the interval above the packers. The specific capacity of interval 2 was 1.5 (gal/min)/ft. The hydrographs for the interval above the packers, the isolated interval, and the interval below the packers (fig. 23) indicate a hydraulic connection between the isolated interval and the intervals above and below the packers. The water level in well 05MW13I declined 0.18 ft in response to pumping interval 2, indicating a hydraulic connection between interval 2 and well 05MW13I.

Interval 3 (136.5-145.5 Feet Below Land Surface)

For the aquifer-isolation test of interval 3, the bottom of the upper packer and the top of the lower packer were set at 136.5 and 145.5 ft bls, respectively, to isolate the fracture zone at 138 ft bls. Before packer inflation, the depth to water in the open borehole was 26.64 ft bls. After packer inflation, the depth to water in the isolated interval decreased 0.03 ft; the depth to water in the interval below the packers increased 0.01 ft; and the depth to water in the interval above the packers increased 0.13 ft. This is generally consistent with the heatpulse-flowmeter measurements, which showed downward flow to the fracture at 138 ft bls. Pumping began at an initial rate of 2.5 gal/min. After 3 minutes, the pumping rate was increased to 3.0 gal/min. The average pumping rate was 2.9 gal/min. Drawdown was 3.62 ft in the isolated interval, 0.36 ft in the interval below the packers, and 0.64 ft in the interval above the packers. The specific capacity of interval 3 was 0.80 (gal/min)/ft. The hydrographs for the interval above the packers, the isolated interval, and the interval below the packers (fig. 24) indicate a hydraulic connection between the isolated interval and the intervals above and below the packers. The water level in well 05MW13I declined 0.15 ft in response to pumping interval 3, indicating a hydraulic connection between interval 3 and well 05MW13I.

Interval 4 (124.5-135.5 Feet Below Land Surface)

For the aquifer-isolation test of interval 4, the bottom of the upper packer and the top of the lower packer were set at 124.5 and 135.5 ft bls, respectively, to isolate the fracture zone at 124-125 ft bls. After packer inflation, the depth to water in the isolated interval did not change, the depth to water in the interval below the packers increased 0.03 ft, and the depth to water in the interval above the packers increased 0.75 ft. This is consistent with the heatpulse-flowmeter measurements, which showed downward flow. The average pumping rate was 2.4 gal/min. Drawdown was 6.36 ft in the isolated interval, 0.27 ft in the interval below the packers, and 0.31 ft in the interval above the packers. The specific capacity of interval 4 was 0.38 (gal/min)/ft. The hydrographs for the interval above the packers, the isolated interval, and the interval below the packers (fig. 25) indicate a weak hydraulic connection among the intervals. The water level in well 05MW13I declined 0.14 ft in response to pumping interval 4, indicating a hydraulic connection between interval 4 and well 05MW13I.

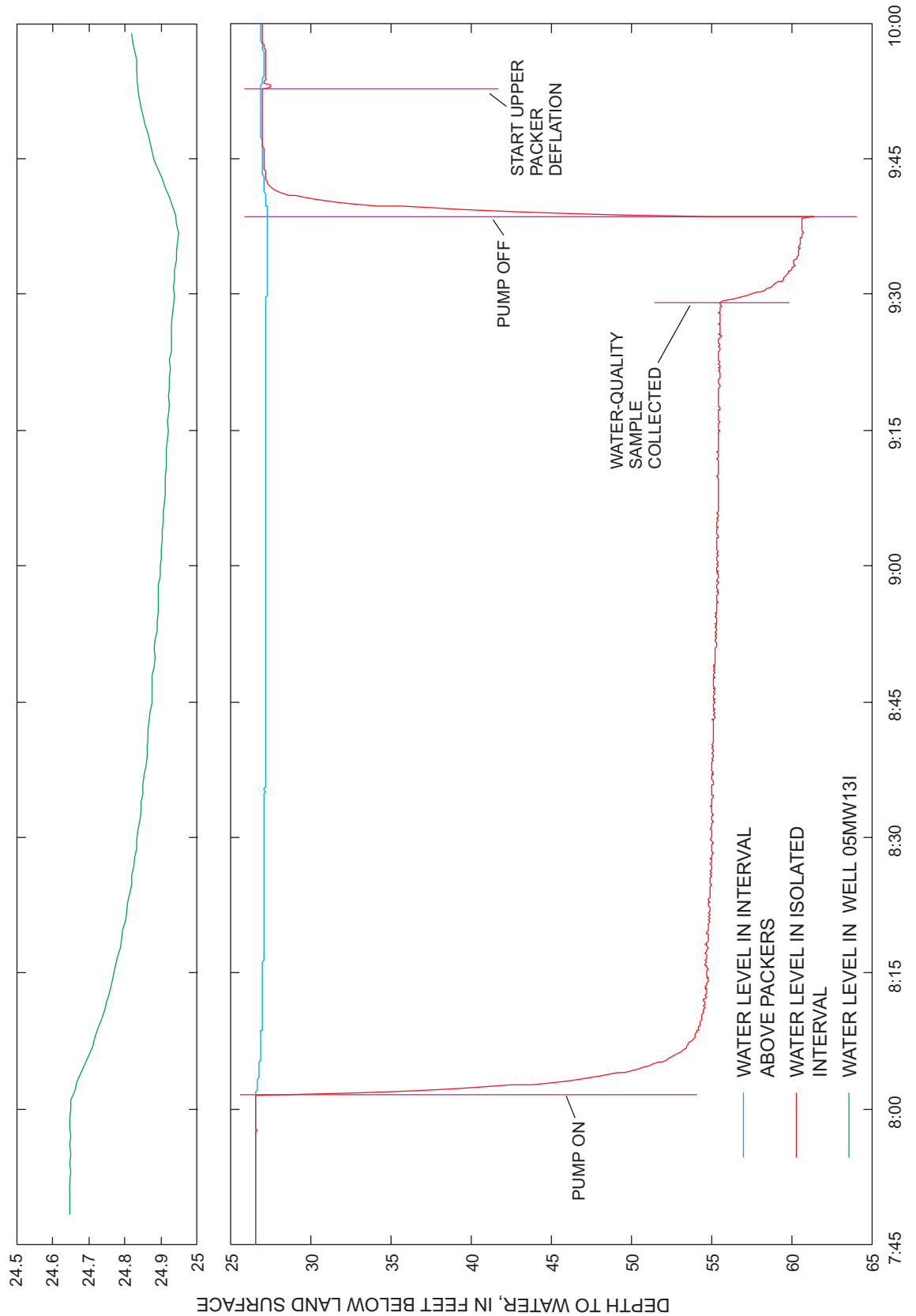

Figure 22. Hydrographs from aquifer-isolation test of interval 1 (178.2-222 feet below land surface) in well 03MW08 (MG-2142), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

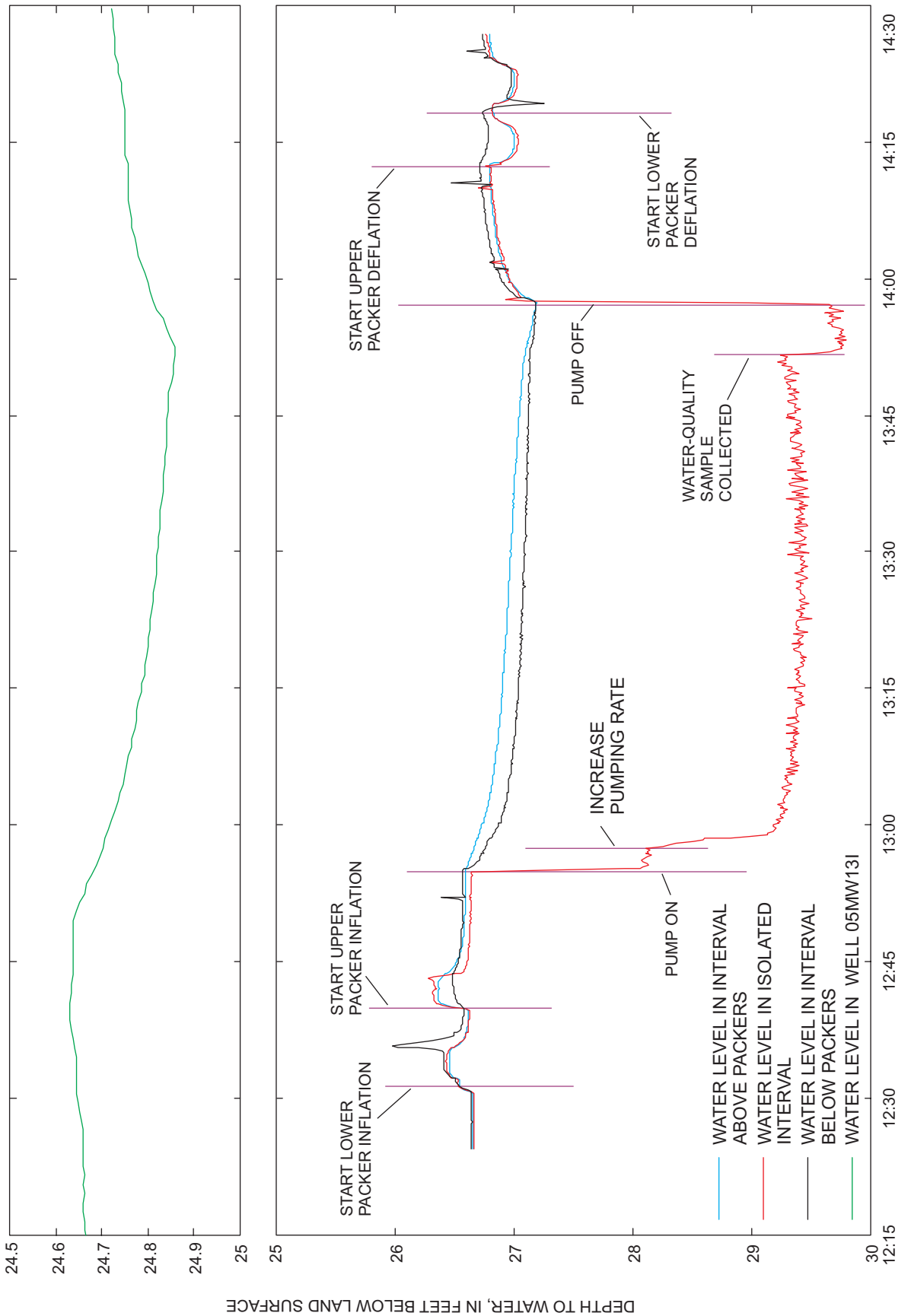

Figure 23. Hydrographs from aquifer-isolation test of interval 2 (162-173 feet below land surface) in well 03MW08 (MG-2142), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

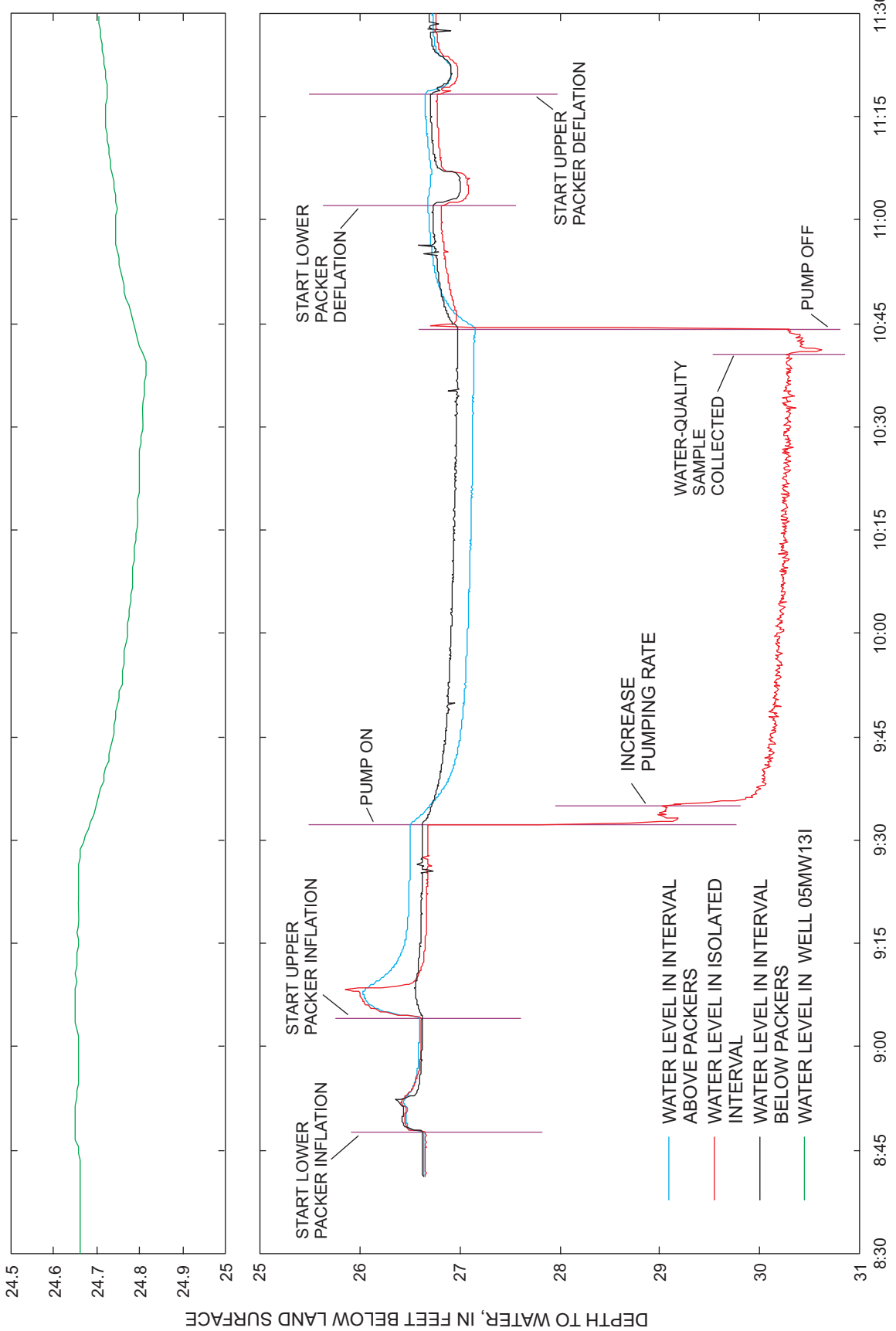

Figure 24. Hydrographs from aquifer-isolation test of interval 3 (136.5-145.5 feet below land surface) in well 03MW08 (MG-2142), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

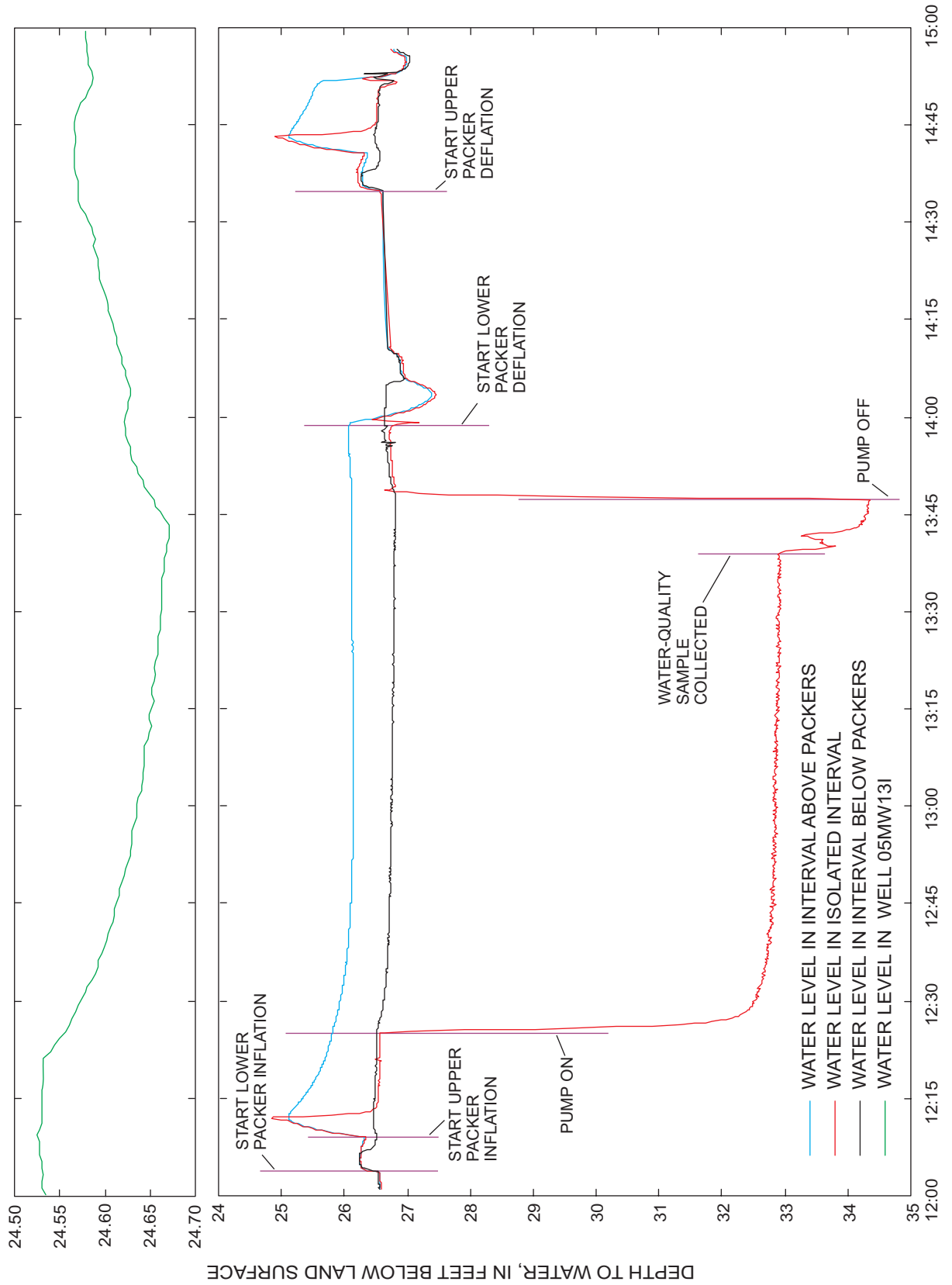

Figure 25. Hydrographs from aquifer-isolation test of interval 4 (124.5-135.5 feet below land surface) in well 03MW08 (MG-2142), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Interval 5 (75.5-86.5 Feet Below Land Surface)

For the aquifer-isolation test of interval 5, the bottom of the upper packer and the top of the lower packer were set at 75.5 and 86.5 ft bls, respectively, to isolate the fracture at 80 ft bls. Before packer inflation, the depth to water in the open borehole was 26.60 ft bls. After packer inflation, the depth to water in the isolated interval increased 0.23 ft, the depth to water in the interval below the packers decreased 0.02 ft, and the depth to water in the interval above the packers increased 2.04 ft. This is generally consistent with the heatpulse-flowmeter measurements, which showed downward flow. The average pumping rate was 1.6 gal/min. Drawdown was 17.12 ft in the isolated interval, 0 ft in the interval below the packers, and 0.80 ft in the interval above the packers. The specific capacity of interval 5 was 0.09 (gal/min)/ft. The water level in the interval above the packers had not stabilized and was still declining at the start of pumping (fig. 26). It appears that the hydrograph of the interval above the packers was slightly affected by pumping, but most of the drawdown probably was the continued decline from inflation of the upper packer. The hydrographs (fig. 26) indicate little hydraulic connection between the isolated interval and the interval above the packers and no hydraulic connection between the isolated interval and the interval below the packers. The water level in well 05MW13I did not change in response to pumping interval 5, indicating no hydraulic connection between interval 5 and well 05MW13I.

Interval 6 (38-68.5 Feet Below Land Surface)

For the aquifer-isolation test of interval 6, only the upper packer was inflated. The top of the upper packer was set at 68.5 ft bls to isolate the upper section of the borehole. Before packer inflation, the depth to water in the open borehole was 26.54 ft bls. After packer inflation, the water level in the interval above the packer (isolated interval) increased 0.06 ft and was still rising at start of pumping. This is consistent with the heatpulse-flowmeter measurements, which showed downward flow from the isolated interval. Pumping began at an initial rate of 2.4 gal/min. The pumping rate dropped during the test. After 52 minutes, the pumping rate was decreased to 0.8 gal/min. The average pumping rate was 1.0 gal/min. Drawdown was 23.12 ft in the isolated interval and 0.04 ft in the interval below the packer. The specific capacity of interval 6 was 0.04 (gal/min)/ft. The hydrographs for the isolated interval and the interval below the packer (fig. 27) indicate no hydraulic connection between these two intervals. The water level in well 05MW13I did not change in response to pumping interval 6, indicating no hydraulic connection between interval 6 and well 05MW13I.

Vertical Distribution of Water-Quality Constituents

During each aquifer-isolation test, water samples were collected by the USGS for field determinations of water-quality constituents and by ECOR Solutions, Inc., for analysis for VOCs. Analytical results were used to determine change in concentration with depth. VOCs detected in water samples collected during aquifer-isolation tests are listed in table 13. Acetone probably is a laboratory contaminant. Concentrations of VOCs were less than 10 µg/L (table 13). The concentration of most VOCs generally increased with depth to interval 2. Concentrations of most VOCs were highest in interval 2. Concentrations of total VOCs in the deepest interval (interval 1) (21 µg/L) were less than concentrations in interval 2 (31 µg/L). Concentrations of dissolved oxygen generally decreased with depth, and specific conductance and temperature increased with depth (table 14). The interval (interval 2) with the highest total VOC concentration also had the lowest dissolved oxygen concentration (3.2 mg/L).

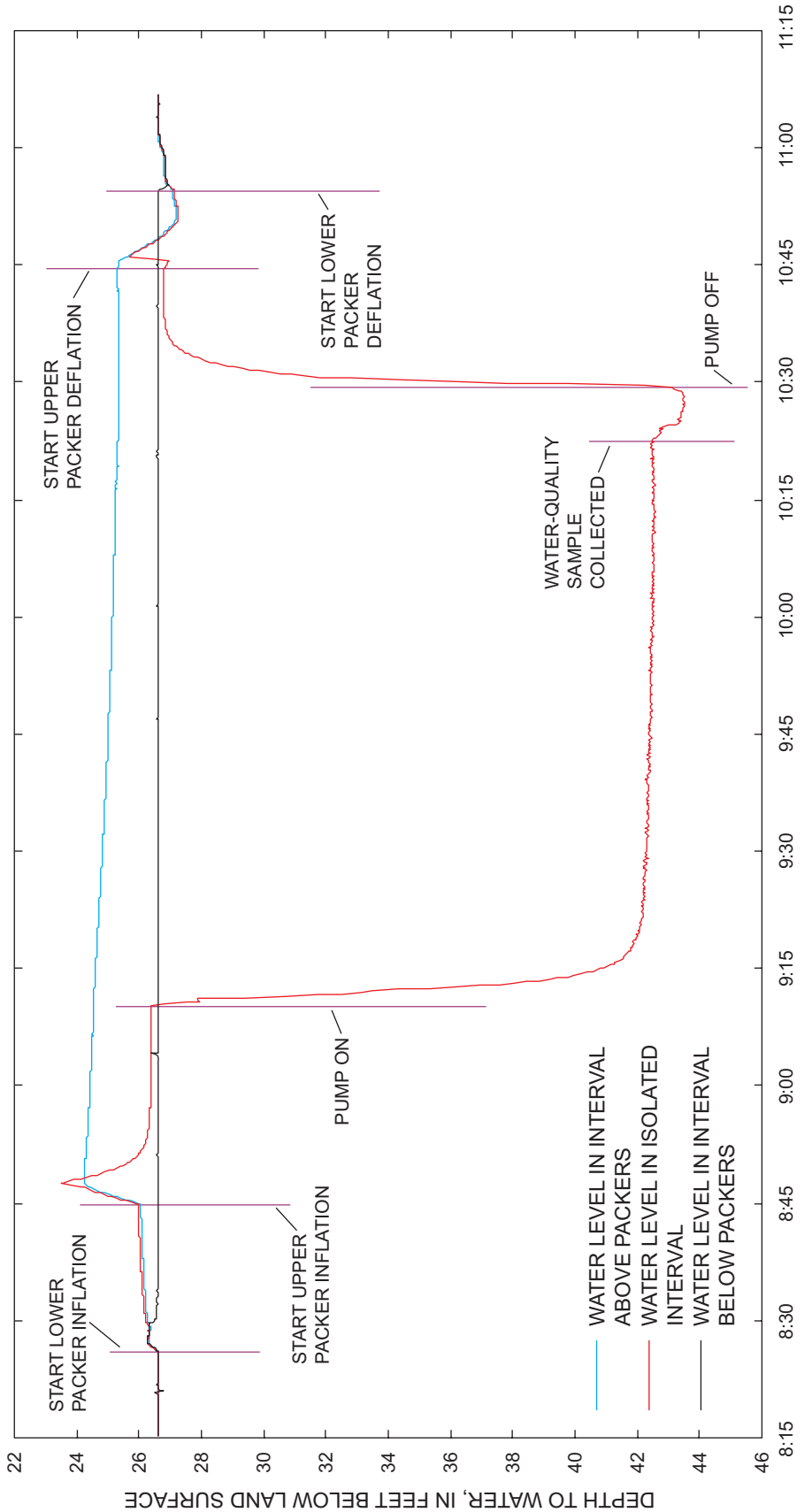

Figure 26. Hydrographs from aquifer-isolation test of interval 5 (75.5-86.5 feet below land surface) in well 03MW08 (MG-2142), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

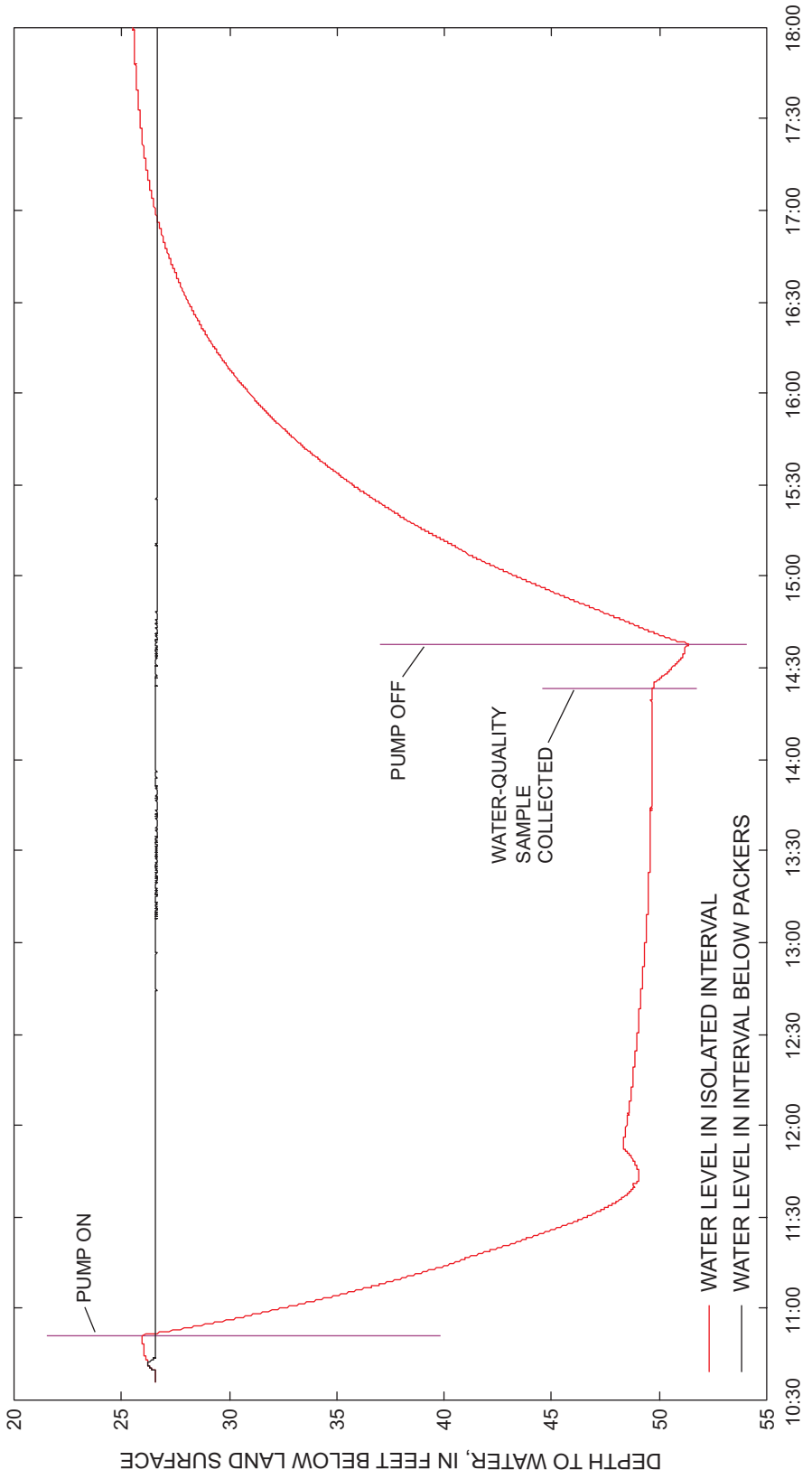

Figure 27. Hydrographs from aquifer-isolation test of interval 6 (38-68.5 feet below land surface) in well 03MW08 (MG-2142), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Table 13. Concentrations of volatile organic compounds detected in water samples collected during aquifer-isolation tests in well 03MW08 (MG-2142), November 22-28, 2005, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[Laboratory results were provided by TetraTech NUS, Inc.; ft bls, feet below land surface; µg/L, micrograms per liter; ND, not detected, reporting limit is 5 µg/L for acetone and 1 µg/L for other constituents listed; J, estimated result less than reporting limit]

Interval	Depth of sample (ft bls)	1,1-dichloroethene (µg/L)	1,1-dichloroethane (µg/L)	Acetone (µg/L)	cis-1,2-dichloroethene (µg/L)	Tetrachloroethylene (µg/L)	Toluene (µg/L)	1,1,1-Trichloroethane (µg/L)	Trichloroethylene (µg/L)
6	38-68.5	ND	ND	2.6 J	ND	ND	2.9	ND	ND
5	75.5-86.5	ND	ND	ND	ND	ND	1.1	ND	ND
4	124.5-135.5	1.2	2.2	ND	0.49 J	1.8	.66 J	1.1	0.89 J
3	136.5-145.5	2.2	4.0	3.2 J	.81 J	1.6	.96 J	2.1	1.6
2	162-173	5.7	9.3	2.8 J	1.6	1.7	.67 J	5.3	3.5
1	178.2-222	5.0	7.3	ND	1.1	.88 J	ND	4.5	2.4

Table 14. Selected water-quality constituents measured in the field in water samples collected during aquifer-isolation tests in well 03MW08 (MG-2142), November 22-28, 2005, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[ft bls, feet below land surface; mg/L, milligrams per liter; µS/cm at 25°C, microsiemens per centimeter at 25 degrees Celsius; C, Celsius; —, no data]

Interval	Depth of sample (ft bls)	Dissolved oxygen (mg/L)	pH (standard units)	Specific conductance (µS/cm at 25°C)	Temperature (degrees C)
6	38-68.5	8.6	6.1	151	13.7
5	75.5-86.5	—	—	—	—
4	124.5-135.5	5.9	7.0	256	13.5
3	136.5-145.5	—	—	—	—
2	162-173	3.2	7.0	304	14.1
1	178.2-222	3.6	6.8	355	14.2

Interpretation of Borehole Geophysical Logs, Aquifer-Isolation Tests, and Water-Quality Data at Site 5

The area of greatest ground-water contamination at Site 5 is near the 05MW01 well cluster (fig. 3) (TetraTech NUS, Inc., 2002, p. 4-106). Wells were drilled directly down dip (05MW12S) and along strike (05MW14I and 05MW15I) from the 05MW01 well cluster.

Well 05MW12S (MG-2136)

Well 05MW12S was drilled approximately 175 ft directly down dip from the 05MW01 well cluster. It is inside the runway fence line.

Interpretation of Borehole Geophysical Logs

A suite of borehole geophysical logs (fig. 28) was collected in well 05MW12S by the USGS on June 27, 2005. The caliper log shows the well is 70 ft deep, cased to 17 ft bls, and major fracture zones are at 17-20, 26-33, 39, 53, and 58-70 ft bls.

Heatpulse-flowmeter measurements were made under nonpumping conditions (table 15). The heatpulse-flowmeter measurements and borehole television survey indicate water entered the borehole at a rate of 0.2 gal/min through a horizontal fracture at 32 ft bls and flowed downward. Water exited the borehole at 65 ft bls through a long vertical fracture below 58 ft bls. Well 05MW12S was screened later from 50 to 70 ft bls to monitor the principle water-producing fracture zone at 58-70 ft bls (fig. 29).

Interpretation of Aquifer-Isolation Tests

On the basis of the borehole geophysical logs, heatpulse-flowmeter measurements, and the borehole television survey, two intervals were selected for aquifer-isolation tests in well 05MW12S (table 16). A straddle-packer assembly was used to isolate discrete fractures to determine depth-discrete specific-capacity values and to obtain depth-discrete water samples. During the test, water levels were measured in seven wells: 05MW01S, 05MW01SI, 05MW01I, 05MW02S, 05MW03S, 05MW03I, and 05MW12I (fig. 3).

For the test of both intervals, a single packer was centered at 48 ft bls and inflated. Before packer inflation, the depth to water in the open borehole was 25.85 ft bls. After packer inflation, the depth to water in the interval above the packer increased 0.56 ft, and the depth to water in the interval below the packer decreased 0.49 ft. This is consistent with the heatpulse-flowmeter measurements, which showed downward flow.

Table 15. Heatpulse-flowmeter measurements made in well 05MW12S (MG-2136) under nonpumping conditions, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania, June 27, 2005.

Depth (feet below land surface)	Flow (gallon per minute)	Flow direction
36.2	0.21	Down
46.1	.26	Down
57.1	.17	Down

Table 16. Intervals isolated during aquifer-isolation tests conducted in well 05MW12S (MG-2136), July 11, 2005, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[ft, feet; ft bls, feet below land surface; gal/min, gallons per minute; (gal/min)/ft, gallons per minute per foot of drawdown]

Interval	Isolated interval (ft bls)	Average pumping rate (gal/min)	Drawdown (ft)	Specific capacity [(gal/min)/ft]
2	17-44.5	3.5	1.15	3.0
1	51.5-70	5.8	2.48	2.3

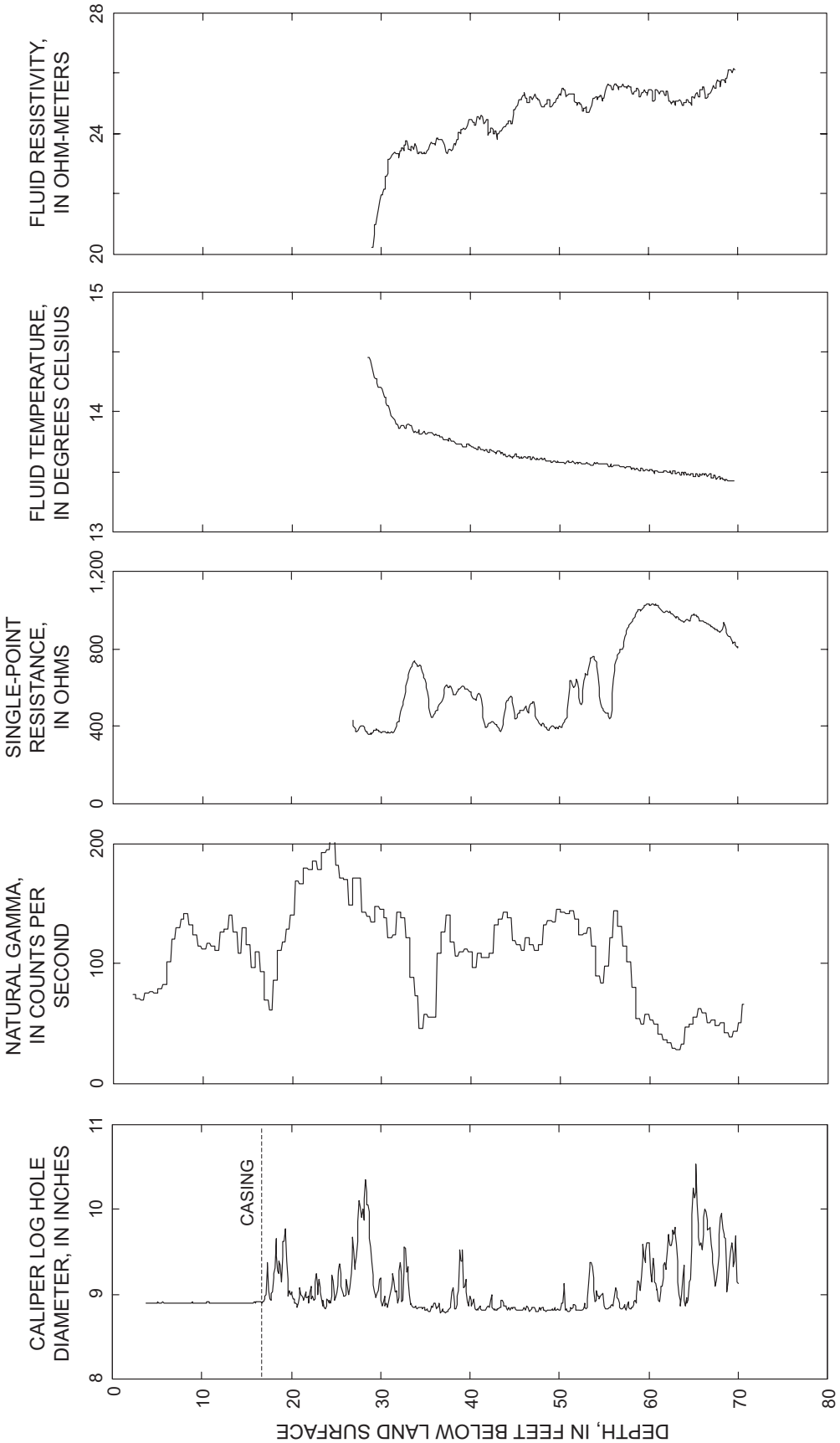

Figure 28. Borehole geophysical logs for well 05MW12S (MG-2136), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania, June 27, 2005.

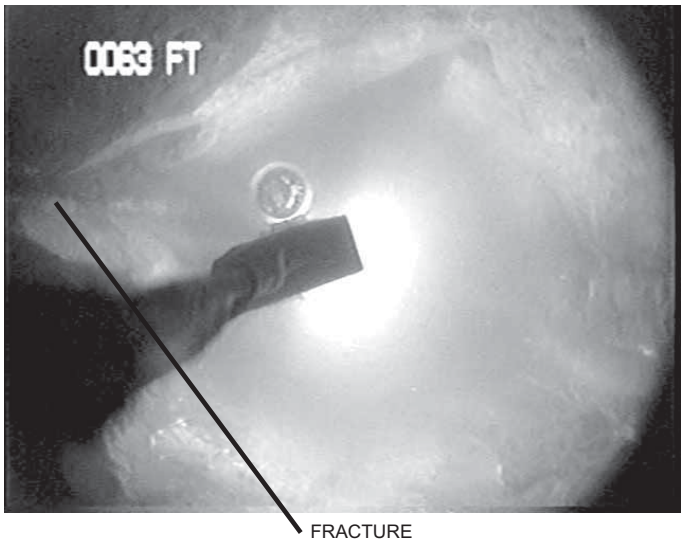

Figure 29. Image from borehole television survey showing vertical fracture at 63 feet below land surface in well 05MW12S (MG-2136), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Interval 1 (51.5-70 Feet Below Land Surface)

For the test of interval 1, the isolated interval was from 51.5 ft bls to 70 ft bls, which was the bottom of the borehole. Pumping began at an initial rate of 4.6 gal/min. After 8 minutes, the pumping rate was increased to 6 gal/min. The average pumping rate was 5.8 gal/min. Drawdown was 2.48 ft in the interval below the packer. The water level rose 0.09 ft in the interval above the packer during the test. The specific capacity of interval 1 was 2.3 (gal/min)/ft. The hydrographs for the intervals above and below the packer (fig. 30) indicate no hydraulic connection between these intervals. During the test of interval 1, no change in water level was measured in wells 05MW01S, 05MW01I, 05MW02S, and 05MW03S indicating no hydraulic connection between these wells and the lower part of well 05MW12S. Drawdowns measured in wells 05MW01SI, 05MW03I, and 05MW12I were 0.28, 0.49, and 0.63 ft, respectively (fig. 30).

Interval 2 (17-44.5 Feet Below Land Surface)

For the test of interval 2, the isolated interval was from the bottom of casing at 17 ft bls to 44.5 ft bls. Pumping began at an initial rate of 2.4 gal/min and then was increased to 3.8 gal/min. The average pumping rate was 3.5 gal/min. Drawdown was 1.15 ft in the isolated interval above the packer. The water level rose throughout the test in the interval below the packer; the water level was still recovering from pumping interval 1. The specific capacity of interval 2 was 3 (gal/min)/ft. The hydrographs for the intervals above and below the packer (fig. 31) indicate no hydraulic connection between the intervals. During the test of interval 2, no change in water level was measured in any of the seven observation wells, indicating no hydraulic connection between these wells and the upper part of well 05MW12S.

Vertical Distribution of Water-Quality Constituents

During each aquifer-isolation test, water samples were collected by the USGS for field determinations of water-quality constituents and by TetraTech NUS, Inc., for analysis for VOCs. Analytical results were used to determine the change in concentration with depth. VOCs detected in water samples collected during aquifer-isolation tests are listed in table 17. Methylene chloride probably is a laboratory contaminant. The concentration of toluene was greater in the shallower interval 2 (4.1 µg/L) than in the deeper interval 1 (0.86 µg/L). PCE (0.38 µg/L) and 1,1-dichloroethane (0.46 µg/L) were detected only in the water sample from interval 1. Specific conductance was higher in interval 1 (170 µS/cm) than in interval 2 (128 µS/cm) (table 18).

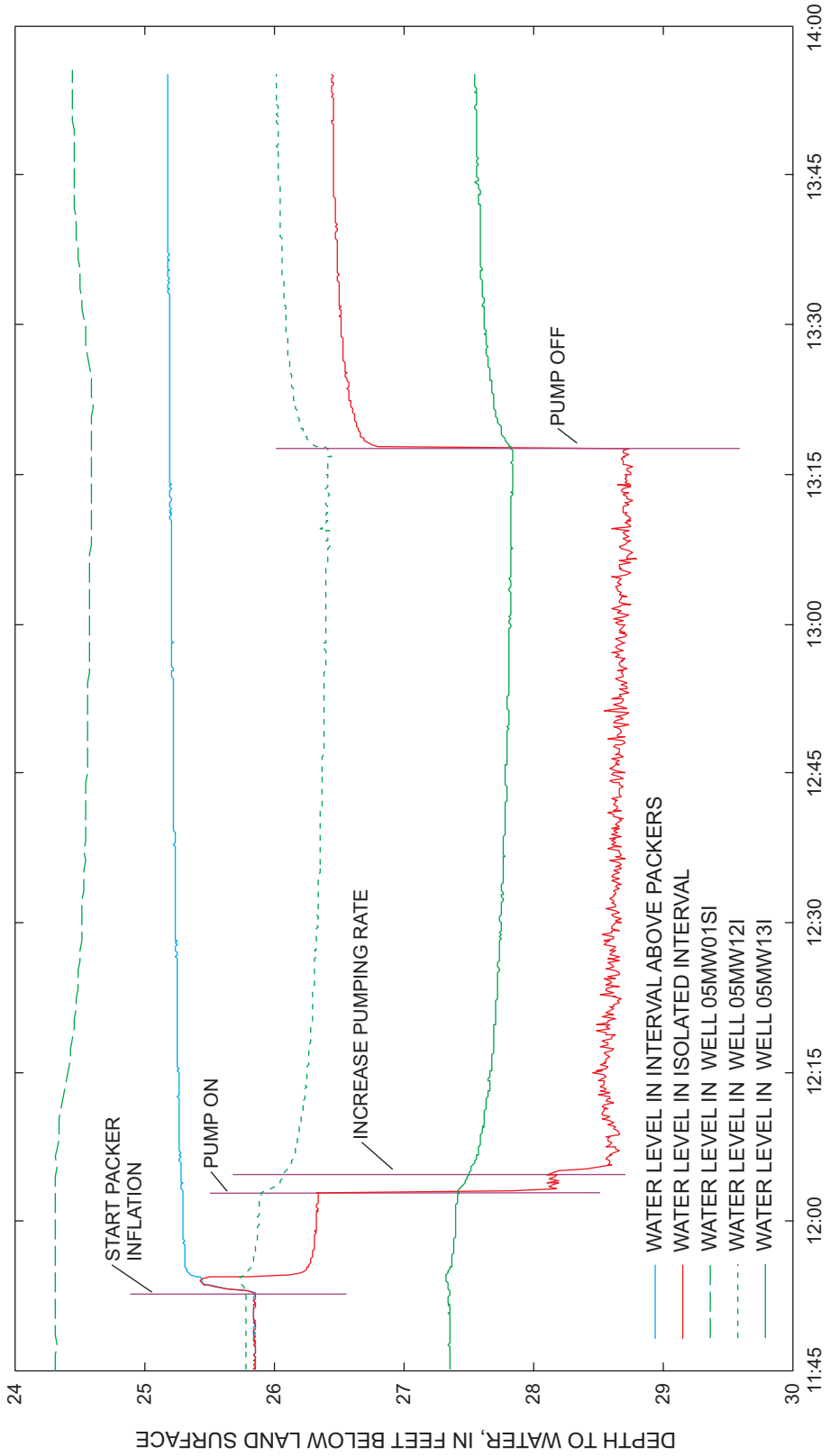

Figure 30. Hydrographs from aquifer-isolation test of interval 1 (51.5-70 feet below land surface) in well 05MW12S (MG-2136), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

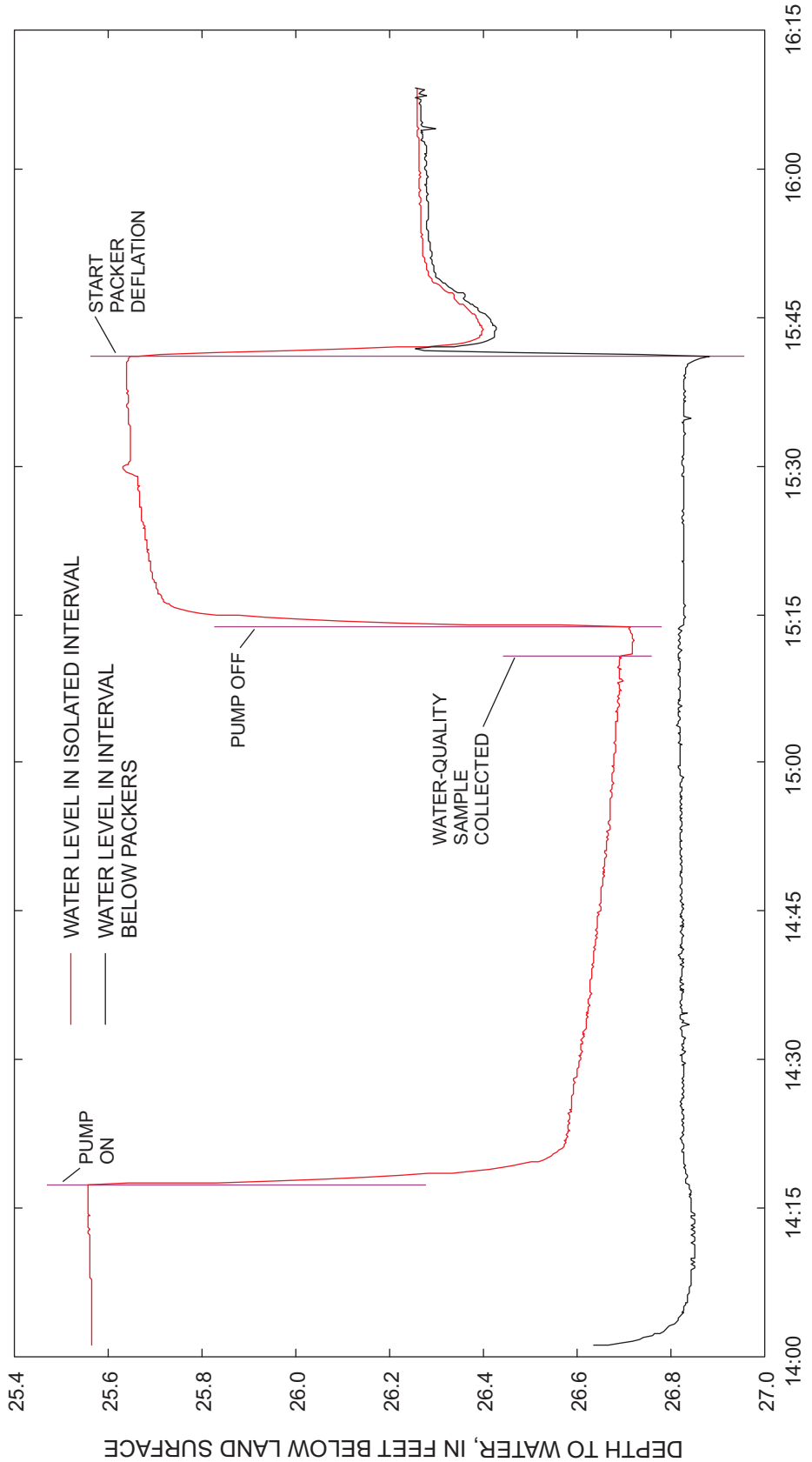

Figure 31. Hydrographs from aquifer-isolation test of interval 2 (17-44.5 feet below land surface) in well 05MW12S (MG-2136), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Table 17. Concentrations of volatile organic compounds detected in water samples collected during aquifer-isolation tests in well 05MW12S (MG-2136), July 11, 2005, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[Laboratory results were provided by TetraTech NUS, Inc.; ft bls, feet below land surface; µg/L, micrograms per liter; ND, not detected, reporting limit is 1 µg/L; J, estimated result less than reporting limit; B, constituent detected in blank]

Interval	Depth of sample (ft bls)	1,1-dichloroethane (µg/L)	Methylene chloride (µg/L)	Tetrachloroethylene (µg/L)	Toluene (µg/L)
2	17 - 44.5	ND	0.69 JB	ND	4.1
1	51.5 - 70	0.46 J	.72 JB	0.38 J	.86 J

Table 18. Selected water-quality constituents measured in the field in water samples collected during aquifer-isolation tests in well 05MW12S (MG-2136), July 11, 2005, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[ft bls, feet below land surface; mg/L, milligrams per liter; µS/cm at 25°C, microsiemens per centimeter at 25 degrees Celsius; C, Celsius]

Interval	Depth of sample (ft bls)	Dissolved oxygen (mg/L)	pH (standard units)	Specific conductance (µS/cm at 25°C)	Temperature (degrees C)
2	17 - 44.5	0.2	9.0	128	16.9
1	51.5 - 70	.2	8.4	170	16.3

Well 05MW13I (MG-2137)

Well 05MW13I was drilled approximately 795 ft west of the 05MW01 well cluster (fig. 3). It is stratigraphically down section of the 05MW01 well cluster.

Interpretation of Borehole Geophysical Logs

A suite of borehole geophysical logs (fig. 32) was collected in well 05MW13I by the USGS on June 29, 2005. The caliper log shows the well is 181 ft deep and is cased to 29 ft bls. The caliper log shows major fractures at 29-34, 67-73, 105, 129, and 159 ft bls. The fluid-temperature log shows sharp breaks in slope at about 73, 105, and 159 ft bls. The fluid-resistivity log shows sharp breaks in slope at about 73 and 151 ft bls. The fluid-temperature and fluid-resistivity logs indicate borehole flow between about 70 and 160 ft bls and possible water-producing zones at about 73, 105, and 159 ft bls.

Heatpulse-flowmeter measurements were made under nonpumping and pumping conditions (table 19). The geophysical logs and heatpulse-flowmeter measurements indicate upward flow throughout most of the borehole. Because a 6-in.-diameter diverter was used in an 8-in.-diameter borehole, some of the flow bypassed the heatpulse flowmeter, and the measured values are relative. The values are used only to determine where water enters and exits the borehole. Water entered the borehole through a horizontal fracture at 159 ft bls and flowed upward. Some water exited the borehole through a vertical fracture zone at 129-139 ft bls. Most of the water exited the borehole through horizontal fractures at 105 and 73 ft bls. Well 05MW13I was screened later from 127 to 142 ft bls to monitor the principle water-producing fracture zone at 129-139 ft bls (fig. 33).

Table 19. Heatpulse-flowmeter measurements made in well 05MW13I (MG-2137), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania, June 29, 2005.

[—, no data]

Depth (feet below land surface)	Nonpumping measurements			Pumping measurements	
	Flow with 8-inch diverter (gallon per minute)	Relative flow with 6-inch diverter (gallon per minute)	Flow direction	Relative flow (gallon per minute)	Pumping rate (gallon per minute)
42.1	0	—	—	0.21	1.25
48.1	0	—	—	.21	1.25
60.2	0	—	—	.21	1.25
70.0	0	—	—	.23	1.25
84.1	.11	—	Up	.28	1.30
92.0	.58	0.12	Up	.26	1.30
109.1	—	.28	Up	.39	1.30
120.1	—	.27	Up	.39	1.22
125.0	—	.30	Up	.44	1.30
133.0	—	.32	Up	.38	1.28
137.1	—	.35	Up	—	—
142.0	—	.33	Up	.50	1.15
150.0	—	.38	Up	.49	1.22
164.4	—	.07	Up	.12	1.22
176.0	—	0	—	—	—

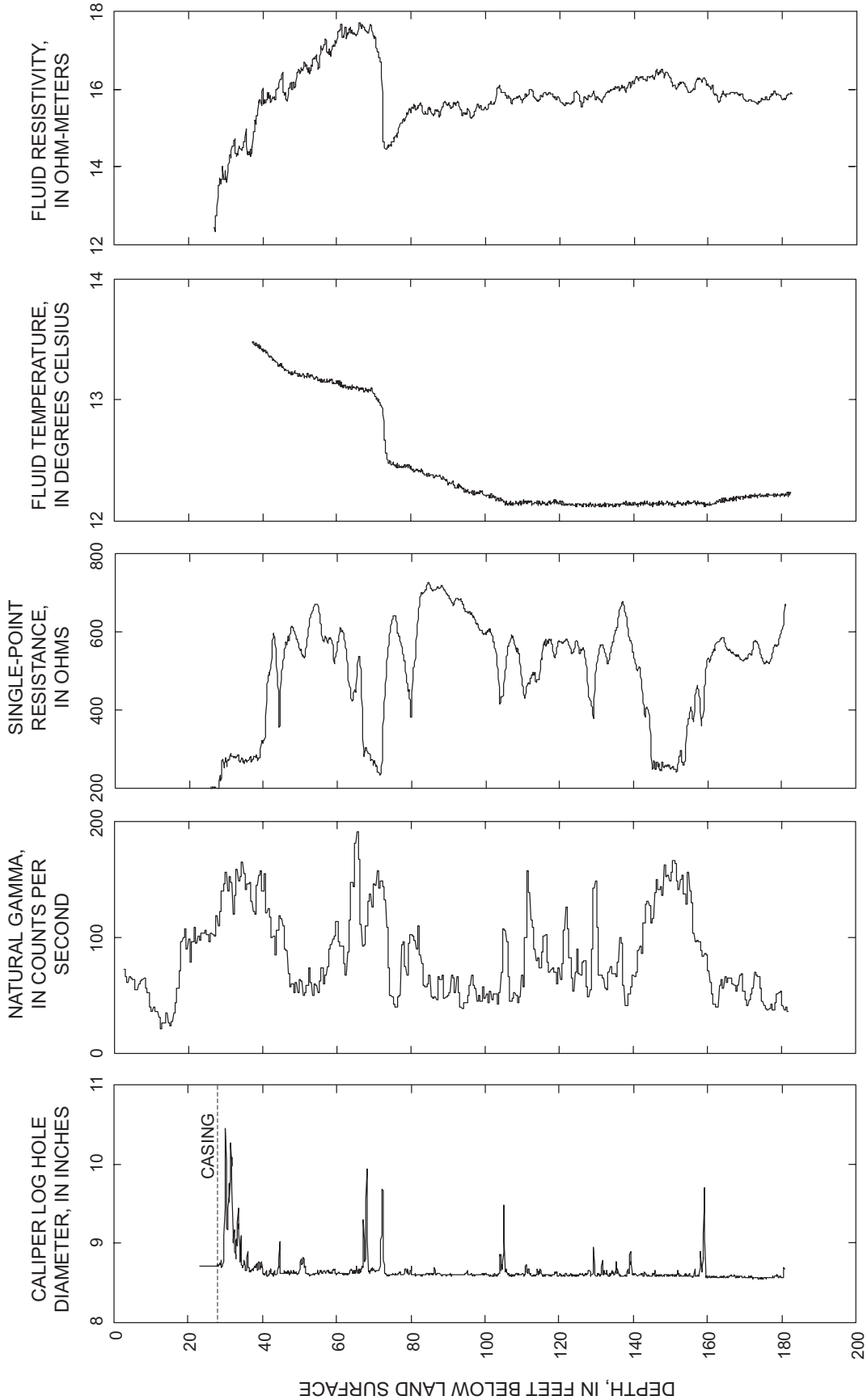

Figure 32. Borehole geophysical logs for well 05MW13I (MG-2137), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania, June 29, 2005.

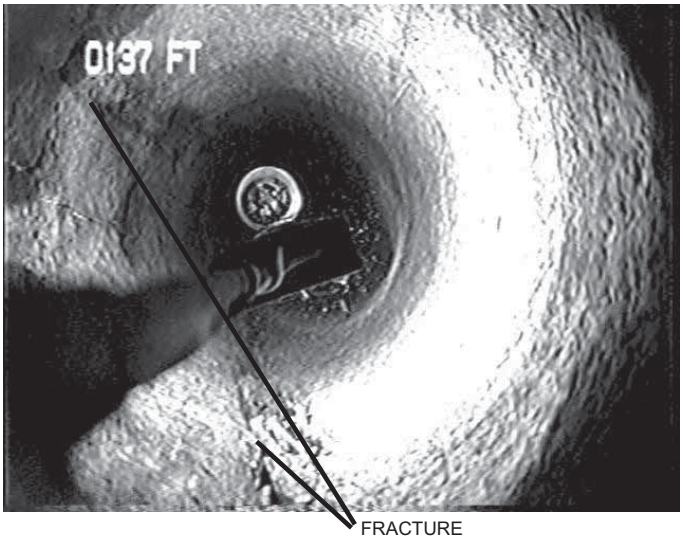

Figure 33. Image from borehole television survey showing vertical fracture at 137 feet below land surface in well 05MW13I (MG-2137), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania, June 28, 2005.

Interpretation of Aquifer-Isolation Tests

On the basis of the borehole geophysical logs, heatpulse-flowmeter measurements, and the borehole television survey, five intervals were selected for aquifer-isolation tests in well 05MW13I (table 20). A straddle-packer assembly was used to isolate discrete fractures to determine depth-discrete specific-capacity values and to obtain depth-discrete water samples. The distance between the bottom of the upper packer and the top of the lower packer was 12 ft. For the test of intervals 1, only the upper packer was inflated. For the test of intervals 2, 3, 4, and 5, both packers were inflated. During the test of well 05MW13I, water levels were measured in wells 05MW14I and 05MW15I (fig. 3).

Interval 1 (162-181 Feet Below Land Surface)

For the aquifer-isolation test of interval 1, the bottom of the upper packer was set at 162 ft bls and inflated to isolate the lower part of the borehole. The yield of this interval was approximately 0.7 gal/min. Interval 1 was rapidly pumped dry and allowed to recover overnight. It was pumped dry again the next morning, allowed to recover, and pumped again to obtain a water sample. No response to pumping interval 1 was measured in wells 05MW14I and 05MW15I.

Table 20. Intervals isolated during aquifer-isolation tests conducted in well 05MW13I (MG-2137), July 19-20, 2005, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[ft, feet; ft bls, feet below land surface; gal/min, gallons per minute; (gal/min)/ft, gallons per minute per foot of drawdown; —, no data]

Interval	Depth of isolated fracture (ft bls)	Bottom of upper packer (ft bls)	Top of lower packer (ft bls)	Average pumping rate (gal/min)	Drawdown (ft)	Specific capacity [(gal/min)/ft]
5	73	64.5	76.5	3.9	3.01	1.3
4	105	100.5	112.5	4.5	.90	5.0
3	129-139	128.5	140.5	4.2	3.43	1.2
2	159	151.5	163.5	4.7	.90	5.2
1	Below 162	162	Not inflated	0.7	—	—

Interval 2 (151.5-163.5 Feet Below Land Surface)

For the aquifer-isolation test of interval 2, the bottom of the upper packer and the top of the lower packer were set at 151.5 and 163.5 ft bls, respectively, to isolate the fracture at 159 ft bls. Before packer inflation, the depth to water in the open borehole was 23.95 ft bls. After packer inflation, the depth to water in the isolated interval decreased 0.08 ft, the depth to water in the interval below the packers increased 0.17 ft, and the depth to water in the interval above the packers increased 0.1 ft. The rise in water level in the interval above the packers may have been caused by recharge from heavy rain proceeding the test. The change in water level in the other two intervals is consistent with the heatpulse-flowmeter measurements, which showed upward flow. Pumping began at the initial rate of 3.2 gal/min. After 6 minutes, the pumping rate was increased to 4.8 gal/min. The average pumping rate was 4.7 gal/min. Drawdown was 0.9 ft in the isolated interval. The water level rose 0.02 ft in the intervals above and below the packers. The specific capacity of interval 2 was 5.2 (gal/min)/ft. The hydrographs for the interval above the packers, the isolated interval, and the interval below the packers (fig. 34) indicate no hydraulic connection among these intervals. Drawdown caused by pumping interval 2 in well 05MW13I was 0.09 ft in wells 05MW14I and 05MW15I.

Interval 3 (128.5-140.5 Feet Below Land Surface)

For the aquifer-isolation test of interval 3, the bottom of the upper packer and the top of the lower packer were set at 128.5 and 140.5 ft bls, respectively, to isolate the fracture zone at 129-139 ft bls. Before packer inflation, the depth to water in the open borehole was 23.91 ft bls. After packer inflation, the depth to water in the isolated interval increased 0.1 ft, the depth to water in the interval below the packers decreased 0.07 ft, and the depth to water in the interval above the packers increased 0.9 ft. The rise in water level in the interval above the packers may have been caused by recharge from heavy rain proceeding the test. The change in water level in the other two intervals was not consistent with the heatpulse-flowmeter measurements, which showed upward flow. The average pumping rate was 4.2 gal/min. Drawdown was 3.43 ft in the isolated interval, 0.04 ft in the interval below the packers, and 0.54 ft in the interval above the packers. The specific capacity of interval 3 was 1.2 (gal/min)/ft. The hydrographs for the interval above the packers, the isolated interval, and the interval below the packers (fig. 35) indicate little hydraulic connection between the isolated interval and the interval below the packers and a weak hydraulic connection between the isolated interval and the interval above the packers. Drawdown in wells 05MW14I and 05MW15I caused by pumping interval 3 in well 05MW13I was 0.04 and 0.07 ft, respectively.

Interval 4 (100.5-112.5 Feet Below Land Surface)

For the aquifer-isolation test of interval 4, the bottom of the upper packer and the top of the lower packer were set at 100.5 and 112.5 ft bls, respectively, to isolate the fracture at 105 ft bls. Before packer inflation, the depth to water in the open borehole was 23.91 ft bls. After packer inflation, the depth to water in the isolated interval increased 0.08 ft, the depth to water in the interval below the packers increased 0.04 ft, and the depth to water in the interval above the packers increased 0.09 ft. The rise in water level in the interval above the packers may have been caused by recharge from heavy rain proceeding the test. The change in water level in the interval below the packers was consistent with the heatpulse-flowmeter measurements, which showed upward flow. A decrease in water level in the isolated interval would be expected. Pumping began at an initial rate of 3.3 gal/min. After 3 minutes, the pumping rate was increased to 4.0 gal/min, and after 19 minutes, the pumping rate was increased to 5.0 gal/min. The average pumping rate was 4.5 gal/min. Drawdown was 0.9 ft in the isolated interval, 0.14 ft in the interval below the packers, and 0.32 ft in the interval above the packers. The specific capacity of interval 4 was 5.0 (gal/min)/ft. The hydrographs for the interval above the packers, the isolated interval, and the interval below the packers (fig. 36) indicate a weak hydraulic connection between the isolated interval and the interval below the packers and a strong hydraulic connection between the isolated interval and the interval above the packers. Drawdown in wells 05MW14I and 05MW15I caused by pumping interval 4 in well 05MW13I was 0.04 and 0.06 ft, respectively.

Interval 5 (64.5-76.5 Feet Below Land Surface)

For the aquifer-isolation test of interval 5, the bottom of the upper packer and the top of the lower packer were set at 64.5 and 76.5 ft bls, respectively, to isolate the fracture at 73 ft bls. Before packer inflation, the depth to water in the open borehole was 23.99 ft bls. After packer inflation, the depth to water in the isolated interval increased 0.09 ft, the depth to water in the interval below the packers increased 0.03 ft, and the depth to water in the interval above the packers increased 0.29 ft. The rise in water level in the interval above the packers may have been caused by recharge from heavy rain proceeding the test. The change in water level in the interval below the packers was consistent with the heatpulse-flowmeter measurements, which showed upward flow. A decrease in water level in the isolated interval would be expected. Pumping began at an initial rate of 2.5 gal/min. After 5 minutes, the pumping rate was increased to 3.4 gal/min, and after 17 minutes, the pumping rate was increased to 4.0 gal/min. The average pumping rate was 3.9 gal/min. Drawdown was 3.01 ft in the isolated interval and 0.15 ft in the interval below the packers. The water level in the interval above the packers rose 0.05 ft during the test. The specific capacity of interval 5 was 1.3 (gal/min)/ft. The hydrographs for the interval above the packers, the isolated interval, and the interval below the packers (fig. 37) indicate a weak hydraulic connection between the isolated interval and the interval below the packers and no hydraulic connection between the isolated interval and the interval above the packers. Drawdown in wells 05MW14I and 05MW15I caused by pumping interval 5 in well 05MW13I was 0.08 and 0.06 ft, respectively.

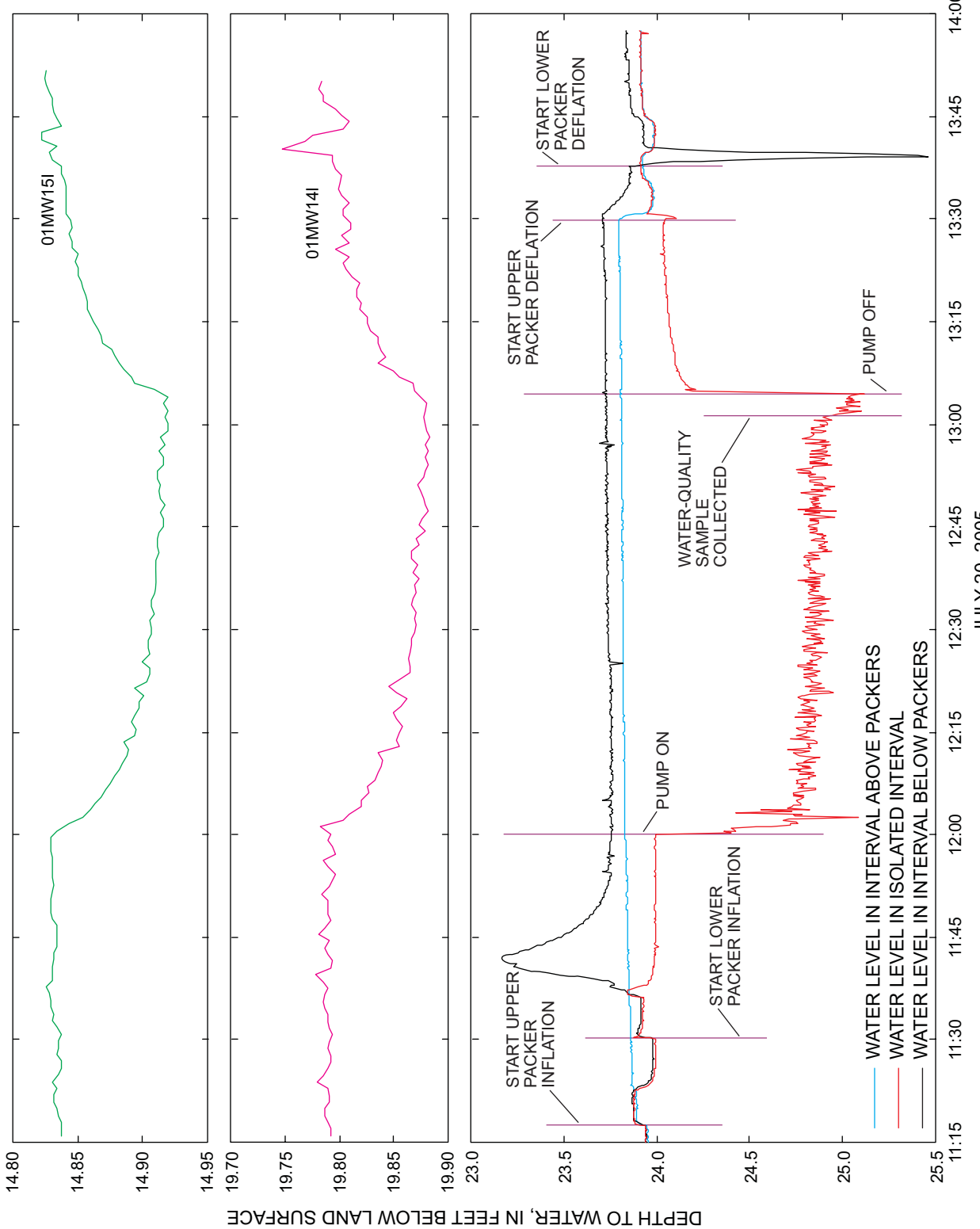

Figure 34. Hydrographs from aquifer-isolation test of interval 2 (151.5-163.5 feet below land surface) in well 05MW13I (MG-2137), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

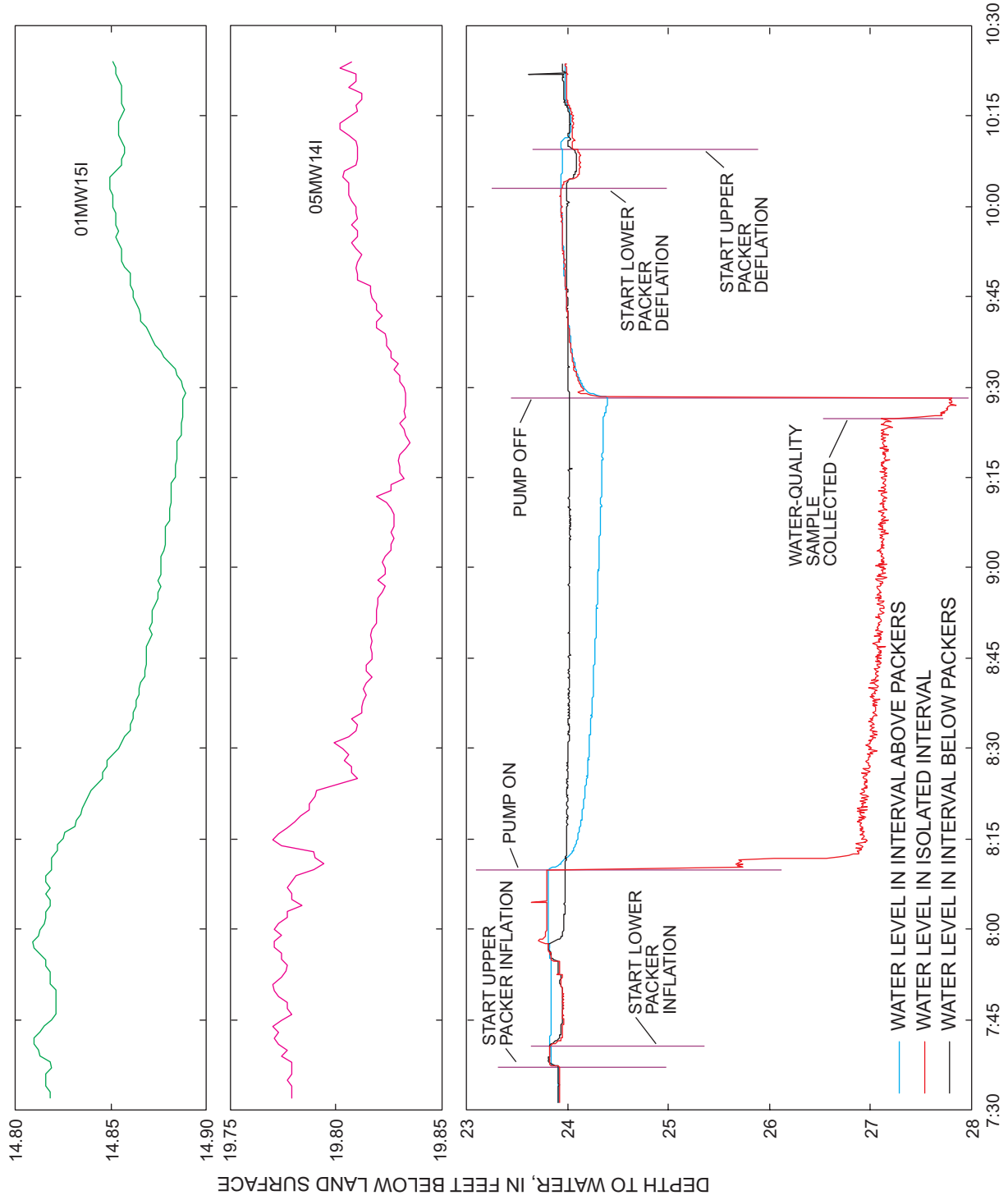

Figure 35. Hydrographs from aquifer-isolation test of interval 3 (128.5-140.5 feet below land surface) in well 05MW13I (MG-2137), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

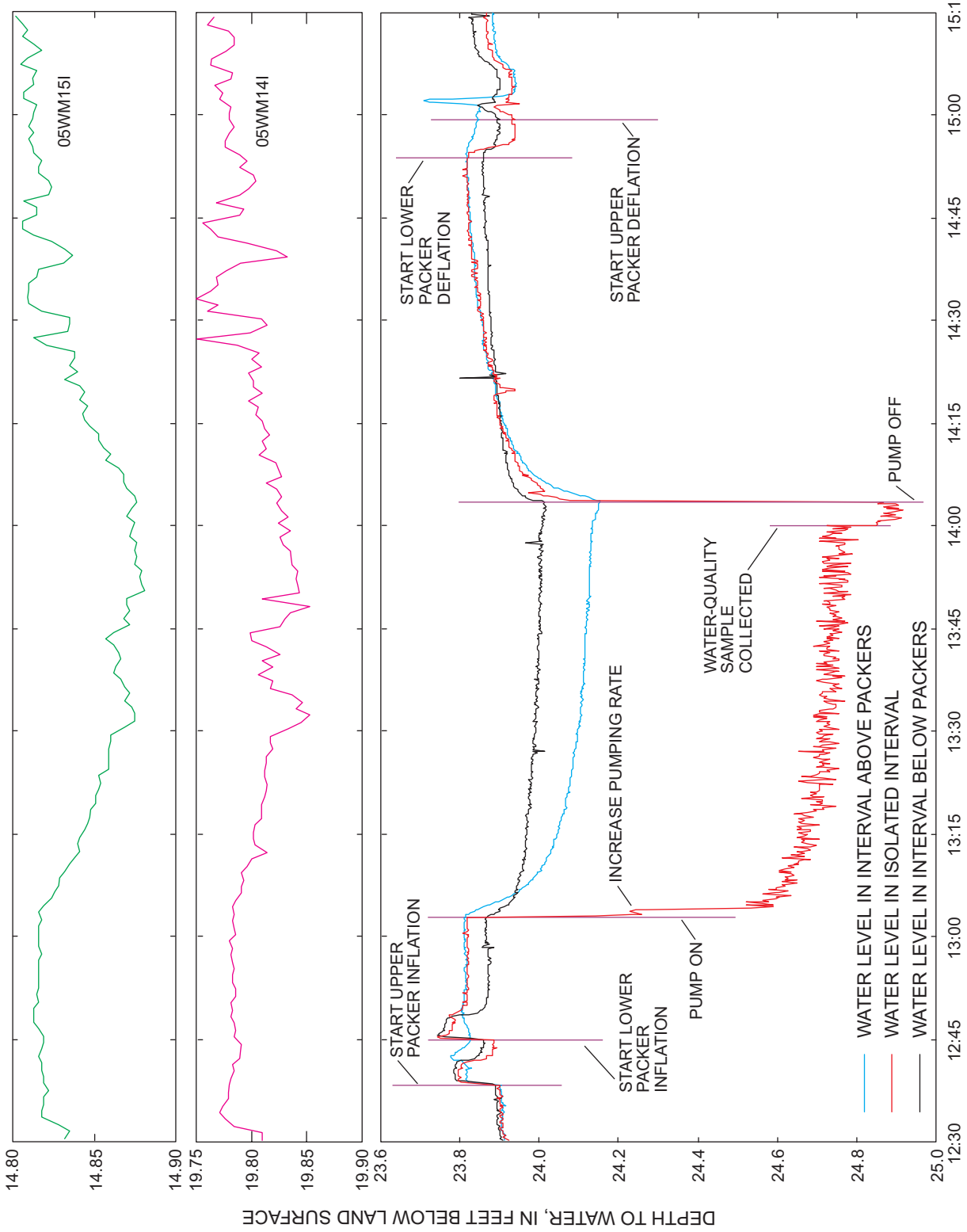

Figure 36. Hydrographs from aquifer-isolation test of interval 4 (100.5-112.5 feet below land surface) in well 05MW13I (MG-2137), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

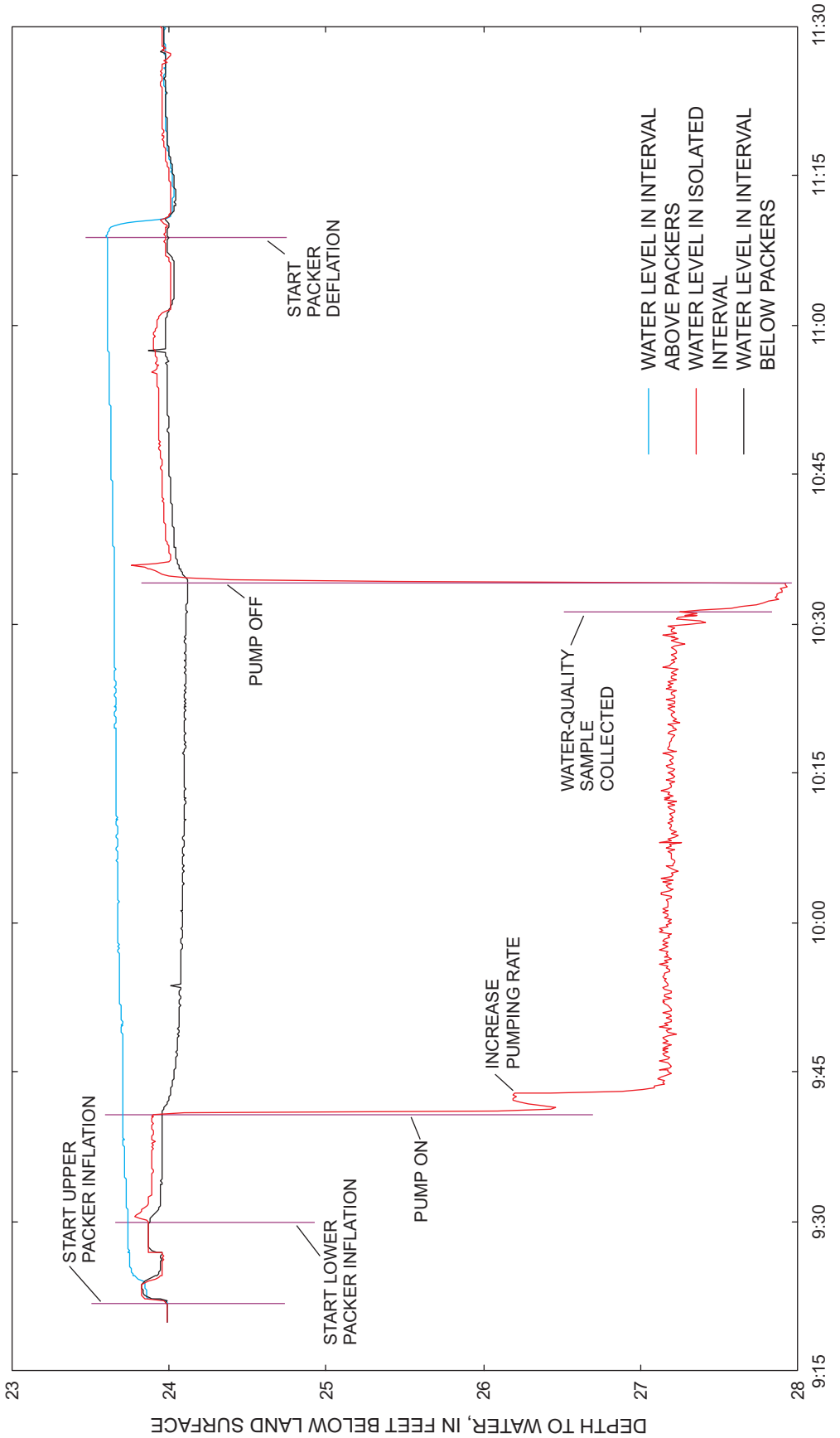

Figure 37. Hydrographs from aquifer-isolation test of interval 5 (64.5-76.5 feet below land surface) in well 05MW13I (MG-2137), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Vertical Distribution of Water-Quality Constituents

During each aquifer-isolation test, water samples were collected by the USGS for field determinations of water-quality constituents and by TetraTech NUS, Inc., for analysis for VOCs. VOCs detected in water samples collected during aquifer-isolation tests are listed in table 21. Acetone, chloroform, and methylene chloride are laboratory or field blank contaminants. The highest concentrations of 1,1-dichloroethylene (16 µg/L), 1,1-dichloroethane (13 µg/L), cis-1,2-dichloroethene (2.4 µg/L), and 1,1,1-trichloroethane (16 µg/L) were measured in the water sample from interval 3. Concentrations of these constituents were similar in intervals 1 and 2 and in intervals 3 and 4. The highest concentration of PCE (4.5 µg/L) and the lowest concentrations of the other constituents were measured in interval 5, the shallowest interval. Concentrations of VOCs generally increased with depth to a maximum in interval 3 and then decreased with depth below interval 3. Specific conductance followed the same pattern (table 26). The interval with the highest chlorinated VOC concentration (interval 3) (58 µg/L) had the lowest dissolved oxygen concentration (1.8 mg/L).

Table 21. Concentrations of volatile organic compounds detected in water samples collected during aquifer-isolation tests in well 05MW13I (MG-2137), July 19-20, 2005, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[Laboratory results were provided by TetraTech NUS, Inc.; ft bls, feet below land surface; µg/L, micrograms per liter; ND, not detected, reporting limit is 5 µg/L for acetone and 1 µg/L for other constituents listed; J, estimated result less than reporting limit; B, constituent detected in blank]

Interval	Depth of sample (ft bls)	1,1-dichloroethene (µg/L)	1,1-dichloroethane (µg/L)	cis-1,2-dichloroethene (µg/L)	1,1,1-trichloroethane (µg/L)	Acetone (µg/L)	Chloroform (µg/L)	Methylene chloride (µg/L)	Toluene (µg/L)	Trichloroethylene (µg/L)	Tetrachloroethylene (µg/L)
5	64.5-76.5	1.6	3.3	0.81J	1.4	12	ND	ND	2.1	1.2	4.5
4	100.5-112.5	11	12	2.3	12	ND	1.3	ND	.96 J	6.4	1.2
3	128.5-140.4	16	13	2.4	16	12 B	1.3 B	0.59 J	1.2	8.1	1.0
2	151.5-163.5	9.2	9.8	2.0	10	12 B	1.3 B	.48 J	9.7	5.4	2.7
1	162-181	9.2	6.4	1.2	5.3	ND	ND	ND	38	3.8	3.0

Table 22. Selected water-quality constituents measured in the field in water samples collected during aquifer-isolation tests in well 05MW13I (MG-2137), July 19-20, 2005, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[ft bls, feet below land surface; mg/L, milligrams per liter; µS/cm at 25°C, microsiemens per centimeter at 25 degrees Celsius; C, Celsius; —, not determined}

Interval	Depth of sample (ft bls)	Dissolved oxygen (mg/L)	pH (standard units)	Specific conductance (µS/cm at 25°C)	Temperature (degrees C)
5	64.5-76.5	2.4	6.6	226	15.4
4	100.5-112.5	2.9	6.9	308	14.5
3	128.5-140.4	1.8	7.0	338	14.0
2	151.5-163.5	2.7	7.2	331	13.7
1	162-181	—	—	—	—

Well 05MW14I (MG-2138)

Well 05MW14I was drilled approximately 495 ft west of the 05MW01 well cluster (fig. 3). It is directly along strike from the 05MW01 well cluster.

Interpretation of Borehole Geophysical Logs

A suite of borehole geophysical logs (fig. 38) was collected in well 05MW14I by the USGS on June 27-28, 2005. The caliper log shows the well is 148 ft deep, is cased to 22 ft bls, and major fractures are at 52, 56, 60, 63, and 90 ft bls. The fluid-temperature log shows breaks in slope at about 60 and 83 ft bls. The fluid-resistivity log shows breaks in slope at about 83 and 100 ft bls. The fluid-temperature and fluid-resistivity logs indicate borehole flow and possible water-producing zones at about 60, 82, and 100 ft bls.

Heatpulse-flowmeter measurements were made under nonpumping conditions and while pumping the well at about 0.8 gal/min (table 23). The geophysical logs and heatpulse-flowmeter measurements indicate downward flow in the borehole. Water entered the borehole at a rate of 0.1 gal/min through a horizontal fracture at 45 ft bls and flowed downward. Some of the water exited the borehole through a small vertical fracture at 81 ft bls. Additional water entered the borehole through a vertical fracture at 100 ft bls and flowed downward. Water exited the borehole through a horizontal fracture at the bottom of the borehole. Well 05MW14I was screened later from 36 to 66 ft bls to monitor the water-producing fractures at 45-64 ft bls (fig. 39A) and from 128-148 ft bls to monitor the water-receiving fracture at the bottom of the borehole (fig. 39B).

Table 23. Heatpulse-flowmeter measurements made in well 05MW14I (MG-2138), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania, June 27, 2005.

[—, no data]

Depth (feet below land surface)	Nonpumping measurements		Pumping measurements	
	Flow (gallon per minute)	Flow direction	Relative flow[1] (gallon per minute)	Pumping rate (gallon per minute)
33	0	—	—	—
40	—	—	—	—
49	—	—	0.63	0.81
50	.10	Down	—	—
58	.07	Down	.63	.81
79	.10	Down	.70	.81
87	.07	Down	[2].14	.82
97	—	—	.61	.82
110	.15	Down	.65	.82
122	.26	Down	.64	.82
130	.25	Down	.69	.81
144	.23	Down	.52	.79

[1]Upward flow.

[2]Poor diverter seal.

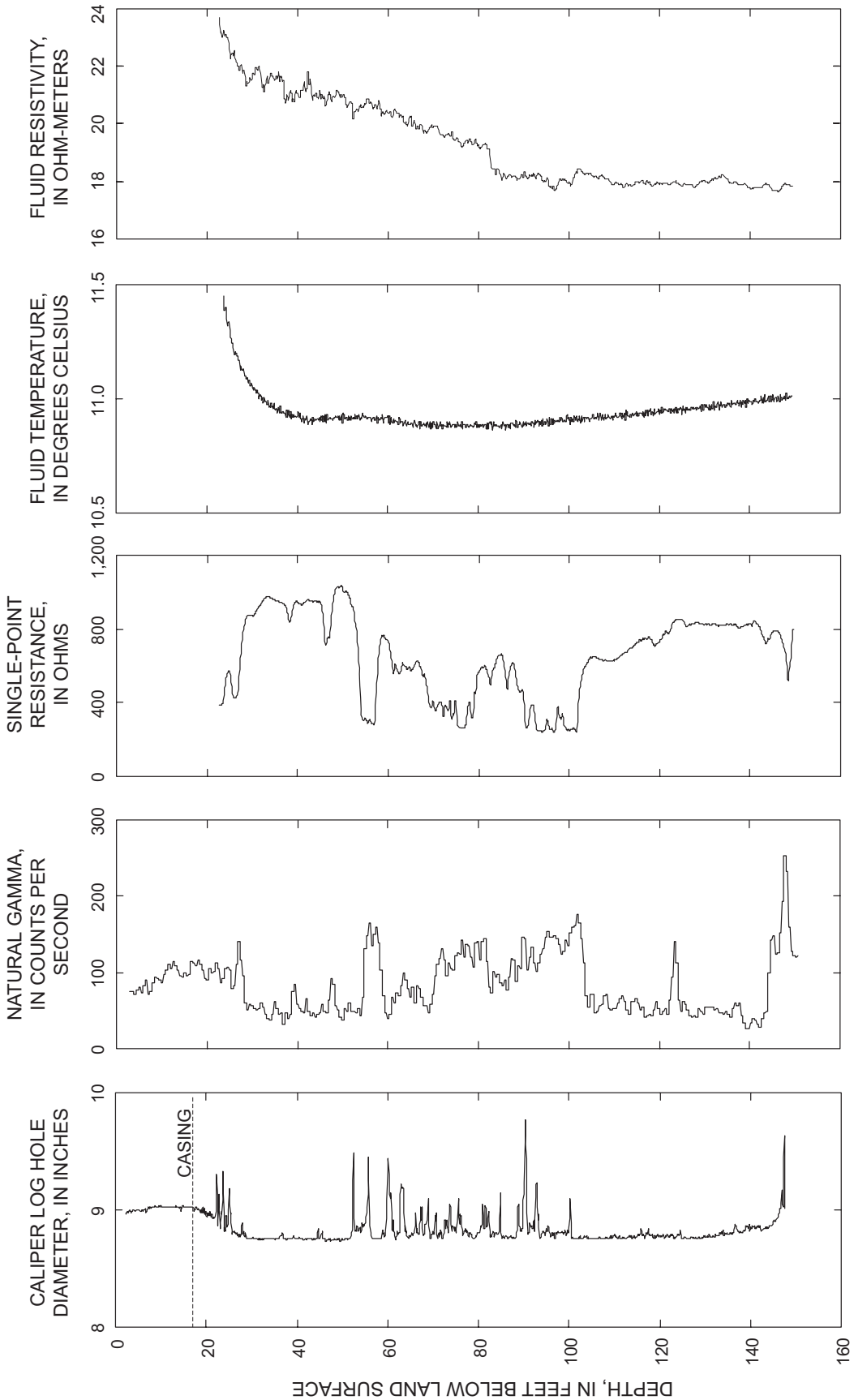

Figure 38. Borehole geophysical logs for well 05MW14I (MG-2138), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania, June 27, 2005.

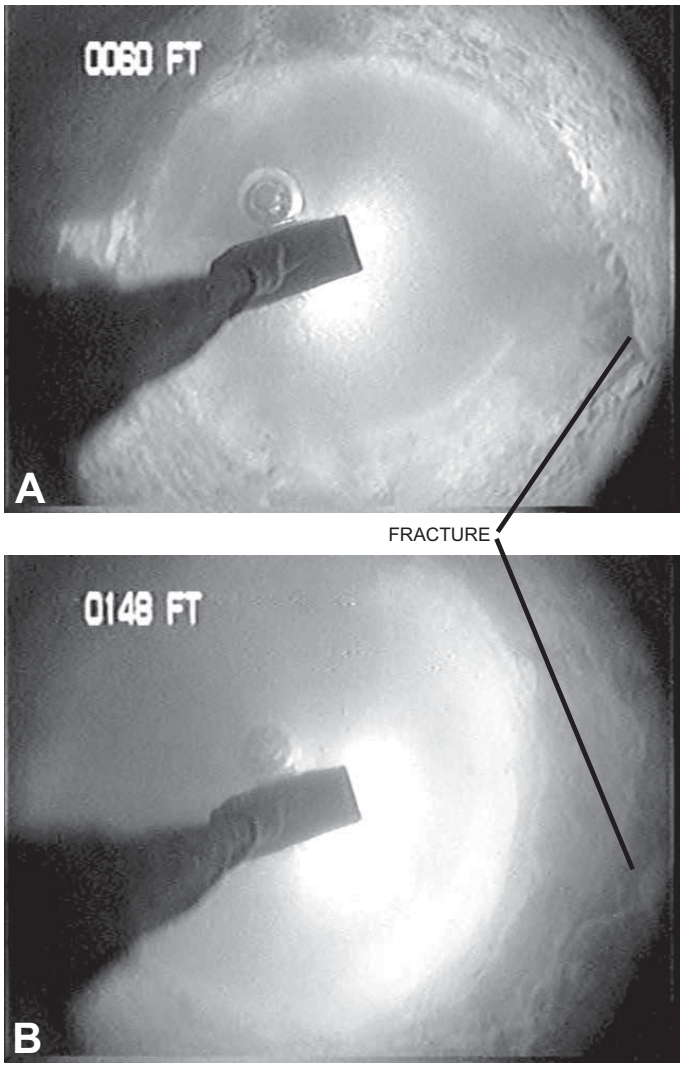

Figure 39. Image from borehole television survey showing (A) vertical fracture at 60 feet below land surface and (B) horizontal fracture at 148 feet below land surface in well 05MW14I (MG-2138), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania, June 28, 2005.

Interpretation of Aquifer-Isolation Tests

On the basis of the borehole geophysical logs, heatpulse-flowmeter measurements, and the borehole television survey, three intervals were selected for aquifer-isolation tests in well 05MW14I (table 24). A straddle-packer assembly was used to isolate discrete fractures to determine depth-discrete specific-capacity values and to obtain depth-discrete water samples. For the test of all intervals, the distance between the bottom of the upper packer and the top of the lower packer was 8 ft. Both packers were inflated for the test of interval 2. For the test of intervals 1 and 3, only the upper packer was inflated. During the tests, water levels were measured in nine wells: 05MW01SI, 05MW05S, 05MW05I, 05MW07S, 05MW07I, 05MW09I, 05MW10S, 05MW10SI, and 05MW10I (fig. 3).

Interval 1 (123.5-148 Feet Below Land Surface)

For the aquifer-isolation test of interval 1, the bottom of the upper packer was set at 123.5 ft bls and inflated to isolate the fractures below 123.5 ft bls. The lower packer was not inflated. Before packer inflation, the depth to water in the open borehole was 20.96 ft bls. After packer inflation, the depth to water in the isolated interval did not change, and the depth to water in the interval above the upper packer increased 0.23 ft. This was consistent with the heatpulse-flowmeter measurements, which showed downward flow. Pumping began at an initial rate of 3 gal/min. After 4 minutes, the pumping rate was increased to 3.5 gal/min. The average pumping rate was 3.4 gal/min. Drawdown was 3.76 ft in the isolated interval. The water level in the interval above the packer rose 0.2 ft during the test. The specific capacity of interval 1 was 0.9 (gal/min)/ft. The hydrographs for the interval above the upper packer and the isolated interval (fig. 40) indicate no hydraulic connection between these intervals. Drawdown in wells 05MW07I, 05MW09I, and 05MW10I caused by pumping interval 1 in well 05MW14I was 0.10, 0.10, and 0.11 ft, respectively. Water levels in wells 05MW01SI, 05MW05S, 05MW05I, 05MW07S, 05MW10S, and 05MW10SI were not affected by pumping interval 1.

Table 24. Intervals isolated during aquifer-isolation tests conducted in well 05MW14I (MG-2138), July 12-13, 2005, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[ft, feet; ft bls, feet below land surface; gal/min, gallons per minute; (gal/min)/ft, gallon per minute per foot of drawdown]

Interval	Depth of isolated fracture (ft bls)	Bottom of upper packer (ft bls)	Top of lower packer (ft bls)	Average pumping rate (gal/min)	Drawdown (ft)	Specific capacity [(gal/min)/ft]
3	Above 63.5	[1]63.5	Not inflated	2.1	3.52	0.60
2	81-82	78.5	86.5	2.1	2.05	1.0
1	123.5-148	123.5	Not inflated	3.4	3.76	.9

[1]Top of upper packer.

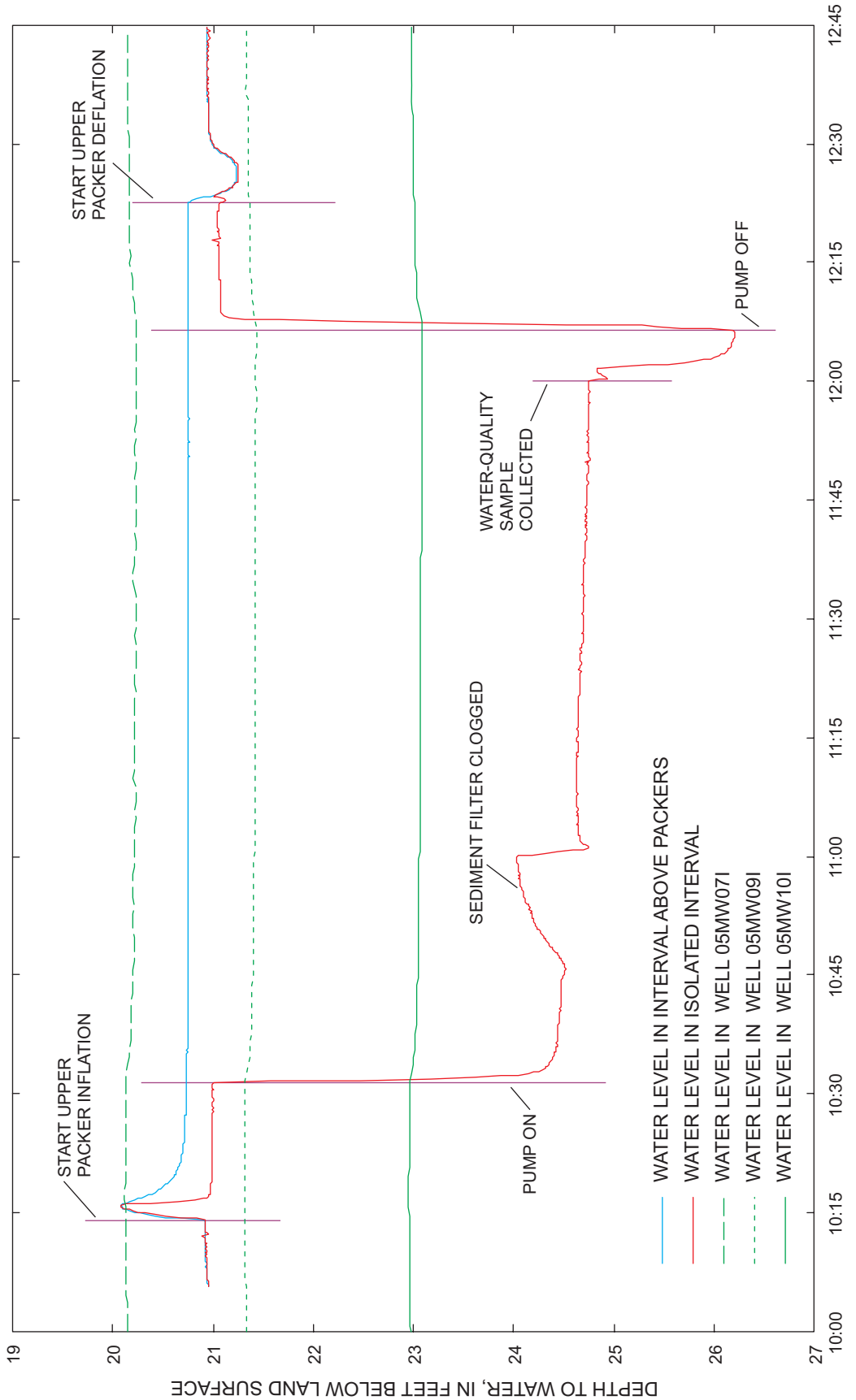

Figure 40. Hydrographs from aquifer-isolation test of interval 1 (123.5-148 feet below land surface) in well 05MW14I (MG-2138), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Interval 2 (78.5-86.5 Feet Below Land Surface)

For the aquifer-isolation test of interval 2, the bottom of the upper packer and the top of the lower packer were set at 78.5 and 86.5 ft bls, respectively, to isolate the fracture zone at 81-82 ft bls. Before packer inflation, the depth to water in the open borehole was 20.90 ft bls. After packer inflation, the depth to water in the isolated interval increased 0.17 ft, the depth to water in the interval below the packers decreased 0.02 ft, and the depth to water in the interval above the packers increased 0.34 ft. This was consistent with the heatpulse-flowmeter measurements, which showed downward flow. The average pumping rate was 2.1 gal/min. Drawdown was 2.05 ft in the isolated interval, 0.09 ft in the interval below the packers, and 0.07 ft in the interval above the packers. The specific capacity of interval 2 was 1.0 (gal/min)/ft. The hydrographs for the interval above the packers, the isolated interval, and the interval below the packers (fig. 41) indicate little hydraulic connection between the isolated interval and the intervals above and below the packers. Drawdown in well 05MW05S caused by pumping interval 2 in well 05MW14I was 0.06 ft. Water levels in wells 05MW01SI, 05MW05I, 05MW07S, 05MW07I, 05MW09I, 05MW10S, 05MW10SI, and 05MW10I were not affected by pumping interval 2.

Interval 3 (45-63.5 Feet Below Land Surface)

For the aquifer-isolation test of interval 3, only the upper packer was inflated. Initially, the top of the upper packer was set at 35.5 ft bls to isolate the fracture at 22-26 ft bls, but this interval was rapidly pumped dry and did not recover, indicating the fractures above 35.5 ft bls were not water bearing. The packer was then lowered so that the top of the upper packer was set at 63.5 ft bls, isolating the fractures above 63.5 ft bls. Because no water was produced above 35.5 ft bls, interval 3 isolates water-producing fractures between 45 and 63.5 ft bls. Before packer inflation, the depth to water in the open borehole was 20.93 ft bls. After packer inflation, the depth to water in the isolated interval above the packer increased 0.02 ft, and the depth to water in the interval below the packer increased 0.08 ft. This was not consistent with the heatpulse-flowmeter measurements, which showed downward flow. The average pumping rate was 2.1 gal/min. Drawdown was 3.52 ft in the isolated interval and 0.43 ft in the interval below the packer. The specific capacity of interval 3 was 0.6 (gal/min)/ft. The hydrographs for the isolated interval above the packer and the interval below the packer (fig. 42) indicate a hydraulic connection between these intervals. Drawdown in well 05MW05S caused by pumping interval 3 was 0.05 ft. Water levels in wells 05MW01SI, 05MW05I, 05MW07S, 05MW07I, 05MW09I, 05MW10S, 05MW10SI, and 05MW10I were not affected by pumping interval 3.

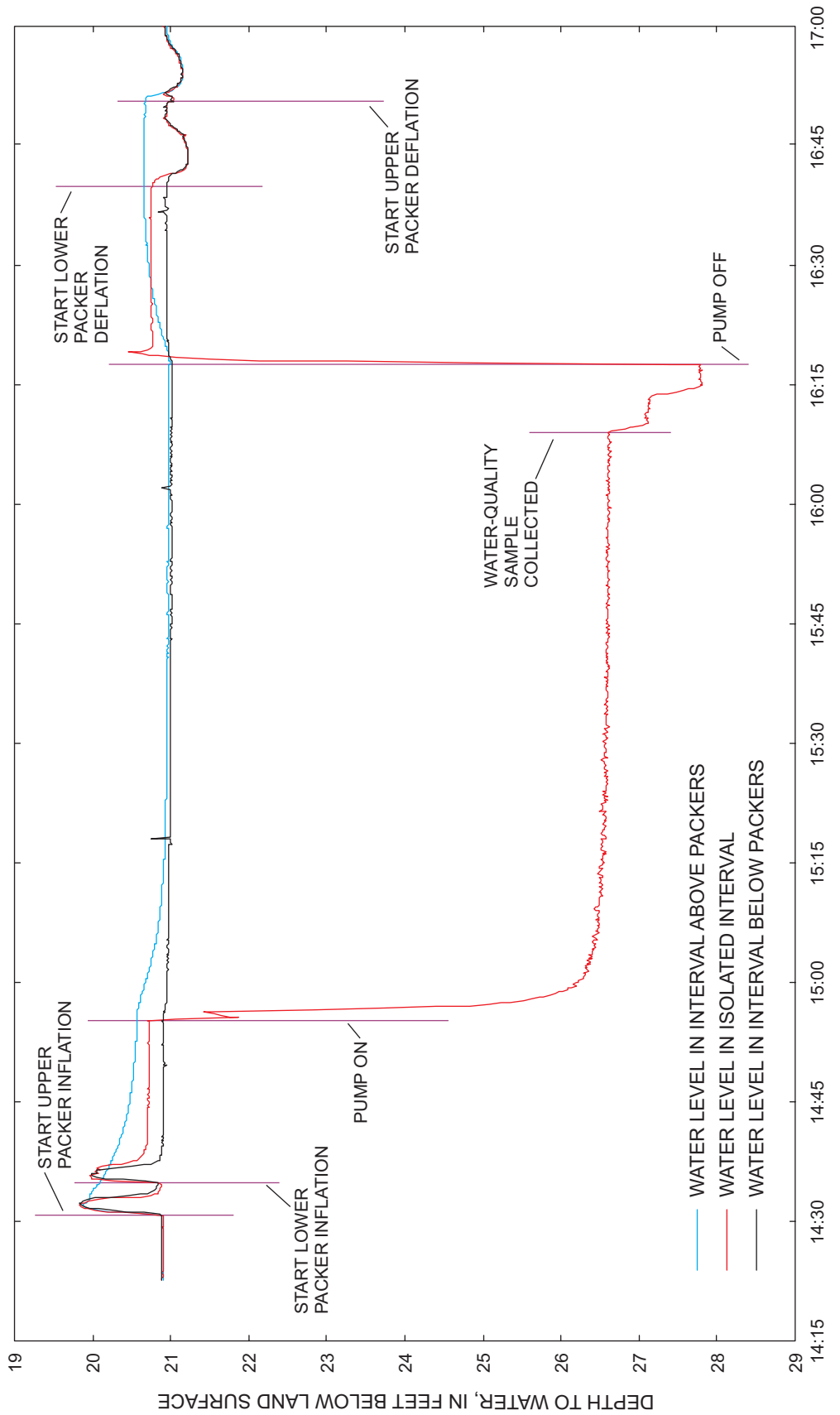

Figure 41. Hydrographs from aquifer-isolation test of interval 2 (78.5-86.5 feet below land surface) in well 05MW14I (MG-2138), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

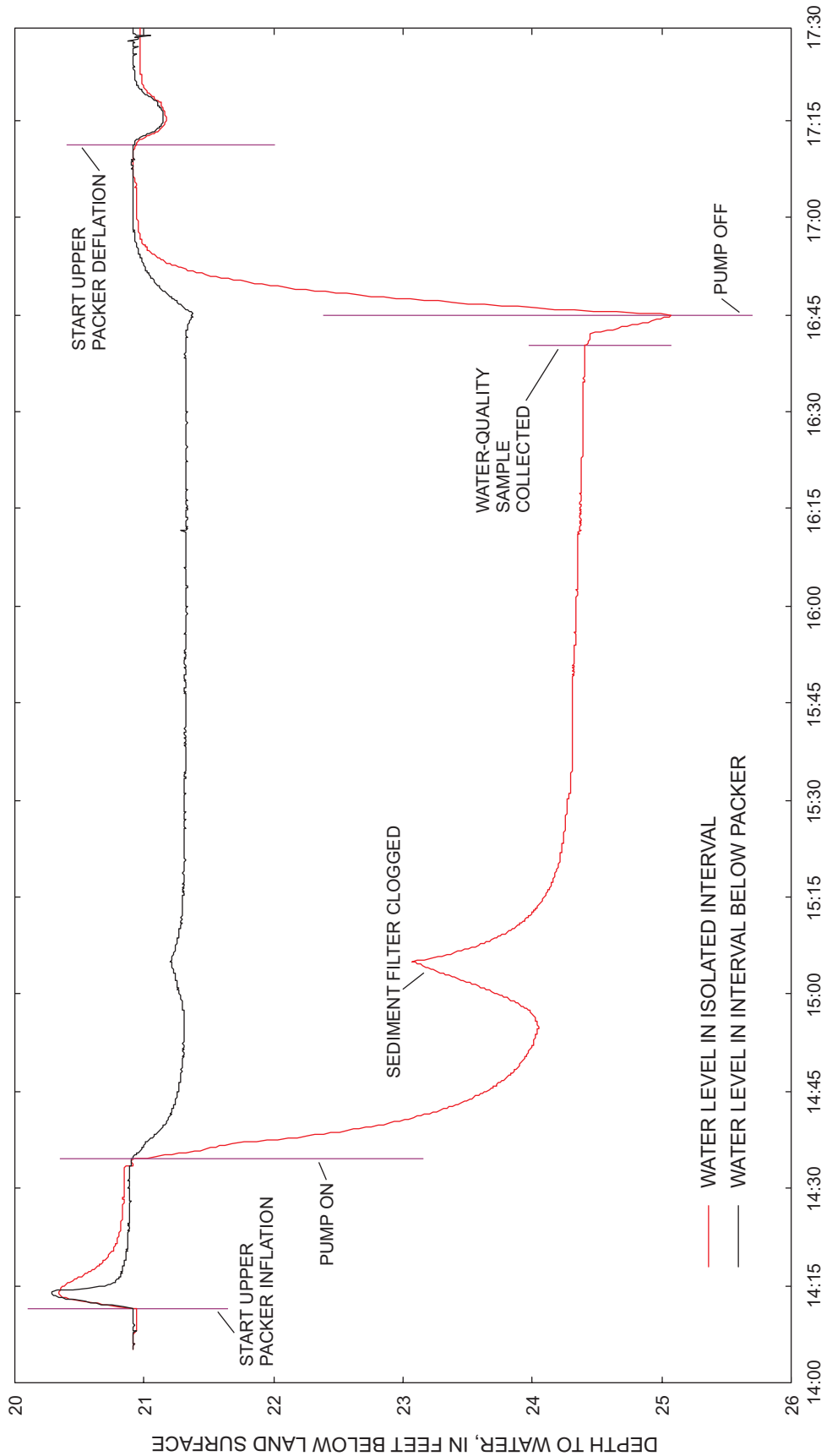

Figure 42. Hydrographs from aquifer-isolation test of interval 3 (45-63.5 feet below land surface) in well 05MW14I (MG-2138), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Vertical Distribution of Water-Quality Constituents

During each aquifer-isolation test, water samples were collected by the USGS for field determinations of water-quality constituents and by TetraTech NUS, Inc., for analysis for VOCs. VOCs detected in water samples collected during aquifer-isolation tests are listed in table 25. Methylene chloride probably is a laboratory contaminant. Concentrations of VOCs except toluene and cis-1,3-dichloropropene were greatest in interval 2 (table 25). Concentrations of VOCs except toluene were greater in interval 1 than in interval 3 (table 25). Concentrations of dissolved oxygen and specific conductance were greater in interval 2 than in interval 3 (table 26).

Table 25. Concentrations of volatile organic compounds detected in water samples collected during aquifer-isolation tests in well 05MW14I (MG-2138), July 12-13, 2005, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[Laboratory results were provided by TetraTech NUS, Inc.; ft bls, feet below land surface; µg/L, micrograms per liter; ND, not detected, reporting limit is 1 µg/L; J, estimated result less than reporting limit; B, constituent detected in blank]

Interval	Depth of sample (ft bls)	1,1-dichloroethene (µg/L)	1,1-dichloroethane (µg/L)	cis-1,2-dichloroethene (µg/L)	cis-1,3-dichloropropene (µg/L)	1,1,1-trichloroethane (µg/L)	1,1,2-trichloroethane (µg/L)	Methylene chloride (µg/L)	Trichloroethylene (µg/L)	Tetrachloroethylene (µg/L)	Toluene (µg/L)
3	45-63.5	12	6.7	1.1	0.42 J	13	ND	0.52 J	4.8	0.35 J	27
2	78.5-86.5	28	16	2.7	ND	33	0.42 J	.61 JB	11	.72 J	2.6
1	123.5-148	17	9.2	1.6	ND	18	.30 J	ND	7.7	.58 J	2.2

Table 26. Selected water-quality constituents measured in the field in water samples collected during aquifer-isolation tests in well 05MW14I (MG-2138), July 12-13, 2005, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[ft bls, feet below land surface; mg/L, milligrams per liter; µS/cm at 25°C, microsiemens per centimeter at 25 degrees Celsius; C, Celsius; —, no data]

Interval	Depth of sample (ft bls)	Dissolved oxygen (mg/L)	pH (standard units)	Specific conductance (µS/cm at 25°C)	Temperature (degrees C)
3	45-63.5	0.8	6.4	273	13.3
2	78.5-86.5	1.0	6.3	332	13.2
1	123.5-148	—	—	—	—

Well 05MW15I (MG-2139)

Well 05MW15I was drilled approximately 955 ft west of the 05MW01 well cluster (fig. 3). It is directly along strike from the 05MW01 well cluster.

Interpretation of Borehole Geophysical Logs

A suite of borehole geophysical logs (fig. 43) was collected in well 05MW15I by the USGS on June 28, 2005. The caliper log shows the well is 150 ft deep, cased to 31 ft bls, and major fractures are at 37, 43, 64-78, and 142-143 ft bls. The fluid-temperature log shows a change in slope between about 68-81 and 111-115 ft bls. The fluid-resistivity log shows sharp breaks in slope at about 59 and 143 ft bls. The fluid-temperature and fluid-resistivity logs indicate possible water-producing zones at these depths.

Heatpulse-flowmeter measurements were made under nonpumping conditions and while pumping the well at 0.65-0.7 gal/min (table 27). Heatpulse-flowmeter measurements made under nonpumping conditions indicated no borehole flow. The geophysical logs and heatpulse-flowmeter measurements indicate water-producing zones at 37, 64-76, and 142-143 ft bls. Well 05MW15I was screened later from 140 to 150 ft bls to monitor the principle water-producing fracture at 142-143 ft bls (fig. 44).

Table 27. Heatpulse-flowmeter measurements made in well 05MW15I (MG-2139), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania, June 28, 2005.

[—, no data]

Depth (feet below land surface)	Nonpumping measurements		Pumping measurements	
	Flow (gallon per minute)	Flow direction	Relative flow[1] (gallon per minute)	Pumping rate (gallon per minute)
34	0	—	0.72	0.72
40	0	—	.53	.71
52	0	—	.91	.71
61	0	—	.53	.71
82	0	—	.14	.70
96	0	—	.11	.70
110	0	—	.11	.67
124	0	—	.16	.65
132	—	—	.09	.65
137.4	0	—	—	—

[1]Upward flow.

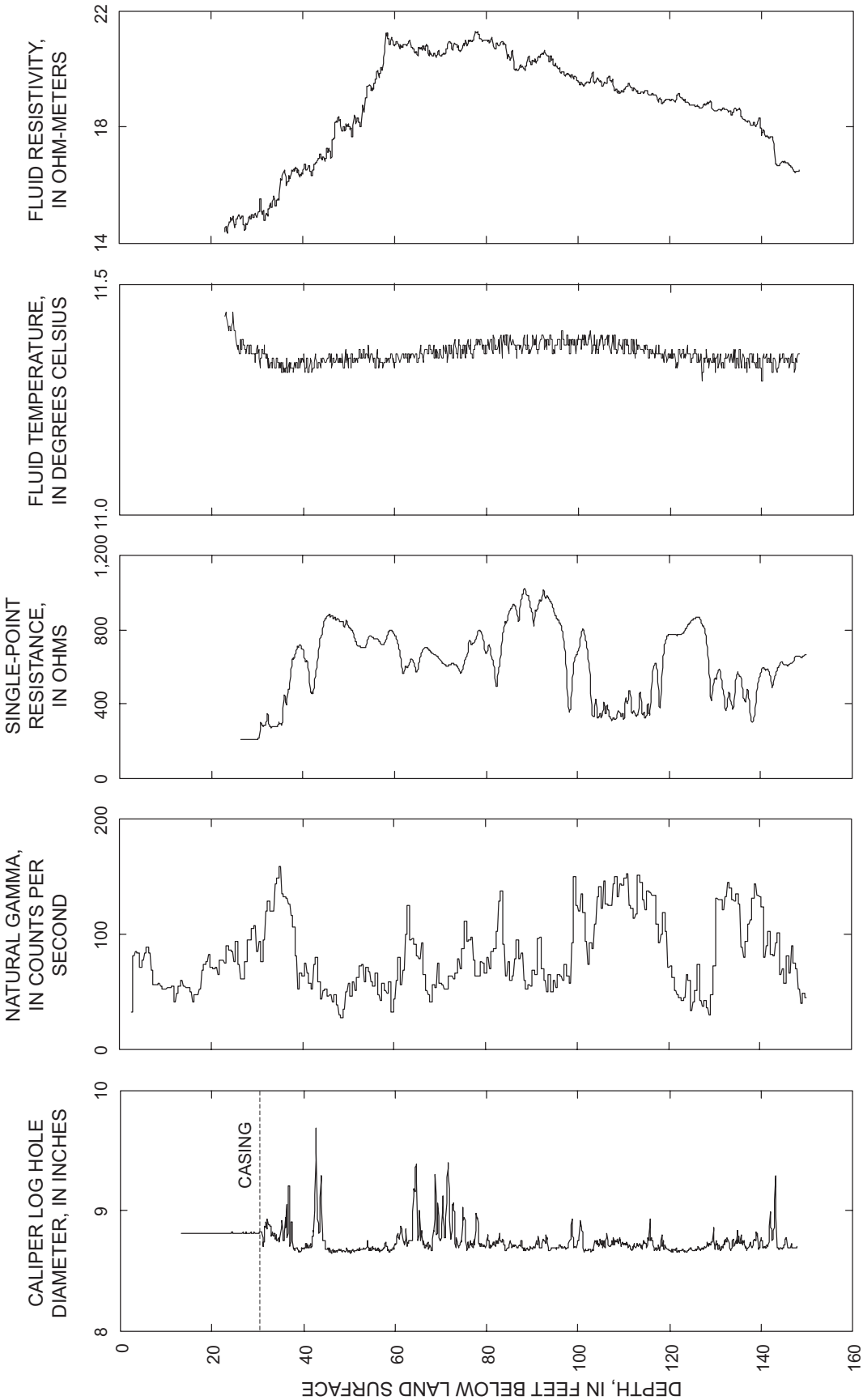

Figure 43. Borehole geophysical logs for well 05MW15I (MG-2139), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania, June 28, 2005.

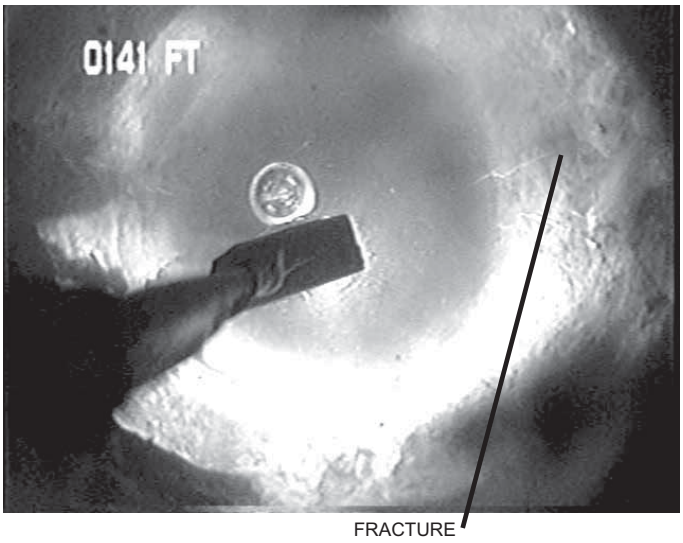

Figure 44. Image from borehole television survey showing vertical fracture at 142 feet below land surface in well 05MW15I (MG-2139), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania, June 27, 2005.

Interpretation of Aquifer-Isolation Tests

On the basis of the borehole geophysical logs and the borehole television survey, four intervals were selected for aquifer-isolation tests in well 05MW15I (table 28). A straddle-packer assembly was used to isolate discrete fractures to determine depth-discrete specific-capacity values and to obtain depth-discrete water samples. For the test of interval 2, the distance between the bottom of the upper packer and the top of the lower packer was 8 ft. For the test of interval 3, the distance between the bottom of the upper packer and the top of the lower packer was 15.8 ft. For the tests of intervals 1 and 4, only the upper packer was inflated. During the tests, water levels were measured in wells 05MW13I and 05MW14I.

Interval 1 (134.5-150 Feet Below Land Surface)

For the aquifer-isolation test of interval 1, the bottom of the upper packer was set at 134.5 ft bls to isolate the fracture zone at 142-143 ft bls. Before packer inflation, the depth to water in the open borehole was 16.08 ft bls. After packer inflation, the depth to water in the isolated interval below the packer decreased 0.07 ft, and the depth to water in the interval above the upper packer increased 0.16 ft. Pumping began at an initial rate of 1.8 gal/min, and 4 minutes later, the pumping rate was increased to 2.7 gal/min. The average pumping rate was 2.6 gal/min. Drawdown was 3.10 ft in the isolated interval and 0.01 ft in the interval above the upper packer. The specific capacity of interval 1 was 0.84 (gal/min)/ft. The hydrographs for the interval above the upper packer and the isolated interval (fig. 45) indicate no hydraulic connection between these intervals. Drawdown in wells 05MW13I and 05MW14I caused by pumping interval 1 in well 05MW15I was 0.08 and 0.10 ft, respectively.

Interval 2 (124.5-132.5 Feet Below Land Surface)

For the aquifer-isolation test of interval 2, the bottom of the upper packer and the top of the lower packer were set at 124.5 and 132.5 ft bls, respectively, to isolate the fracture zone at 130 ft bls. The yield of this interval was approximately 0.4 gal/min. It was pumped dry and allowed to recover overnight. It was pumped dry again the next morning, allowed to recover, and pumped again to collect a water sample. Water levels in wells 05MW13I and 05MW14I were not affected by pumping interval 2.

Table 28. Intervals isolated during aquifer-isolation tests conducted in well 05MW15I (MG-2139), July 14-15, 2005, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[ft, feet; ft bls, feet below land surface; gal/min, gallons per minute; (gal/min)/ft, gallons per minute per foot of drawdown; —, no data]

Interval	Depth of isolated fracture (ft bls)	Bottom of upper packer (ft bls)	Top of lower packer (ft bls)	Average pumping rate (gal/min)	Drawdown (ft)	Specific capacity [(gal/min)/ft]
4	Above 46.5	[1]46.5	Not inflated	0.3	—	—
3	62-76	61.5	77.3	3.6	2.58	1.4
2	130	124.5	132.5	0.4	—	—
1	142-143	134.5	Not inflated	2.6	3.10	0.84

[1]Top of packer.

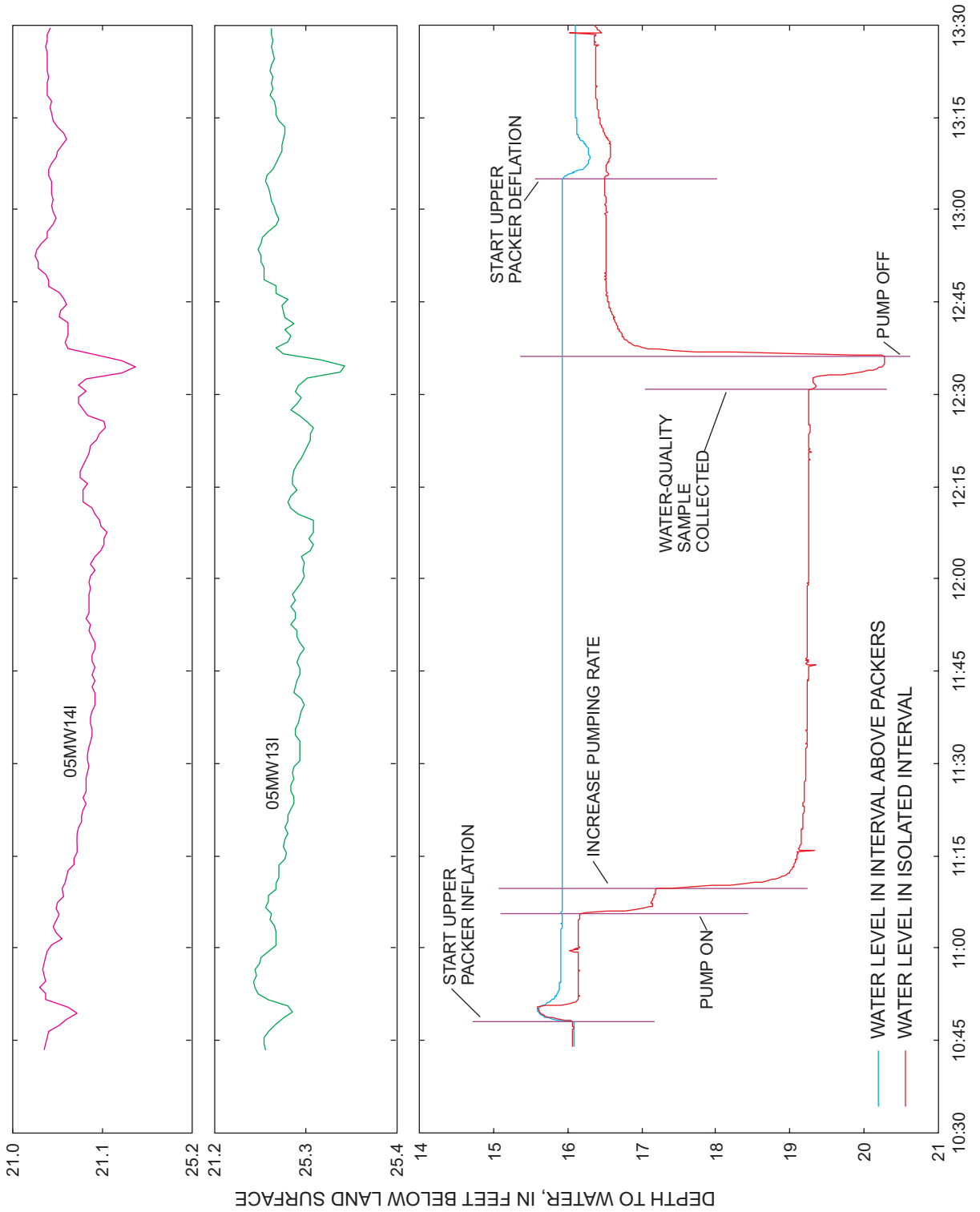

Figure 45. Hydrographs from aquifer-isolation test of interval 1 (134.5-150 feet below land surface) in well 05MW15I (MG-2139), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Interval 3 (61.5-77.3 Feet Below Land Surface)

For the aquifer-isolation test of interval 3, the bottom of the upper packer and the top of the lower packer were set at 61.5 and 77.3 ft bls, respectively, to isolate the fracture zone at 62-76 ft bls. Before packer inflation, the depth to water in the open borehole was 14.98 ft bls. After packer inflation, the depth to water in the isolated interval increased 0.17 ft, the depth to water in the interval below the packers decreased 0.10 ft, and the depth to water in the interval above the packers increased 0.35 ft. The rise in water level in the interval above the packers was caused by recharge from heavy rain during the 2 days prior to the test. The average pumping rate was 3.6 gal/min. Drawdown was 2.58 ft in the isolated interval, 0.11 ft in the interval below the packers, and 0.50 ft in the interval above the packers. The specific capacity of interval 3 was 1.4 (gal/min)/ft. The hydrographs for the interval above the packers, the isolated interval, and the interval below the packers (fig. 46) indicate a weak hydraulic connection between the isolated interval and the intervals above and below the packers. Water levels in wells 05MW13I and 05MW14I were not affected by pumping interval 3.

Interval 4 (31-46.5 Feet Below Land Surface)

For the aquifer-isolation test of interval 4, the top of the upper packer was set at 46.5 ft bls, and the bottom packer was not inflated. This isolated the fracture zones at 36-38 and 42-44 ft bls. The yield of this interval was approximately 0.3 gal/min. It was pumped dry, allowed to recover, and pumped again to obtain a water sample. Water levels in wells 05MW13I and 05MW14I were not affected by pumping interval 4.

Vertical Distribution of Water-Quality Constituents

During each aquifer-isolation test, water samples were collected by TetraTech NUS, Inc., for analysis for VOCs. VOCs detected in water samples collected during aquifer-isolation tests are listed in table 29. Chloroform and methylene chloride are laboratory or field blank contaminants. Concentrations of VOCs except toluene were less than 2 µg/L (table 29). Concentrations of toluene ranged from 0.63 µg/L in interval 3 to 77 µg/L in interval 2. The highest concentrations of most of the other VOCs were in the water sample from interval 1. Field determinations of water-quality constituents by the USGS were made only for interval 1. The dissolved oxygen concentration was 1.9 mg/L, pH was 6.3, specific conductance was 297 µS/cm, and the temperature was 13.1° C.

Table 29. Concentrations of volatile organic compounds detected in water samples collected during aquifer-isolation tests in well 05MW15I (MG-2139), July 14-18, 2005, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[Laboratory results were provided by TetraTech NUS, Inc.; ft bls, feet below land surface; µg/L, micrograms per liter; ND, not detected, reporting limit is 1 µg/L; D, determined from diluted sample; J, estimated result less than reporting limit; B, constituent detected in blank]

Interval	Depth of sample (ft bls)	1,1-dichloroethene (µg/L)	1,1-dichloroethane (µg/L)	1,1,1-trichloroethane (µg/L)	Chloroform (µg/L)	Methylene chloride (µg/L)	Methylcyclohexane (µg/L)	Toluene (µg/L)	Trichloroethylene (µg/L)	m- and p-xlyenes (µg/L)
4	31-46.5	ND	ND	ND	ND	ND	ND	45 D	ND	ND
3	61.5-77.3	ND	ND	0.53 J	1.3	ND	ND	.63 J	ND	ND
2	124.5-132.5	0.77 J	0.34 J	.48 J	ND	0.56 JB	0.50 J	77 D	0.30 J	0.34 J
1	134.5-150	1.8	.75 J	1.0	ND	ND	ND	2.8	.62 J	ND

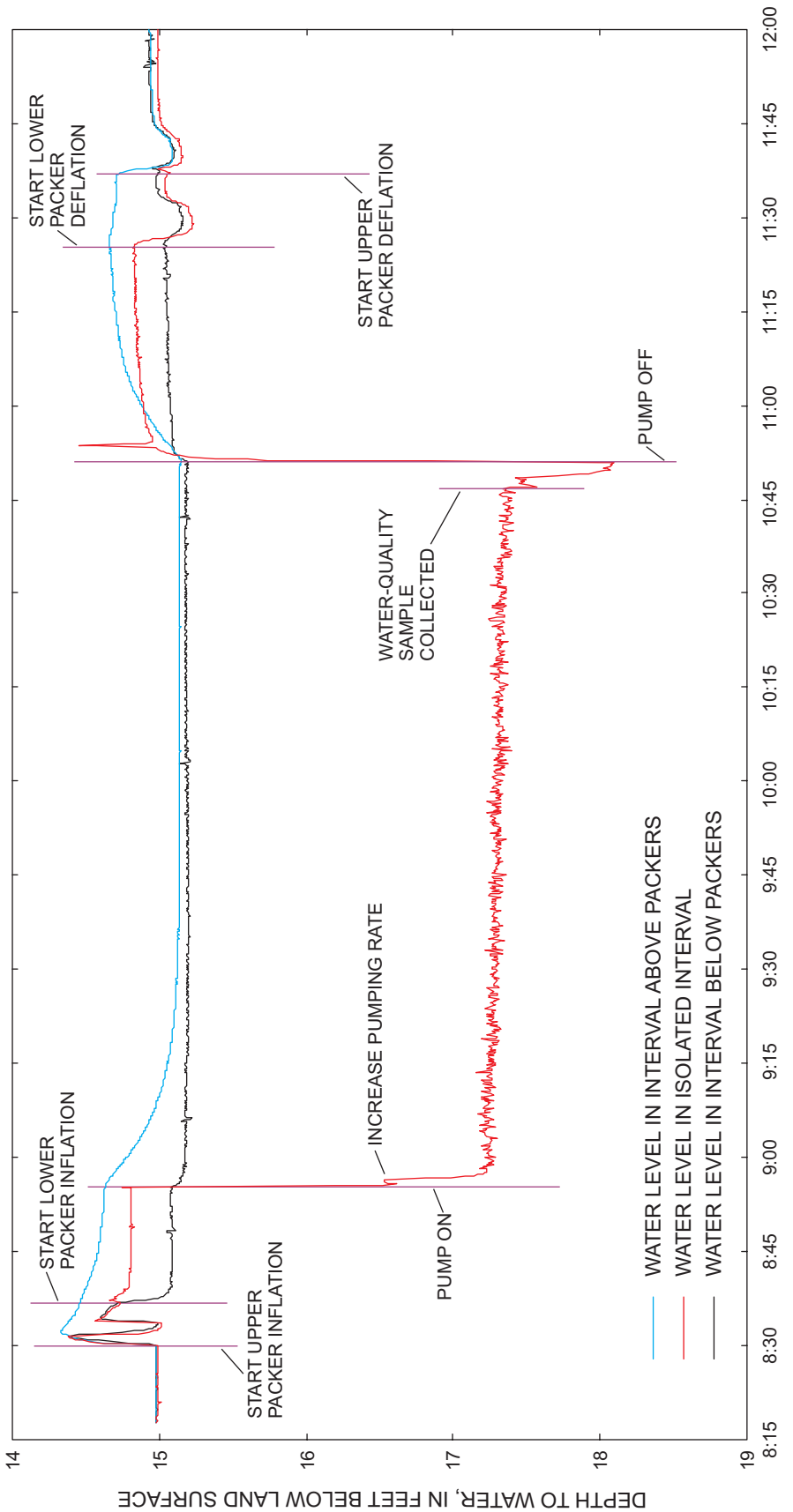

Figure 46. Hydrographs from aquifer-isolation test of interval 3 (61.5-77.3 feet below land surface) in well 05MW15I (MG-2139), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Summary and Conclusions

This study was done by U.S. Geological Survey (USGS) in cooperation with the U.S. Navy at the Willow Grove Naval Air Station/Joint Reserve Base (NAS/JRB) in Horsham Township, Montgomery County, Pa., in support of hydrogeological investigations conducted by the Navy to address ground-water contamination. The study presents an interpretation of borehole geophysical logs, heatpulse-flowmeter measurements, aquifer-isolation tests, and water-quality data for seven wells. The Willow Grove NAS/JRB is underlain by the Stockton Formation, which consists of sedimentary rocks of Triassic age. At the base, bedding in the Stockton Formation strikes N. 76° E. and dips about 7° NW. The rocks of the Stockton Formation form a complex, heterogeneous aquifer with partially connected zones of high permeability. Ground water in the unweathered part of the Stockton Formation primarily flows through a network of interconnecting secondary openings—bedding-plane fractures and joints. Wells generally penetrate several major water-producing zones with different hydraulic properties. Each water-producing zone usually has a different hydraulic head (water level) than adjacent zones. The head in an open-hole well is the composite of the heads in the water-producing zones penetrated. This can cause heads in some wells to be different than heads in adjacent wells of different depths. Where differences in head exist between water-producing zones, water in the well bore flows in the direction of decreasing head.

Borehole geophysical logging, heatpulse-flowmeter measurements, borehole television surveys, and aquifer-isolation tests were made in seven boreholes ranging from 70 to 350 ft deep. The aquifer-isolation tests isolated 30 discrete fractures or fracture zones in the seven boreholes for collection of depth-discrete hydraulic data and water-quality samples. An upward vertical hydraulic gradient was measured in one well (well 05MW13I), a downward vertical hydraulic gradient was measured in four wells (wells 01MW10, 03MW08, 05MW12S, and 05MW14I), both an upward and a downward vertical hydraulic gradient were measured in one well (well 01MW09), and no flow was measurable in one well (well 05MW15I). Of the 30 fractures identified as potentially water producing, 26 fractures (87 percent) produced more than 1 gallon per minute (gal/min) of water. The specific capacity of the isolated intervals producing more than 1 gal/min ranged from 0.02 to 5.2 gallons per minute per foot ([gal/min]/ft). There was no relation between specific capacity and depth of the fracture.

At Site 1, wells 01MW09 and 01MW10 were tested. The water level in these wells is greatly affected by the pumping of the base supply wells. Well 01MW09 was drilled to 150 feet (ft) and cased to 29 ft below land surface (bls). Water entered the borehole through a large vertical fracture at 59-66 ft bls and flowed both upward and downward. Water flowing upward exited the borehole through fractures above 44 ft bls, and water flowing downward exited through a horizontal fracture at 125 ft bls. Three intervals were selected for aquifer-isolation tests. Interval 3 (29-50 ft bls) produced little water. Interval 2 (57-67 ft bls) had a higher specific capacity [0.44 (gal/min)/ft] than interval 1 (120.5-131.5 ft bls), which had a specific capacity of 0.02 (gal/min)/ft. Concentrations of PCE (tetrachloroethylene) (4.1 µg/L) and TCE (trichlororethylene) (1.5 µg/L) above the laboratory reporting limit were detected only in the water sample from interval 1. Interval 1 is in lithologic unit H, which had the greatest PCE concentration in well SW-1.

Well 01MW10 was drilled to 350 ft and cased to 39 ft bls. All measured flow was downward, except for the measurement made at 316.2 ft bls, which was upward. Water entered the borehole through fractures at 43, 55-56, 71-86, 110, 153, and 215 ft bls. Water exited the borehole through a horizontal fracture at 310 ft bls. Eight intervals were selected for aquifer-isolation tests. Specific capacity ranged from 0.05 to 3.0 (gal/min)/ft. The highest concentrations of PCE (62 µg/L), TCE (4.5 µg/L), and cis-1,2-dichloroethene (3.4 µg/L) were in water samples collected from interval 5 (148.7-159.7 ft bls). Interval 5 straddles lithologic units F and G. Concentrations of VOCs from intervals 1 (305-316 ft bls) and 2 (263-274 ft bls) were similar. The second greatest concentrations of PCE were from intervals 1 and 2 (both 30 µg/L). Intervals 1 and 2 are in lithologic units M and L, respectively. No VOCs were detected in the shallowest interval (38-62.7 ft bls). The water sample from interval 5 had the lowest temperature (13.0 °C) and concentration of dissolved oxygen (1.9 mg/L) and the highest concentration of VOCs, pH (7.2), and specific conductance (855 µS/cm) of the intervals sampled.

At Site 3, well 03MW08 was tested. Well 03MW08 was drilled to 222 ft and cased to 38 ft bls. Water entered the borehole through the fracture zone above 70 ft bls and flowed downward. Additional water entered the borehole through a horizontal fracture at 80 ft bls and flowed downward. Water flowing downward exited the borehole through horizontal fractures at 121-124, 138, and 169 ft bls. Six intervals were selected for aquifer-isolation tests. Specific capacity ranged from 0.04 to 1.5 (gal/min)/ft. Concentrations of VOCs were less than 10 µg/L. The most prevalent compound at Site 3 was 1,1-dichloroethane; concentrations were as great as 9.3 µg/L. The concentration of most VOCs generally increased with depth to interval 2 (162-173 ft bls). Concentrations of VOCs were highest in interval 2. Concentrations of VOCs in the deepest interval (interval 1) (21 µg/L) were less than concentrations in interval 2 (31 µg/L). Concentrations of dissolved oxygen generally decreased with depth, and specific conductance and temperature increased with depth. The interval (interval 2) with the highest total VOC concentration also had the lowest dissolved oxygen concentration (3.2 mg/L).

At Site 5, wells 05MW12S, 05MW13I, 05MW14I, and 05MW15I were tested. Well 05MW12S was drilled to 70 ft and cased to 17 ft bls. Water entered the borehole through a horizontal fracture at 32 ft bls and flowed downward. Water exited the borehole at 65 ft bls through a long vertical fracture. Two intervals were selected for aquifer-isolation tests. Specific capacity was 2.3 (gal/min)/ft for interval 1 (51.5-70 ft bls) and 3 (gal/min)/ft for interval 2 (17-44.5 ft bls). The concentration of toluene was greater in the shallower interval 2 (4.1 µg/L) than

in the deeper interval 1 (0.86 µg/L). PCE (0.38 µg/L) and 1,1-dichloroethane (0.46 µg/L) were detected only in the water sample from interval 1.

Well 05MW13I was drilled to 181 ft and cased to 29 ft bls. Water entered the borehole through a horizontal fracture at 159 ft bls and flowed upward. Some water exited the borehole through a vertical fracture zone at 129-139 ft bls. Most of the water exited the borehole through horizontal fractures at 105 and 73 ft bls. Five intervals were selected for aquifer-isolation tests. Specific capacity ranged from 1.3 to 5 (gal/min)/ft. The highest concentrations of VOCs (58 µg/L) were measured in interval 3 (128.5-140.4 ft bls). Concentrations of VOCs were similar in intervals 2 (151.5-163.5 ft bls) and 3 and in intervals 4 (100.5-112.5 ft bls) and 5 (64.5-76.5 ft bls). The lowest concentrations of VOCs were measured in interval 5 (15 µg/L), the shallowest interval. Concentrations of VOCs generally increased with depth to a maximum in interval 3 and then decreased with depth below interval 3. Specific conductance followed the same pattern. The interval (interval 3) with the highest total VOC concentration also had the lowest dissolved oxygen concentration (1.8 mg/L).

Well 05MW14I was drilled to 148 ft and cased to 22 ft bls. Water entered the borehole through a horizontal fracture at 45 ft bls and flowed downward. Some of the water exited the borehole through a small vertical fracture at 81 ft bls. Additional water entered the borehole through a vertical fracture at 100 ft bls and flowed downward. Water exited the borehole through a horizontal fracture at the bottom of the borehole (147-148 ft bls). Three intervals were selected for aquifer-isolation tests. Specific capacity ranged from 0.6 to 1 (gal/min)/ft. Concentrations of VOCs (94 µg/L) were greatest in interval 2 (78.5-86.5 ft bls). Concentrations of chlorinated VOCs were greater in interval 1 (123.5-148 ft bls) (54 µg/L) than in interval 3 (45-63.5 ft bls) (38 µg/L).

Well 05MW15I was drilled to 150 ft and cased to 31 ft bls. No borehole flow was measurable in well 05MW15I. Four intervals were selected for aquifer-isolation tests. Two intervals produced little water. The specific capacity of the other two intervals was 0.84 and 1.4 (gal/min)/ft. Concentrations of VOCs except toluene were less than 2 µg/L. Concentrations of toluene ranged from 0.63 µg/L in interval 3 to 77 µg/L in interval 2. The highest concentrations of most of the other VOCs were in the water sample from interval 1 (134.5-150 ft bls).

PCE was the most prevalent compound at Site 1; concentrations were as great as 62 µg/L. 1,1-dichloroethane was the most prevalent compound at Site 3; concentrations were as great as 9.3 µg/L. Toluene was the most prevalent compound at Site 5; concentrations were as great as 77 µg/L. For five out of the six wells sampled for field determinations (83 percent), the interval with the lowest dissolved oxygen concentration had the highest total VOC concentration.

Acknowledgments

VOC data used for this study and presented in this report were provided by TetraTech NUS, Inc., and ECOR Solutions, Inc. Borehole geophysical logging was done by Randall Conger of the USGS. Borehole television surveys were made by Philip Bird of the USGS. Aquifer-isolation tests were conducted by Peter Cinotto, Robert Rosman, Leif Olson, Randall Conger, and Philip Bird of the USGS. Critical reviews of this report were completed by Glen Carleton and Randall Conger of the USGS and Kevin Kilmartin of TetraTech NUS, Inc.

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