In cooperation with the
U.S. NAVY

Interpretation of Borehole Geophysical Logs, Aquifer-Isolation Tests, and Water Quality, Supply Wells 1 and 2, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania

by Ronald A. Sloto, Daniel J. Goode, and Steven M. Frasch

Water-Resources Investigations Report 01-4264

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

New Cumberland, Pennsylvania
2002

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

For additional information
write to:

District Chief
U.S. Geological Survey
215 Limekiln Road
New Cumberland, Pennsylvania 17070-2424
Email: dc_pa@usgs.gov
Internet Address: http://pa.water.usgs.gov

Copies of this report may be
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U.S. Geological Survey
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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
	Length	
inch (in)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
acre	0.4047	hectare
	Volume	
gallon (gal)	3.785	liter
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second
	Specific capacity	
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter
	Temperature	
degree Fahrenheit (°F)	°C=5/9 (°F-32)	degree Celsius

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

Abbreviated water-quality units used in report:

mg/L, milligrams per liter
µg/L, micrograms per liter
µS/cm, microsiemens per centimeter at 25 degrees Celsius

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ABSTRACT

Ground water pumped from supply wells 1 and 2 on the Willow Grove Naval Air Station/Joint Reserve Base (NAS/JRB) provides water for use at the base, including potable water for drinking. The supply wells have been contaminated by volatile organic compounds (VOC's), particularly trichloroethylene (TCE) and tetrachloroethylene (PCE), and the water is treated to remove the VOC's. The Willow Grove NAS/JRB and surrounding area are underlain by sedimentary rocks of the Triassic-age Stockton Formation, which form a complex, heterogeneous aquifer.

The ground-water-flow system for the supply wells was characterized by use of borehole geophysical logs and heatpulse-flowmeter measurements. The heatpulse-flowmeter measurements showed upward and downward borehole flow under nonpumping conditions in both wells. The hydraulic and chemical properties of discrete water-bearing fractures in the supply wells were characterized by isolating each water-bearing fracture with straddle packers. Eight fractures in supply well 1 and five fractures in supply well 2 were selected for testing on the basis of the borehole geophysical logs and borehole television surveys. Water samples were collected from each isolated fracture and analyzed for VOC's and inorganic constituents.

Fractures at 50–59, 79–80, 196, 124–152, 182, 241, 256, and 350–354 ft btoc (feet below top of casing) were isolated in supply well 1. Specific capacities ranged from 0.26 to 5.7 (gal/min)/ft (gallons per minute per foot) of drawdown. The highest specific capacity was for the fracture isolated at 179.8–188 ft btoc. Specific capacity and depth of fracture were not related in either supply well. The highest concentrations of PCE were in water samples collected from fractures isolated at 236.8–245 and 249.8–258 ft btoc, which are hydraulically connected. The concentration of PCE generally increased with depth to a maximum of 39 µg/L (micrograms per liter) at a depth of 249.8–258 ft btoc and then decreased to 21 µg/L at a depth of 345.3–389 ft btoc.

Fractures at 68–74, 115, 162, 182, 205, and 314 ft btoc were isolated in supply well 2. Specific capacities ranged from 0.08 to less than 2.9 (gal/ min)/ft. The highest specific capacity was for the fracture isolated at 157–165.2 ft btoc. Concentrations of detected VOC's in water samples were 3.6 µg/L or less.

Lithologic units penetrated by both supply wells were determined by correlating natural-gamma and single-point-resistance borehole geophysical logs. All lithologic units are not continuous water-bearing units because water-bearing fractures are not necessarily present in the same lithologic units in each well. Although the wells penetrate the same lithologic units, the lithologic location of only three water-bearing fractures are common to both wells. The same lithologic unit may have different hydraulic properties in each well.

A regional ground-water divide is southeast of the supply wells. From this divide, ground water flows northwest toward Park Creek, a tributary to Little Neshaminy Creek. Potentiometric-surface maps were prepared from water levels measured in shallow and deep wells. For both depth intervals, the direction of ground-water flow is toward the northwest. For most well clusters, the vertical head gradient is downward from the shallow to the deeper part of the aquifer. Pumping of the supply wells at times can cause the vertical flow direction to reverse.

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 U.S. Marine and U.S. Army activities. The U.S. Air Force has property holdings within the base boundary and shares

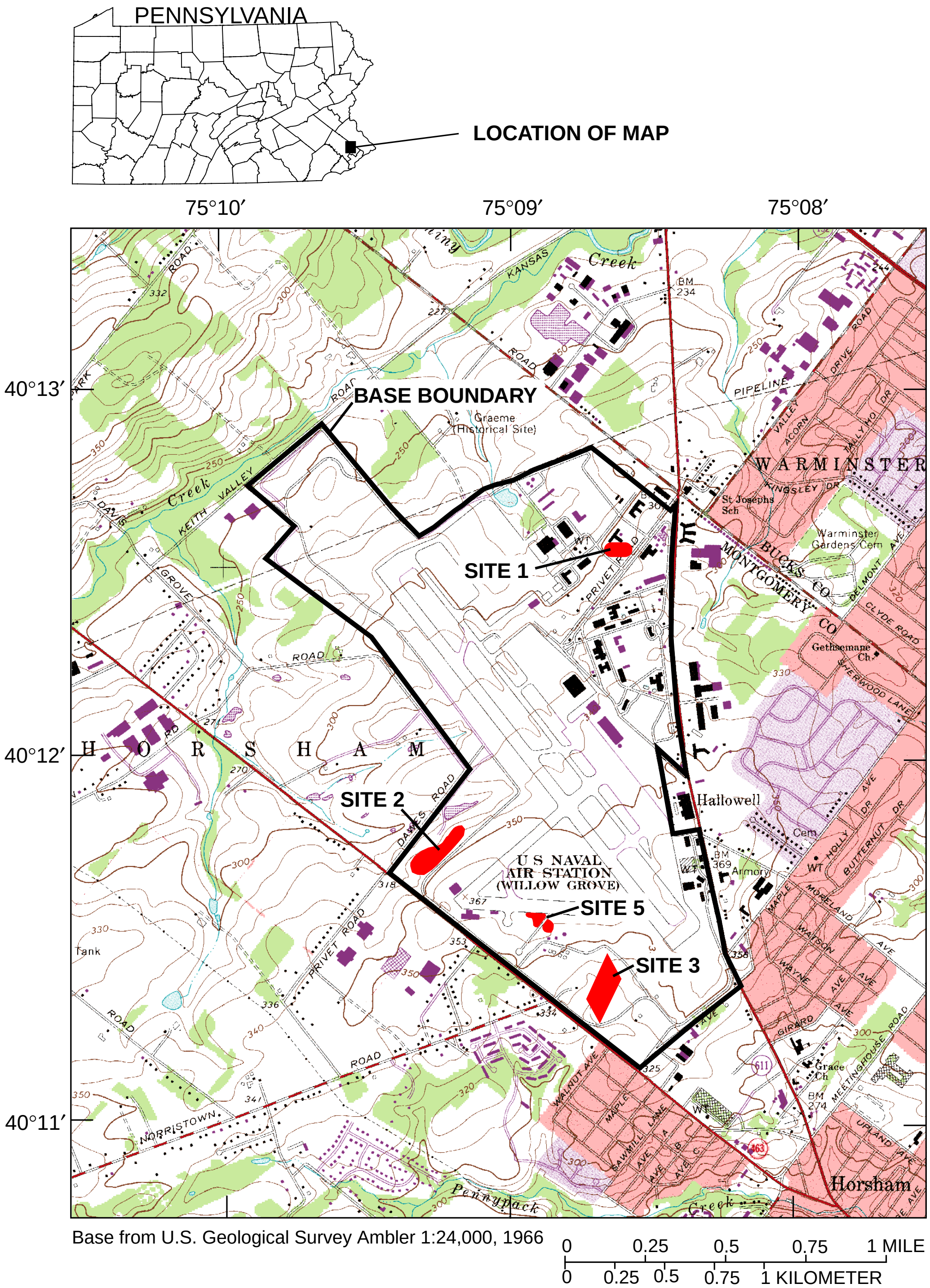


Figure 1. Location of the Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

common facilities with the U.S. Navy. Contaminated sites within the base (fig. 1) 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 as part of the U.S. Navy's Installation Restoration Program to address ground-water contamination at these sites.

Ground water pumped from supply well 1 (MG–209) and supply well 2 (MG–210) at the Willow Grove NAS/JRB provides water for use at the base, including potable water for drinking. The wells are at Site 1 (figs. 1 and 2). The supply wells have been contaminated by volatile organic compounds (VOC's), particularly trichloroethylene (TCE) and tetrachloroethylene (PCE), and the water is treated to remove the VOC's. Replacement of the pumps in these wells provided an opportunity for investigation of the geophysical and hydraulic properties of the wells and measurement of contaminant concentrations at different depths. This information can be used to further identify the contamination sources and to evaluate alternative management strategies for improving well efficiency and water quality.

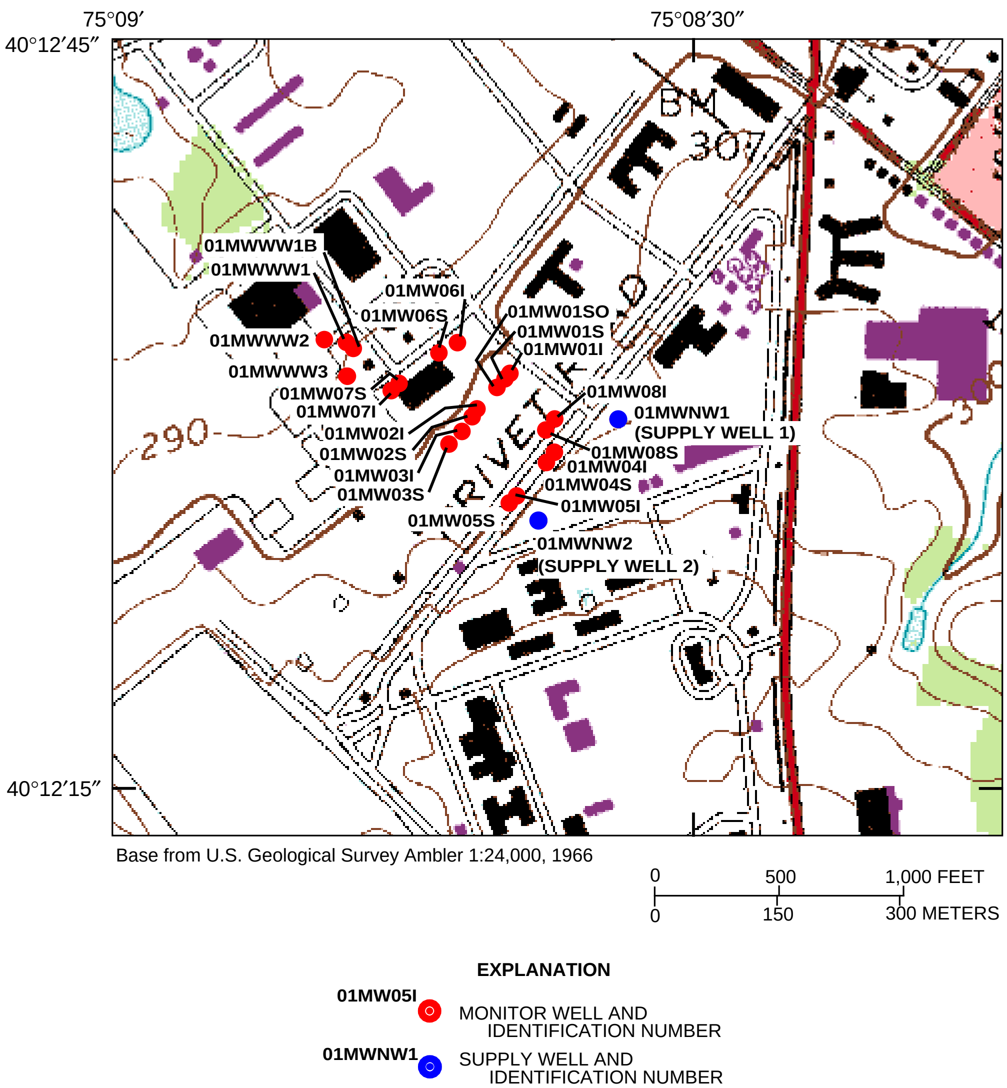


Figure 2. Locations of selected wells, Willow Grove Naval Air Station/ Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

The U.S. Navy requested the U.S. Geological Survey (USGS) provide technical assistance to their hydrogeological investigation. Specifically, the USGS was asked to conduct borehole geophysical logging and aquifer-isolation (packer) tests in supply wells 1 and 2 to characterize the geophysical and hydraulic properties, characterize the water quality of water-producing fractures, and collect and analyze water-level data. This work is a continuation of the Phase I and II borehole geophysical logging by the USGS (Conger, 1997; 1999). The USGS prepared this report as part of the environmental hydrogeological investigation at the Willow Grove NAS/JRB in cooperation with the U.S. Navy. Some data used for this study and presented in this report were provided by TetraTech NUS, Inc., an environmental contractor for the U.S. Navy.

Purpose and Scope

This report provides an interpretation and correlation of borehole geophysical logs and heat-pulse-flowmeter measurements collected in supply wells 1 and 2 by the USGS at the Willow Grove NAS/JRB and aquifer-isolation (packer) tests conducted by the USGS in those wells. This report describes drawdowns, water-level distributions, and specific capacities of isolated fractures. It describes the distribution of VOC's and inorganic constituents with depth. It also provides an interpretation of water-level data collected in the vicinity of the supply wells.

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, and 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—fractures, bedding planes, and joints. Primary porosity that originally may have been present has been almost eliminated by compaction and cementation. Ground water in the weathered zone 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.

Deep wells (greater than 100 ft) may penetrate several major water-bearing zones with different hydraulic properties. Each water-bearing zone usually has a different hydraulic head (water level). The head in a deep, open-hole well is the composite of the heads in the water-bearing 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-bearing zones, water in the well bore flows in the direction of decreasing head. Wells that connect several water-bearing 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 also 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. U.S. Navy well-identification numbers are used for wells at the Willow Grove NAS/JRB. U.S. Navy well-identification numbers 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). Well 01MW01S would indicate a shallow well in cluster 1 at Site 1. 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 U.S. Navy and USGS well-identification numbers is given in table 1. Locations of the wells are shown on figure 2.

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

[Depths are given in feet below land surface. Water levels were measured on October 7, 1999; --, no data]

Site well-identification number	U.S. Geological Survey well-identification number	Well depth (feet)	Casing diameter (inches)	Open interval (feet)	Water level elevation (feet above sea level)
01MWNW1 (supply well 1)	MG–209	389	10	50–389	--
01MWNW2 (supply well 2)	MG–210	340	10	43–340	--
01MW01S	MG–1879	18	2	8–18	291.32
01MW01SO	MG–1880	33	2	23–33	291.31
01MW01I	MG–1632	85	2	75–85	291.49
01MW02S	MG–1881	27	4	7–27	291.50
01MW02I	MG–1882	88	4	78–88	291.58
01MW03S	MG–1883	26.5	4	6.5–26.5	291.53
01MW03I	MG–1631	79	2	69–79	291.59
01MW04S	MG–1884	35	4	15–35	291.82
01MW04I	MG–1885	90	4	80–90	294.39
01MW05S	MG–1886	38.5	4	18.5–38.5	291.73
01MW05I	MG–1887	85	4	75–85	295.76
01MW06S	MG–1888	26	4	6–26	290.54
01MW06I	MG–1889	85.5	4	74.5–84.5	290.53
01MW07S	MG–1890	26	4	2–26	290.39
01MW07I	MG–1891	84	4	74–84	291.45
01MW08S	MG–1892	34	2	23–34	291.76
01MW08I	MG–1633	86	2	76–86	291.72
01MWWW1	MG–1893	29	4	9–29	286.18
01MWWW1B	MG–1894	100	4	80–100	288.23
01MWWW2	MG–1895	21.7	4	--	284.07
01MWWW3	MG–1896	21.95	4	--	286.47

Previous Investigations

The geology and hydrology of the Stockton Formation in southeastern Pennsylvania were described by Rima and others (1962). Sloto and others (1996) described the use of borehole geophysical methods to determine the extent of aquifer cross-contamination by VOC's through open boreholes in the Stockton Formation in adjacent Hatboro Borough and Warminster Township.

Previous studies at the Willow Grove NAS/JRB were conducted by Halliburton NUS Environmental Corporation (1993), and Brown and Root Environmental, Inc. (1997; 1998). USGS reports by Conger (1997; 1999) described the interpretation of borehole geophysical logs collected at the base. Sloto and others (2001) presented a potentiometric-surface map of the Willow Grove NAS/JRB and vicinity. Sloto (2002) described USGS hydrogeological investigations conducted at Site 5 and vicinity.

Acknowledgments

Borehole geophysical logging was conducted by Randall Conger, and borehole television surveys were conducted by Philip Bird of the USGS Pennsylvania District. Kevin Grazul, Abdul Mohammad, and Leif Olson of the USGS Pennsylvania District and Robert Rosman, Nicholas Smith, and Timothy Oden of the USGS New Jersey District assisted with the aquifer-isolation tests. Their assistance is appreciated greatly.

METHODS OF INVESTIGATION

Borehole Geophysical Logs

Caliper, natural-gamma, single-point-resistance, fluid-resistivity, and fluid-temperature borehole geophysical logs were collected in supply wells 1 and 2. The logs were used to locate water-bearing fractures, determine the rate and direction of vertical movement of water in the borehole, and 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-bearing 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. However, well casing reduces the gamma response. The gamma log also is used to correlate geologic units between wells (Keys, 1990).

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-bearing 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 wells and may help identify water-bearing 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.

Measurement of Vertical Borehole Flow

The direction and rate of borehole-fluid movement were measured with a high-resolution heat-pulse 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. 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 in supply wells 1 and 2 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-bearing 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-bearing fractures rather than through primary openings in the bedrock, it is important to define the hydraulic and chemical characteristics of important, discrete water-bearing fractures. This characterization only can be performed by isolating each water-bearing fracture with straddle packers so that its properties can be separated from the other water-bearing 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 top to the bottom of the well.

Several aquifer-isolation tests were conducted in each supply well. 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. 3A). For the test of the lowermost isolated interval in supply well 1, only the upper packer was inflated (fig. 3B). 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 were allowed to stabilize before pumping began. Because of interference caused by the pumping of the supply well not being tested, 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 recorded by a digital datalogger. 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 $\pm$0.06 ft. The

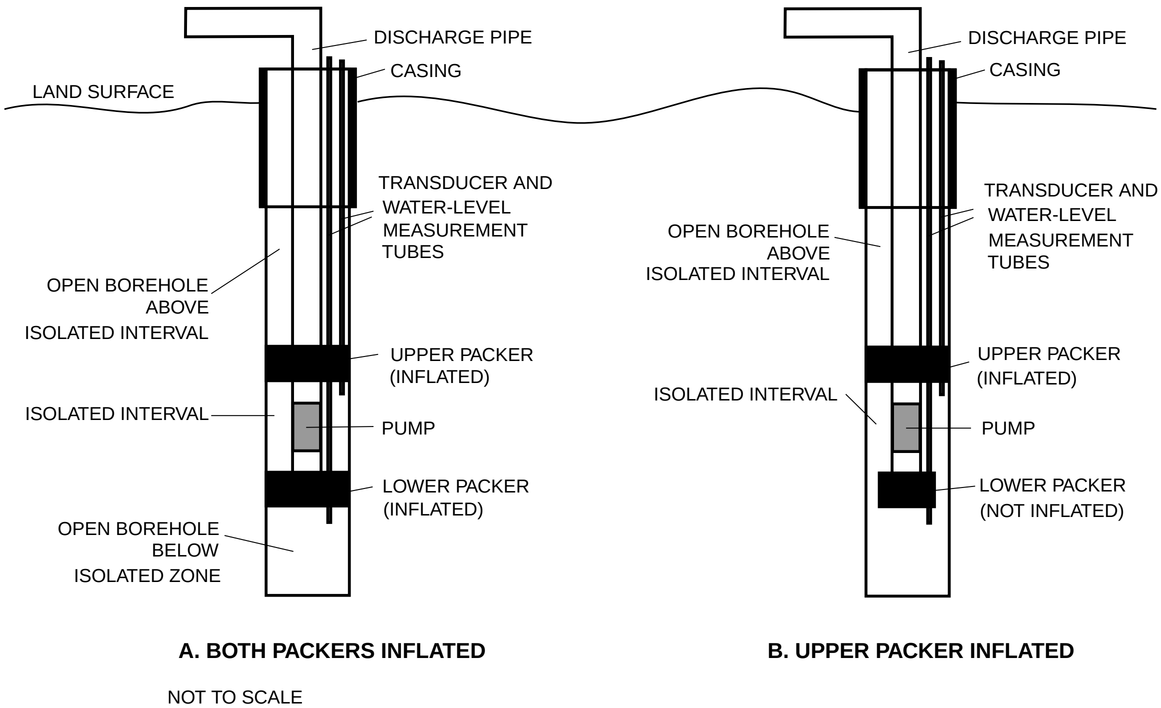


Figure 3. Generalized sketch of straddle-packer assembly and pump in borehole.

accuracy of the transducers used in the intervals above and below the isolated interval was ± 0.03 ft. Top of casing is used as a reference for all water-level measurements in this report. Calibrated, in-line flowmeters were used to measure discharge.

The specific capacity of each isolated interval was determined by dividing the pumping rate by the drawdown. 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

Water samples were collected for field determinations (dissolved oxygen, pH, specific conductance, and temperature) and laboratory analysis for inorganic constituents by the USGS and for laboratory analysis for VOC's by TetraTech NUS, Inc. Samples were collected near the end of each aquifer-isolation test from a sampling port placed in the discharge line before the flowmeter. Samples for field determinations and inorganic constituents were collected and measured according to established procedures (Wood, 1981). Samples for VOC analysis were collected in 40-milliliter septum bottles, placed on ice, and shipped overnight to the laboratory.

SUPPLY WELL 1

Supply well 1 (MG–209) is one of two wells supplying the U.S. Navy part of the Willow Grove NAS/JRB with potable water. USGS records from 1947 indicate the well was drilled in 1942 to a depth of 397 ft and cased with 26 ft of 16-in.-diameter outer casing and 52 ft of 10-in.-diameter inner casing.

Interpretation of Borehole Geophysical Logs

A suite of borehole geophysical logs (fig. 4) was collected in supply well 1 by the USGS on April 14, 2000. At the time of geophysical logging, supply well 2 was pumping, and the water-level decline in the aquifer was nearing stabilization; this stabilization was determined from the water level in well 01MW05I, which is affected by the pumping of supply well 2 (fig. 5). The fluid-temperature and fluid-resistivity logs and heat-pulse-flowmeter measurements are affected by the pumping of supply well 2 and reflect borehole conditions in supply well 1 during the pumping of supply well 2. The caliper log shows the well is 389 ft deep and is cased to 50 ft below top of casing (btoc). The well was drilled as a 10-in.-diameter borehole to 208 ft btoc and as an 8-in.-diameter borehole below 208 ft btoc. The caliper log shows major fractures at 50–59, 80, 85, 124–152, 165, 182, 199, 256, 296–300, 320, 350–355, 360–365, and 374–380 ft btoc. The fluid-temperature and fluid-resistivity logs indicate possible water-bearing zones at about 106, 144, 181, 257, and 353 ft btoc.

Heatpulse-flowmeter measurements were made under nonpumping conditions at 74, 120, 155, 175, 192, 220, 264, and 358 ft btoc (table 2). Flow measurements were attempted at 98, 309, and 340 ft btoc, but the rate and direction of flow could not be determined. On the basis of the geophysical logs, heatpulse-flowmeter measurements, and borehole television survey, water enters the upper part of the borehole through a vertical fracture just below casing at 50–59 ft btoc (1.2 gal/min) and flows downward. Water also enters the borehole through a horizontal fracture at 106 ft btoc (>0.3 gal/min) and flows downward. The fluid-resistivity and fluid-temperature logs indicate water may enter or exit the borehole through fractures between 140 and 150 ft btoc; however, this movement could not be confirmed because flow in this part of the borehole exceeded the upper resolution limit (1.5 gal/min) of the heatpulse flowmeter. Water flowing downward exits the borehole through a horizontal fracture at 182 ft btoc (2.1 gal/min) (fig. 6). Water also enters the borehole through horizontal fractures at 241–244 (determined from the head-distribution data for the aquifer-isolation test of interval 6), 256, and 350–355 ft btoc (>1.5 gal/min) and flows upward. Water flowing upward exits the borehole through fractures at 182 and 199 ft btoc (>0.8 gal/min). The principal water-bearing zones in supply well 1 are at 50–59, 106, 182, 199, 256, and 350–354 ft btoc. The fractures at 50–60, 106, 256, and 350–355 ft btoc are water-producing fractures. The fractures at 182 and 199 ft btoc are water-receiving fractures.

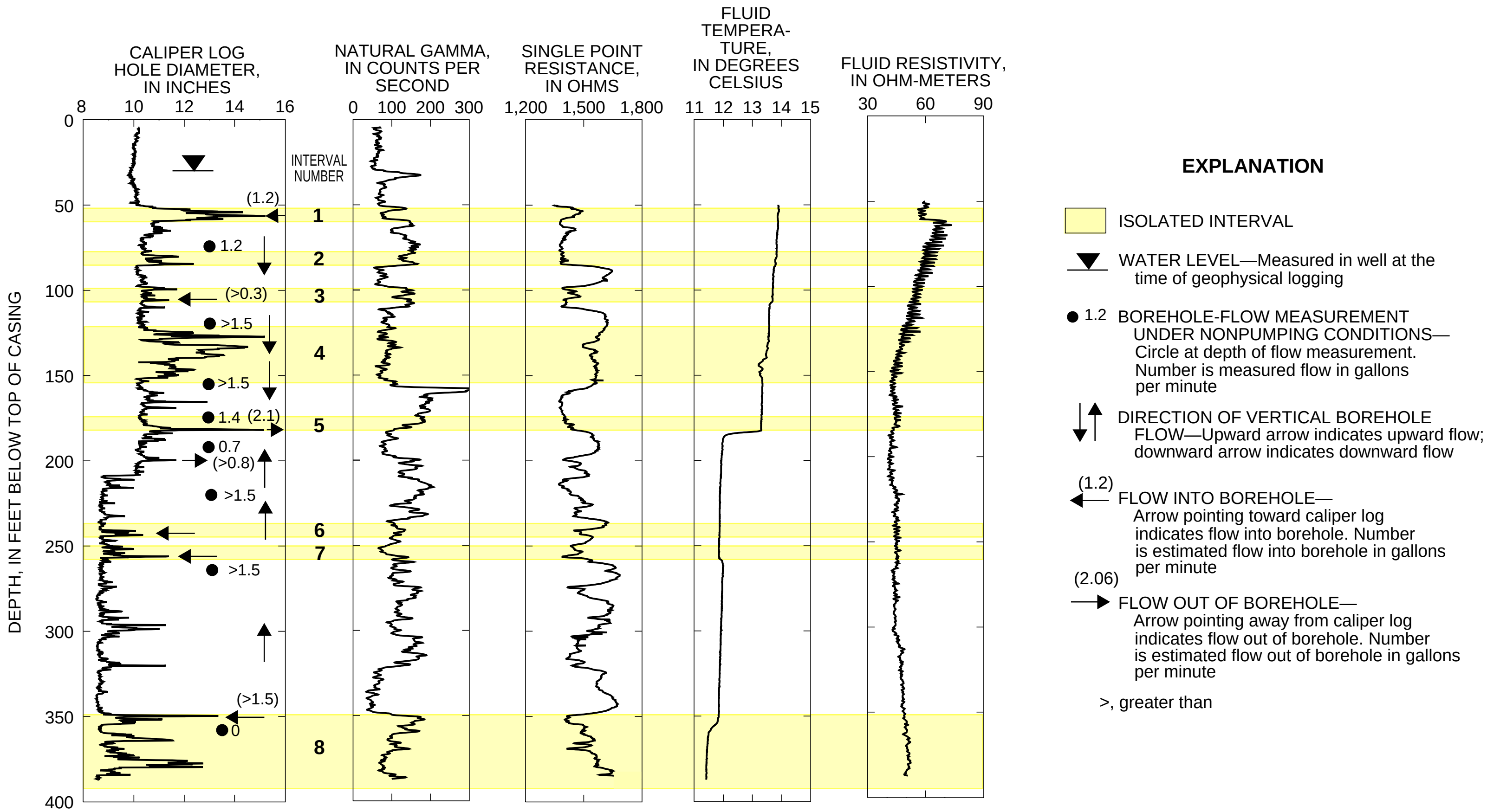


Figure 4. Borehole geophysical logs for supply well 1 (MG–209), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

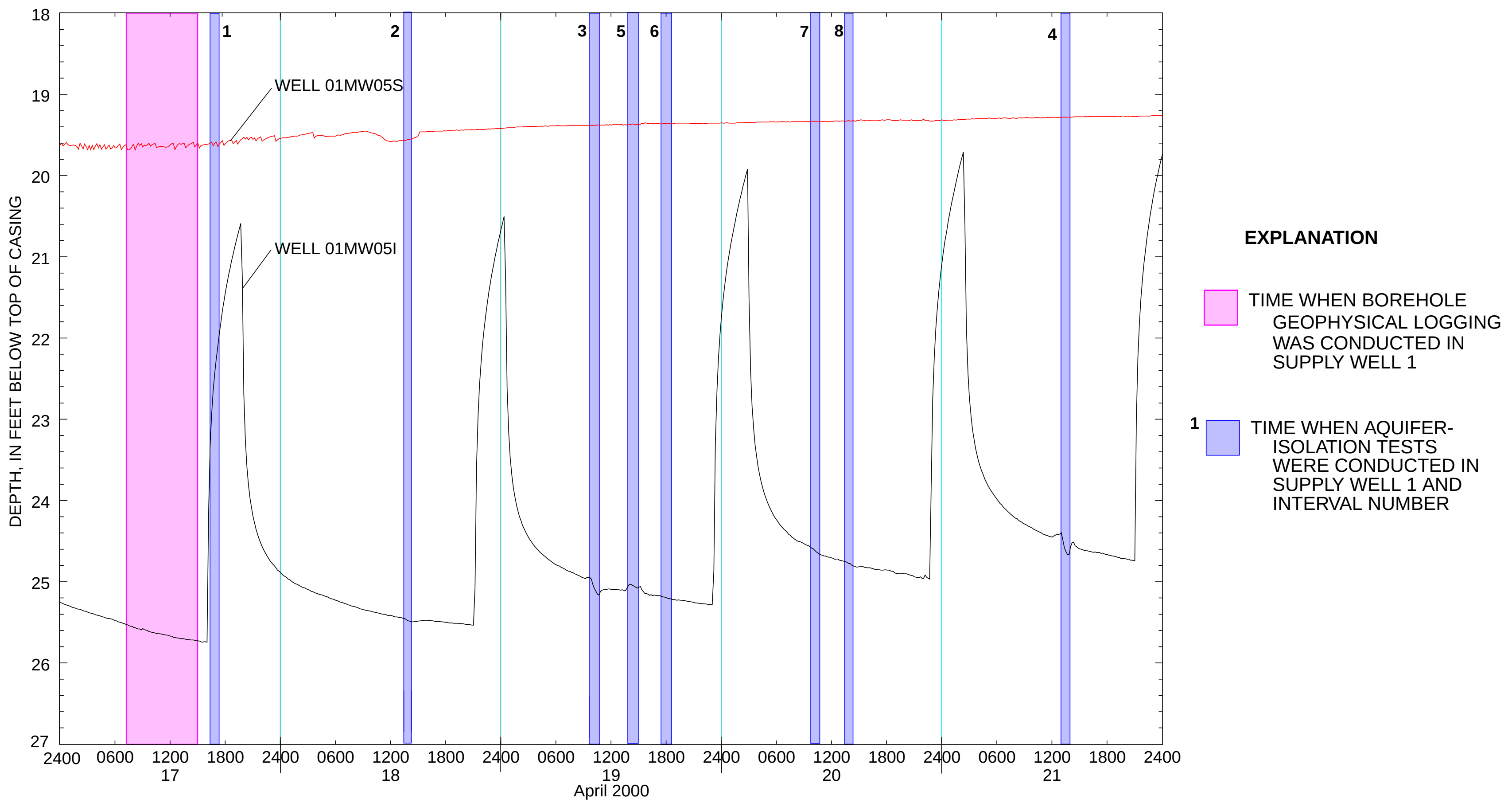


Figure 5. Hydrographs from wells 01MW05S and 01MW05I showing effect of pumping supply well 2, April 17–21, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Table 2. *Heatpulse-flowmeter measurements made in supply well 1 (MG–209), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

[>, greater than; --, flow occurring but rate and direction could not be determined]

Depth (feet below top of casing)	Flow (gallons per minute)	Flow direction
74	1.2	Down
98	--	--
120	>1.5	Down
155	>1.5	Down
175	1.4	Down
192	.7	Up
220	>1.5	Up
264	>1.5	Up
309	--	--
340	--	--
358	0	No flow

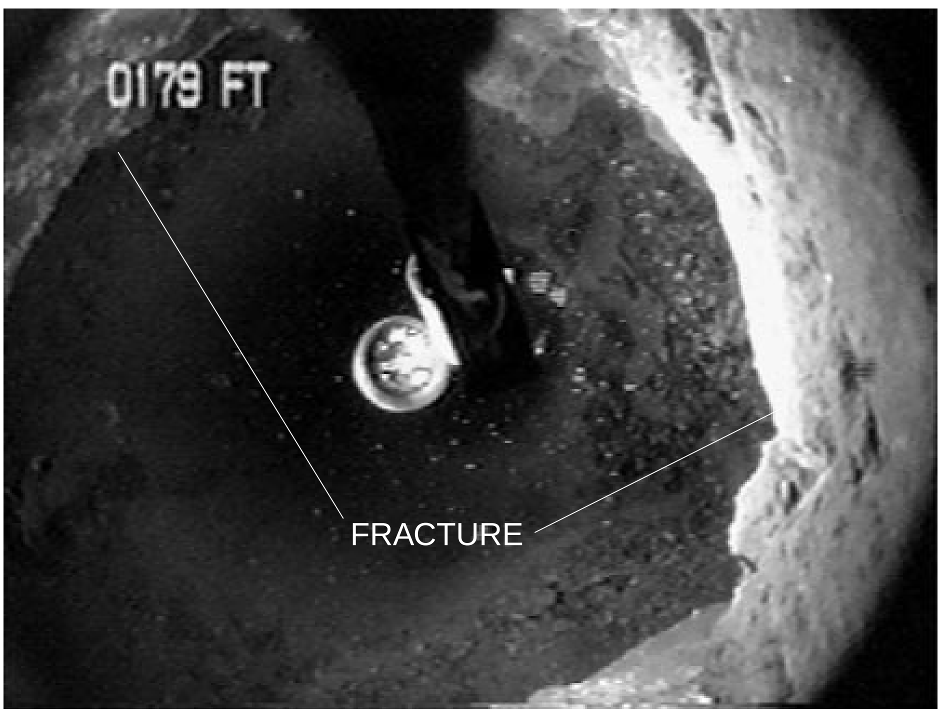


Figure 6. Borehole television survey showing horizontal fracture at 182 feet below top of casing in supply well 1 (MG–209), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Aquifer-Isolation Tests

On the basis of the borehole geophysical measurements, eight intervals were selected for aquifer-isolation tests in supply well 1 (table 3). 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 except interval 4, the distance between the bottom of the upper packer and the top of the lower packer was 8.2 ft, and both packers were inflated. For the test of interval 4, packer spacing was increased to 32.4 ft. For the test of interval 8, only the upper packer was inflated. Except for the test of interval 1, supply well 2 was pumping, and drawdown in the aquifer was nearing stabilization (fig. 5); this stabilization was determined from the water level in well 01MW05I, which is affected by the pumping of supply well 2.

Interval 1 (51.8–60 Feet Below Top of Casing)

For the aquifer-isolation test of interval 1, the bottom of the upper packer and the top of the lower packer were set at 51.8 and 60 ft btoc, respectively, to isolate the fracture zone at 50–59 ft btoc. Most of the upper packer was in the casing. Before packer inflation, the depth to water in the open borehole was 32.27 ft btoc. Fifty minutes after packer inflation, the depth to water in the isolated interval was 32.27 ft btoc (no change), and the depth to water in the interval below the packers was 32.18 ft btoc, an increase of 0.09 ft. The small change in water level probably was the result of a poor seal between the lower packer and the borehole wall.

At approximately 16:00 on April 17, the pump in supply well 2 shut down, and the water levels in both intervals began to rise. Pumping supply well 1 began at 16:12 at an initial rate of 5 gal/min, and the water levels continued to rise at approximately the same rate. The pumping rate then was increased to 23 gal/min. The water levels in both intervals continued to rise but at a lesser rate. After 65 minutes of pumping, the depth to water in the isolated interval rose 5.41 ft, and the depth to water in the interval below the packers rose 4.20 ft. The specific capacity of interval 1 could not be calculated because the water level in the isolated interval rose throughout the test.

Table 3. *Intervals isolated during aquifer-isolation tests conducted in supply well 1 (MG–209), April 17–21, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

[ft, feet; ft btoc, feet below top of casing; gal/min, gallons per minute; (gal/min)/ft, gallons per minute per foot of drawdown; --, no data]

Interval	Depth of isolated fracture (ft btoc)	Bottom of top packer (ft btoc)	Top of bottom packer (ft btoc)	Final pumping rate (gal/min)	Drawdown (ft)	Specific capacity [(gal/min)/ft]
1	50–59	51.8	60	23	--	--
2	79–85	77.8	86	5.8	20.90	0.28
3	106	98.8	107	21	50.01	.42
4	124–152	121	153.4	16	48.63	.33
5	182	179.8	188	22	3.87	5.7
6	241–244	236.8	245	12.7	49.57	.26
7	256	249.8	258	20	35.55	.56
8	350–354	345.3	Not inflated	22	6.01	3.7
--	Open-hole test[1]	--	--	200	20	10

[1] From data provided by TetraTech NUS, Inc., from an 8-hour open-hole aquifer test conducted March 15–16, 2000.

Interval 2 (77.8–86 Feet Below Top of Casing)

For the aquifer-isolation test of interval 2, the bottom of the upper packer and the top of the lower packer were set at 77.8 and 86 ft btoc, respectively, to isolate the fracture zone at 79–85 ft btoc. Supply well 2 was pumping during this test and all subsequent tests. Before packer inflation, the depth to water in the open borehole was 31.92 ft btoc. Eighty-nine minutes after packer inflation, the depth to water in the isolated interval was 22.38 ft btoc, an increase of 9.54 ft; the depth to water in the interval below the packers was 27.21 ft btoc, an increase of 4.71 ft; and the depth to water in the interval above the packers was 20.42 ft, an increase of 11.50 ft. This is consistent with the heatpulse-flowmeter measurements, which showed downward flow.

Pumping began at 13:30 at a rate of 5.5 gal/min (table 4). Because of sediment partially clogging the filter, the rate was unstable throughout the first 15 minutes of pumping. After the first 15 minutes, the rate became more stable and averaged about 5.8 gal/min. Total drawdown was 20.90 ft in the isolated interval, 1.03 ft in the interval below the packers, and 2.37 ft in the interval above the packers. The specific capacity of interval 2 is 0.28 (gal/min)/ft. The hydrographs for the interval above the packers, isolated interval, and interval below the packers (fig. 7) indicate a weak hydraulic connection among the three intervals.

Table 4. *Schedule for the aquifer-isolation test of interval 2 (77.8–86 feet below top of casing) in supply well 1 (MG–209), April 18, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

Time	Activity
10:51	Start datalogger
12:03	Begin upper packer inflation
12:36	Begin lower packer inflation
13:30	Pump on
14:15	Pump off
14:26	Begin upper packer deflation
14:32	Begin lower packer deflation
14:45	Stop datalogger

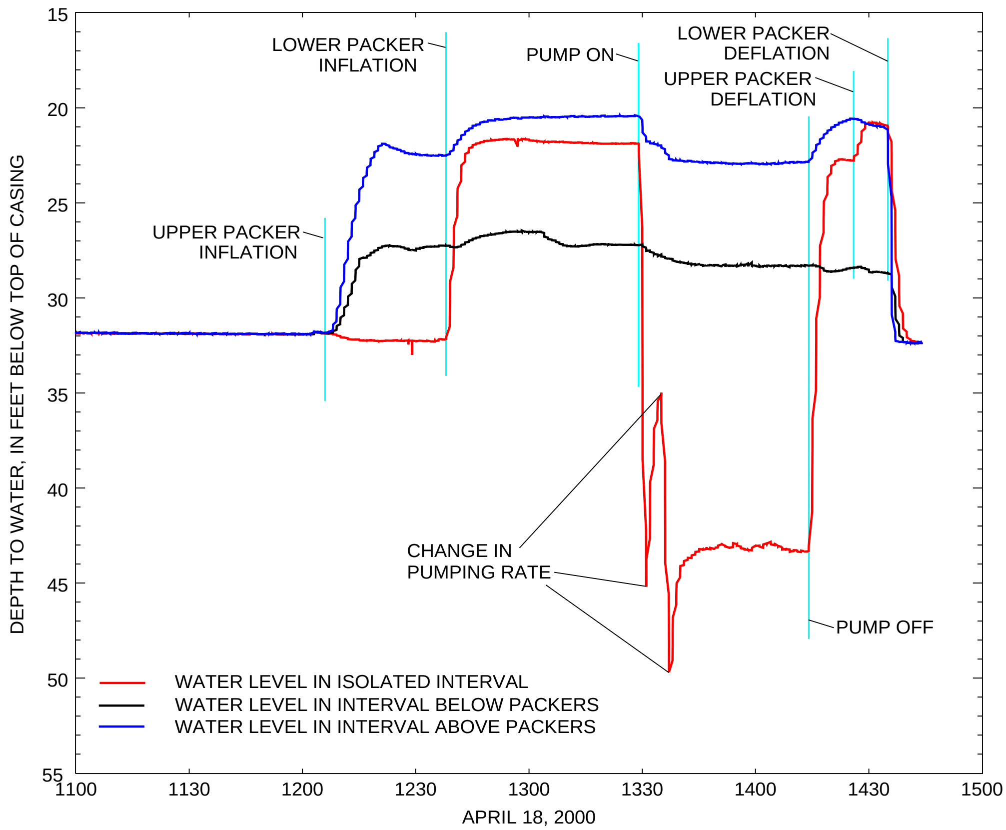


Figure 7. Hydrographs from aquifer-isolation test of interval 2 (77.8–86 feet below top of casing) in supply well 1 (MG–209), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Interval 3 (98.8–107 Feet Below Top of Casing)

For the aquifer-isolation test of interval 3, the bottom of the upper packer and the top of the lower packer were set at 98.8 and 107 ft btoc, respectively, to isolate the fracture at 106 ft btoc. Before packer inflation, the depth to water in the open borehole was 31.30 ft btoc. Twenty-seven minutes after packer inflation, the depth to water in the isolated interval was 21.4 ft btoc, an increase of 9.9 ft; the depth to water in the interval below the packers was 30.44 ft btoc, an increase of 0.86 ft; and the depth to water in the interval above the packers was 21.05 ft btoc, an increase of 10.25 ft. This is consistent with the heatpulse-flowmeter measurements, which showed downward flow.

Pumping began at 9:47 at an initial rate of 7 gal/min (table 5). After 6 minutes, the pumping rate was increased to 21 gal/min. Total drawdown was 50.01 ft in the isolated interval, 1.74 ft in the interval below the packers, and 19.94 ft in the interval above the packers. The specific capacity of interval 3 is 0.42 (gal/min)/ft. The hydrographs for the interval above the packers, isolated interval, and interval below the packers (fig. 8) 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.

Table 5. *Schedule and pumping rates for the aquifer-isolation test of interval 3 (98.8-107 feet below top of casing) in supply well 1 (MG–209), April 19, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

Time	Activity
8:45	Start datalogger
9:05	Begin lower packer inflation
9:20	Begin upper packer inflation
9:47	Pump on at 7 gallons per minute
9:53	Increase pumping rate to 21 gallons per minute
10:40	Pump off
10:52	Begin lower packer deflation
11:05	Begin upper packer deflation
11:15	Stop datalogger

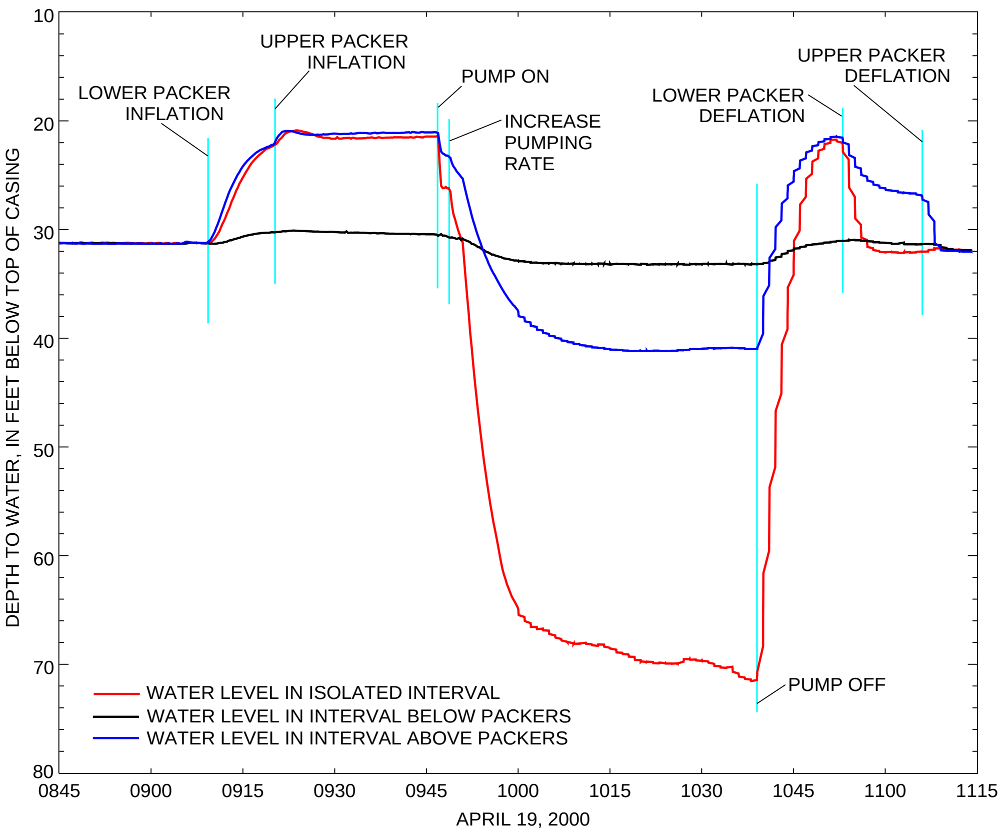


Figure 8. Hydrographs from aquifer-isolation test of interval 3 (96.8–107 feet below top of casing) in supply well 1 (MG–209), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Interval 4 (121–153.4 Feet Below Top of Casing)

For the aquifer-isolation test of interval 4, the bottom of the upper packer and the top of the lower packer were set at 121 and 153.4 ft btoc, respectively, to isolate the fracture zone from 124–152 ft btoc. Before packer inflation, the depth to water in the open borehole was 30.86 ft btoc. Sixty-seven minutes after packer inflation, the depth to water in the isolated interval was 21.02 ft btoc, an increase of 9.84 ft; the depth to water in the interval below the packers was 31.53 ft btoc, a decrease of 0.67 ft; and the depth to water in the interval above the packers was 20.21 ft btoc, an increase of 10.65 ft. This is consistent with the heatpulse-flowmeter measurements, which showed downward flow.

Pumping began at 13:02 at a rate of 6.5 gal/min (table 6). After 5 minutes, the pumping rate was increased to 21 gal/min. After 8 minutes at this rate, the pumping rate was decreased to 16 gal/min. Total drawdown was 48.63 ft in the isolated interval, 0.68 ft in the interval below the packers, and 0.97 ft in the interval above the packers. The specific capacity of interval 4 is 0.33 (gal/min)/ft. The hydrographs for the interval above the packers, isolated interval, and interval below the packers (fig. 9) indicate a weak hydraulic connection among the three intervals.

Table 6. *Schedule and pumping rates for the aquifer-isolation test of interval 4 (121–153.4 feet below top of casing) in supply well 1 (MG–209), April 21, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

Time	Activity
11:48	Start datalogger
11:55	Begin upper packer inflation
12:13	Begin lower packer inflation
13:02	Pump on at 6.5 gallons per minute
13:07	Increase pumping rate to 21 gallons per minute
13:15	Decrease pumping rate to 16 gallons per minute
13:50	Pump off
14:01	Begin upper packer deflation
14:17	Begin lower packer deflation
14:31	Stop datalogger

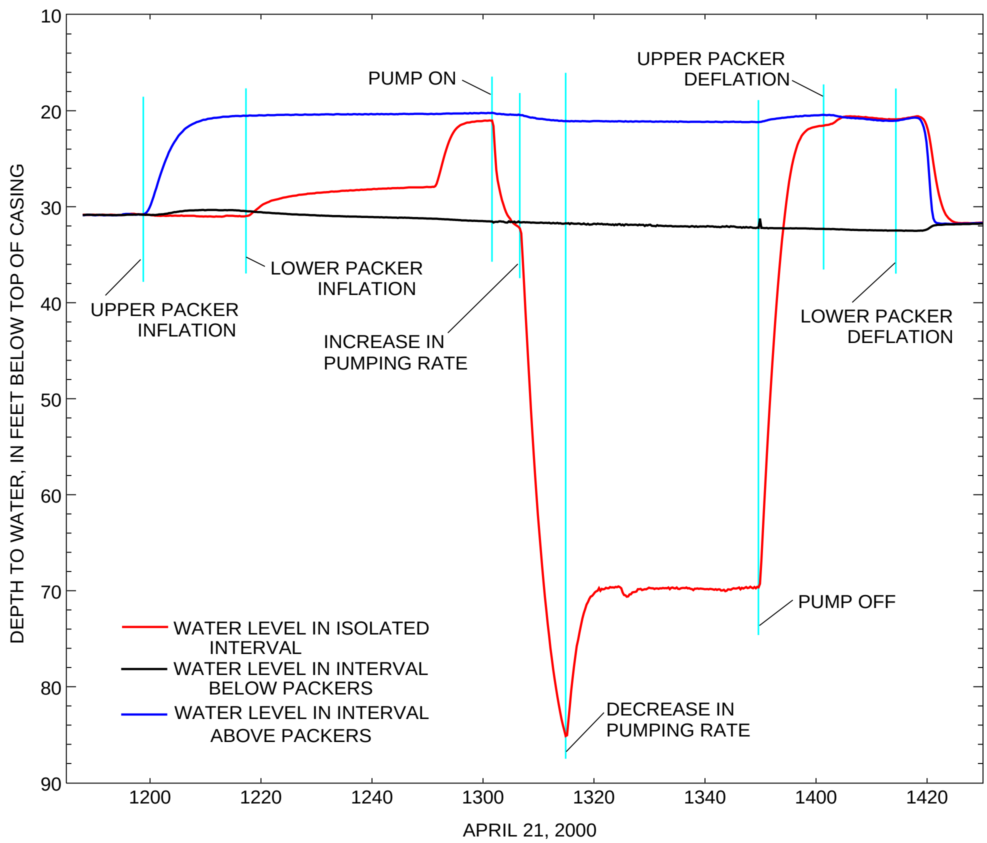


Figure 9. Hydrographs from aquifer-isolation test of interval 4 (121–153.4 feet below top of casing) in supply well 1 (MG–209), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Interval 5 (179.8–188 Feet Below Top of Casing)

For the aquifer-isolation test of interval 5, the bottom of the upper packer and the top of the lower packer were set at 179.8 and 188 ft btoc, respectively, to isolate the fracture at 182 ft btoc. Before packer inflation, the depth to water in the open borehole was 31.77 ft btoc. Twenty-three minutes after packer inflation, the depth to water in the isolated interval was 33.60 ft btoc, a decrease of 1.83 ft; the depth to water in the interval below the packers was 29.11 ft btoc, an increase of 2.66 ft; and the depth to water in the interval above the packers was 21.40 ft btoc, an increase of 10.37 ft. This is consistent with the heatpulse-flowmeter measurements, which showed downward flow from above the isolated interval and upward flow from below the isolated interval.

Pumping began at 13:55 at a rate of 7 gal/min (table 7). After 2 minutes, the pumping rate was increased to 22 gal/min. Total drawdown was 3.87 ft in the isolated interval and 0.73 ft in the interval below the packers. The water level rose 0.31 ft in the interval above the packers. The specific capacity of interval 5 is 5.7 (gal/min)/ft. The hydrographs for the interval above the packers, isolated interval, and interval below the packers (fig. 10) 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.

The fracture at 182 ft btoc, which was isolated in the test of interval 5, has the greatest specific capacity of the isolated intervals tested in supply well 1. It is a water-receiving fracture, through which water flowing up and down the well bore exits the well. This fracture is the most hydraulically important fracture in supply well 1.

Table 7. *Schedule and pumping rates for the aquifer-isolation test of interval 5 (179.8–188 feet below top of casing) in supply well 1 (MG–209), April 19, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

Time	Activity
12:54	Start datalogger
13:07	Begin lower packer inflation
13:32	Begin upper packer inflation
13:55	Pump on at 7 gallons per minute
13:57	Increase pumping rate to 22 gallons per minute
14:45	Pump off
14:53	Begin lower packer deflation
15:10	Begin upper packer deflation
15:20	Stop datalogger

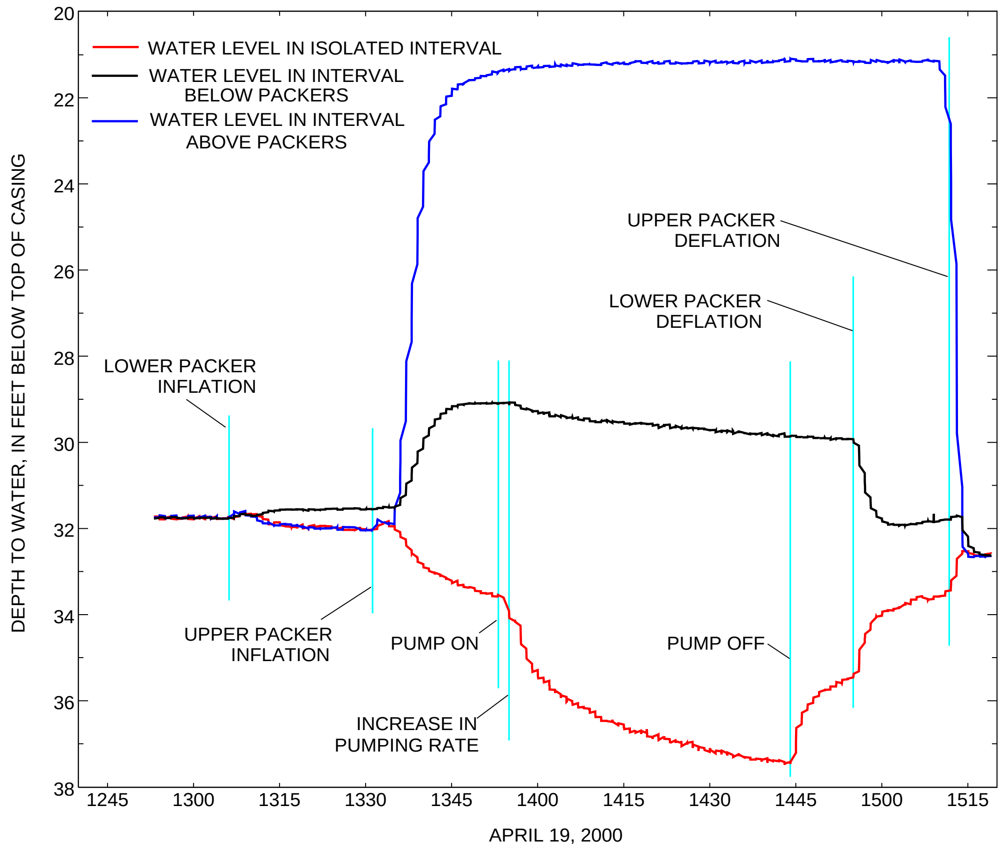


Figure 10. Hydrographs from aquifer-isolation test of interval 5 (179.8–188 feet below top of casing) in supply well 1 (MG–209), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Interval 6 (236.8–245 Feet Below Top of Casing)

For the aquifer-isolation test of interval 6, the bottom of the upper packer and the top of the lower packer were set at 236.8 and 245 ft btoc, respectively, to isolate the fractures at 241–244 ft btoc. Before packer inflation, the depth to water in the open borehole was 32.10 ft btoc. Twenty-nine minutes after packer inflation, the depth to water in the isolated interval was 31.60 ft btoc, a decrease of 0.50 ft; the depth to water in the interval below the packers was 31.95 ft btoc, an increase of 0.15 ft; and the depth to water in the interval above the packers was 32.30 ft btoc, a decrease of 0.20 ft. This is consistent with the heatpulse-flowmeter measurements, which showed upward flow. The head distribution indicates the fracture isolated in this interval is a water-producing fracture that contributes water to borehole flow.

Pumping began at 17:35 at a rate of 12 gal/min (table 8). Total drawdown was 49.57 ft in the isolated interval, 1.59 ft in the interval below the packers, and 0.12 ft in the interval above the packers. The specific capacity of interval 6 is 0.26 (gal/min)/ft. The hydrographs for the interval above the packers, isolated interval, and interval below the packers (fig. 11) 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.

Table 8. *Schedule for the aquifer-isolation test of interval 6 (236.8–245 feet below top of casing) in supply well 1 (MG–209), April 19–20, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

Date	Time	Activity
April 19	17:00	Start datalogger
-	17:06	Begin lower packer inflation
-	17:17	Begin upper packer inflation
-	17:35	Pump on at 12 gallons per minute
-	18:16	Pump off
-	23:10	Supply well 2 off
April 20	3:00	Supply well 2 on
-	7:55	Begin lower packer deflation
-	8:11	Begin upper packer deflation
-	8:27	Stop datalogger

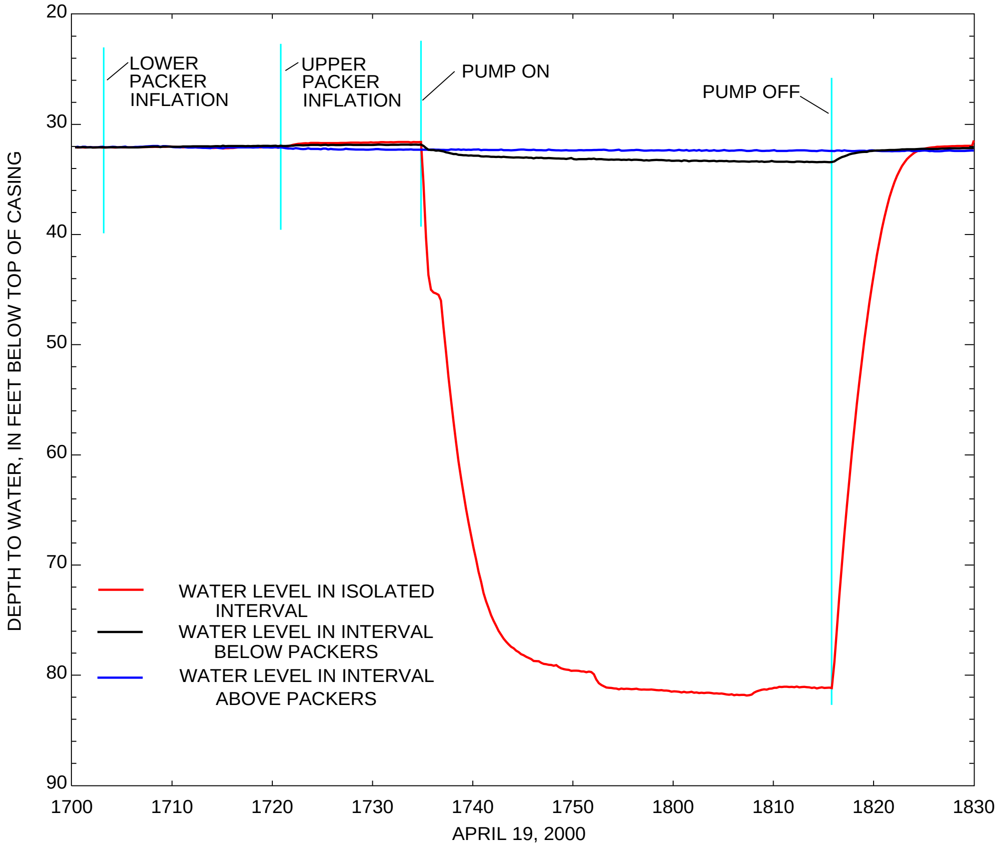


Figure 11. Hydrographs from aquifer-isolation test of interval 6 (236.8–245 feet below top of casing) in supply well 1 (MG–209), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

The packers were left inflated, and the datalogger was left running overnight. At approximately 23:10 on April 19, the pump in supply well 2 shut down. It restarted at approximately 3:00 on the morning of April 20. During this time period, the water levels in the three intervals of supply well 1 recovered. The depth to water in the isolated interval rose from 31.69 ft to 23.39 ft btoc, an increase of 8.30 ft. The depth to water in the interval below the packers rose from 31.96 ft to 23.10 ft btoc, an increase of 8.86 ft. The depth to water in the interval above the packers rose from 32.49 ft to 20.92 ft btoc, an increase of 11.57 ft (fig. 12).

While supply well 2 was pumping, the vertical flow direction was downward from the interval above the packers to the isolated interval and upward from the interval below the packers to the isolated interval. When supply well 2 stopped pumping, the vertical flow direction reversed, and flow was upward from the isolated interval to the interval above the packers and downward from the isolated interval to the interval below the packers.

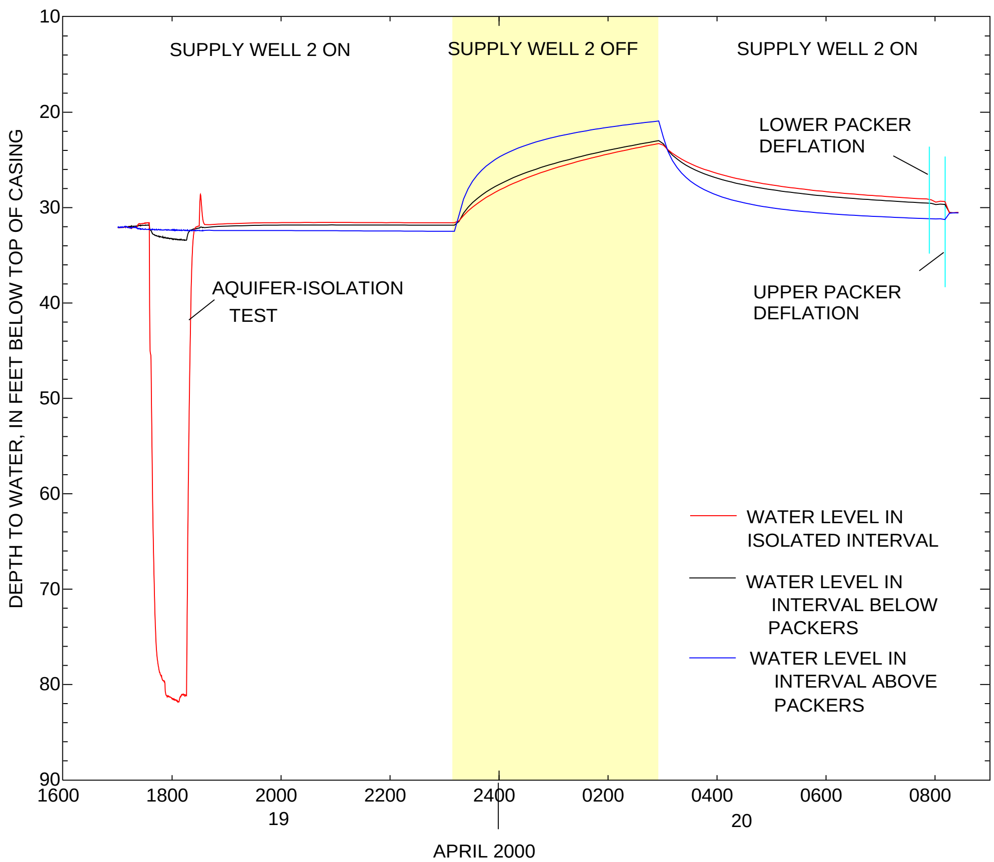


Figure 12. Hydrographs during and after aquifer-isolation test of interval 6 (236.8–245 feet below top of casing) in supply well 1 (MG–209), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Interval 7 (249.8–258 Feet Below Top of Casing)

For the aquifer-isolation test of interval 7, the bottom of the upper packer and the top of the lower packer were set at 249.8 and 258 ft btoc, respectively, to isolate the fracture at 256 ft btoc. Before packer inflation, the depth to water in the open borehole was 30.69 ft btoc. Twenty-three minutes after packer inflation, the depth to water in the isolated interval was 28.97 ft btoc, an increase of 1.72 ft; the depth to water in the interval below the packers was 30.53 ft btoc, an increase of 0.16 ft; and the depth to water in the interval above the packers was 31.20 ft btoc, a decrease of 0.51 ft. This is consistent with the heatpulse-flowmeter measurements, which showed upward flow. The water-level distribution confirms the fracture isolated in this interval is a water-producing fracture that contributes water to borehole flow.

Pumping began at 9:45 at an initial rate of 5 gal/min (table 9). After 5 minutes, the pumping rate was increased to 20 gal/min. Total drawdown was 35.55 ft in the isolated interval, 0.53 ft in the interval below the packers, and 0.56 ft in the interval above the packers. The specific capacity of interval 7 is 0.56 (gal/min)/ft. The hydrographs for the interval above the packers, isolated interval, and interval below the packers (fig. 13) indicate a weak hydraulic connection among the three intervals.

Table 9. *Schedule and pumping rates for the aquifer-isolation test of interval 7 (249.8–258 feet below top of casing) in supply well 1 (MG–209), April 20, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

Time	Activity
9:12	Start datalogger
9:17	Begin lower packer inflation
9:28	Begin upper packer inflation
9:45	Pump on at 5 gallons per minute
9:50	Increase pumping rate to 20 gallons per minute
10:25	Pump off
10:34	Begin lower packer deflation
10:42	Begin upper packer deflation
10:51	Stop datalogger

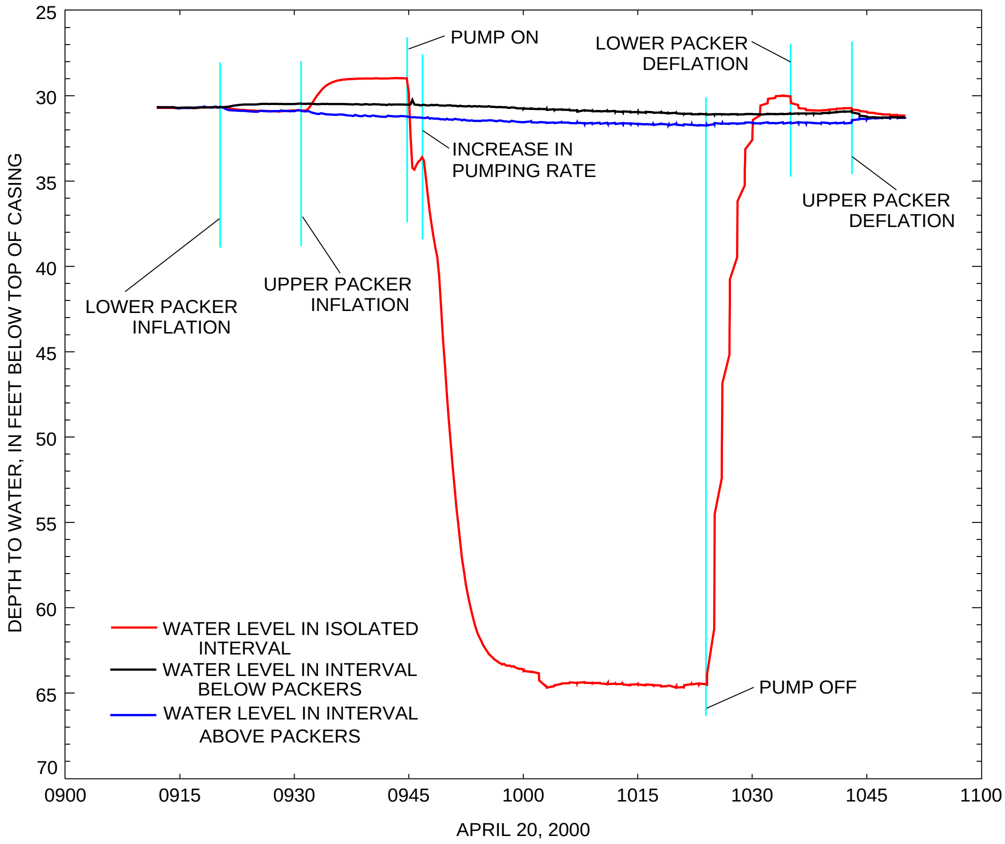


Figure 13. Hydrographs from aquifer-isolation test of interval 7 (249.8–258 feet below top of casing) in supply well 1 (MG–209), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Interval 8 (345.3–389 Feet Below Top of Casing)

For the aquifer-isolation test of interval 8, the bottom of the upper packer was set at 345.3 ft btoc, and the lower packer was not inflated. Before packer inflation, the depth to water in the open borehole was 31.29 ft btoc. Twenty minutes after packer inflation, the depth to water in the isolated interval was 31.15 ft btoc, an increase of 0.14 ft, and the depth to water in the interval above the packers was 31.32 ft btoc, a decrease of 0.03 ft. This is consistent with the heatpulse-flowmeter data, which showed upward flow.

Pumping began at 13:20 at a rate of 4 gal/min (table 10). After 2 minutes, the pumping rate was increased to 22 gal/min. Total drawdown was 6.01 ft in the isolated interval and 0.49 ft in the interval above the packers. The specific capacity of interval 8 is 3.7 (gal/min)/ft. Isolated interval 8 has the second highest specific capacity of the isolated intervals tested in supply well 1. This may be, in part, because isolated interval 8 is longer (43.7 ft) than the other isolated intervals (8.3 ft for intervals 1–3 and 5–7 and 37.4 ft for interval 4). The hydrographs for the interval above the packers and the isolated interval (fig. 14) indicate a weak hydraulic connection between the two intervals.

Table 10. *Schedule and pumping rates for the aquifer-isolation test of interval 8 (345.3–389 feet below top of casing) in supply well 1 (MG–209), April 20, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

Time	Activity
12:55	Start datalogger
13:00	Begin upper packer inflation
13:20	Pump on at 4 gallons per minute
13:22	Increase pumping rate to 22 gallons per minute
14:15	Pump off
14:25	Begin upper packer deflation
14:48	Stop datalogger

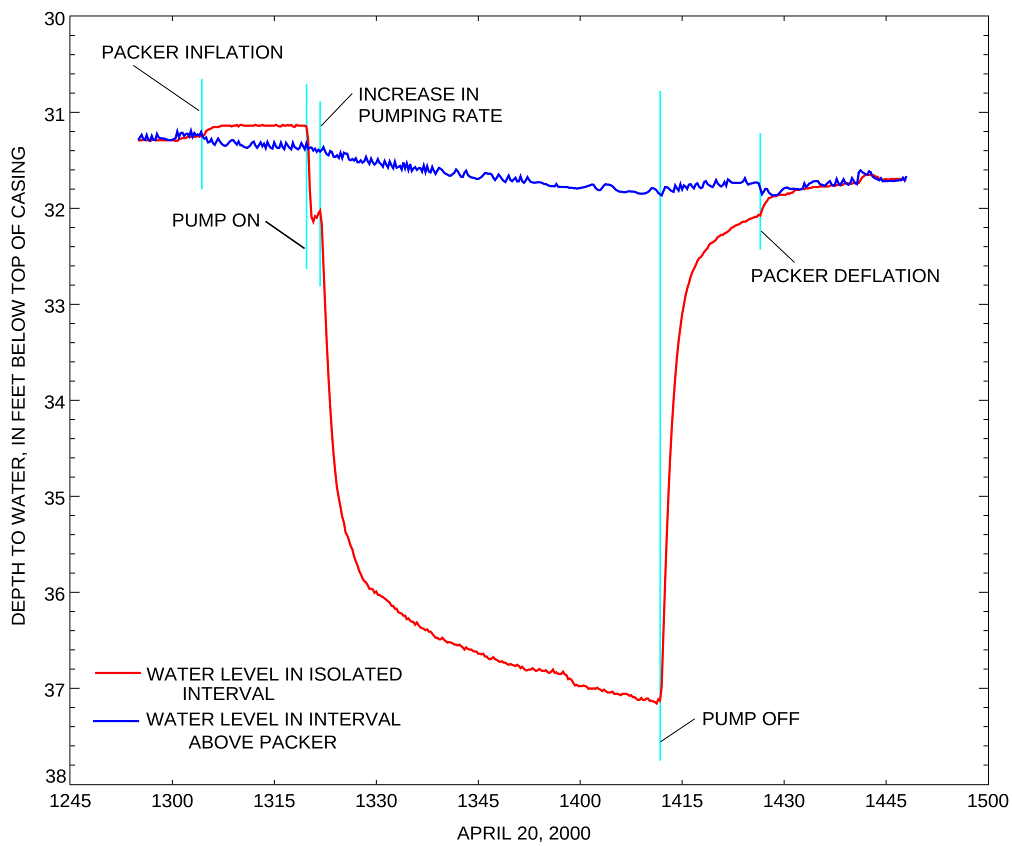


Figure 14. Hydrographs from aquifer-isolation test of interval 8 (345.3–389 feet below top of casing) in supply well 1 (MG–209), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Vertical Distribution of Water-Quality Constituents

During each aquifer-isolation test, water samples were collected by the USGS and analyzed for inorganic constituents and by TetraTech NUS, Inc. and analyzed for VOC's. Analytical results were used to determine change in concentration with depth. However, vertical mixing occurs in the aquifer and the well because of drawdown and recovery cycles in the supply wells, borehole flow when the supply wells are not pumping, and the pumping of one supply well affecting water levels (well interference) and borehole flow in the other supply well.

VOC's detected in water samples collected during aquifer-isolation tests and not attributable to laboratory contamination are listed in table 11. Cis-1,2-dichloroethylene (cis-1,2-DCE) is a degradation product of PCE and TCE and is present in samples where PCE is greater than 10 µg/L. Concentrations of cis-1,2-DCE, methylene chloride, TCE, toluene, and 1,1,1-trichloro-ethane (TCA) were less than 10 µg/L (table 11). The concentration of PCE generally increased with depth to a maximum of 39 µg/L at a depth of 249.8–258 ft btoc and then decreased to 21 µg/L at a depth of 345.3–389 ft btoc (fig. 15). The sample collected at 179.8–188 ft btoc was the only one in which toluene, TCE, PCE, and TCA all were detected.

The highest concentrations of PCE and TCE were in water samples collected from fractures isolated at 236.8–245 (interval 6) and 249.8–258 ft btoc (interval 7) (fig. 15). Concentrations of PCE and TCE were similar in those samples as were concentrations of dissolved oxygen and total dissolved solids (fig. 15), which indicates these fractures are hydraulically connected. The aquifer-isolation tests also indicated a hydraulic connection between the two intervals.

Inorganic constituents in water samples collected during aquifer-isolation tests are listed in table 12. The concentrations of total dissolved solids (fig. 15), calcium, magnesium (fig. 16), and strontium generally increase with depth. The concentrations of dissolved oxygen (fig. 15), chloride, and sulfate (fig. 16) generally decrease with depth.

Table 11. *Concentrations of selected volatile organic compounds in water samples collected during aquifer-isolation tests in supply well 1 (MG–209), April 17–21, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

[Laboratory results were provided by TetraTech NUS, Inc.; ft btoc, feet below top of casing; µg/L, micrograms per liter; ND, not detected, reporting limit is 10 µg/L; J, estimated result less than reporting limit of 10 µg/L]

Interval	Depth of sample (ft btoc)	Date sampled	cis-1,2-Dichloro-ethylene (µg/L)	Methylene chloride (µg/L)	Tetrachloro-ethylene (µg/L)	Trichloro-ethylene (µg/L)	Toluene (µg/L)	1,1,1-Trichloro-ethane (µg/L)
1	51.8–60	4/17/2000	ND	ND	4.0 J	ND	1.3 J	1.5 J
2	77.8–86	4/18/2000	ND	ND	1.7 J	ND	4.7 J	2.6 J
3	98.8–107	4/19/2000	ND	ND	2.0 J	ND	2.0 J	2.3 J
4	121–153.4	4/21/2000	ND	ND	6.2 J	ND	ND	ND
5	179.8–188	4/19/2000	1.0 J	ND	16	2.4 J	1.1 J	1.9 J
6	236.8–245	4/19/2000	3.9 J	ND	34	9.0 J	ND	ND
7	249.8–258	4/20/2000	4.7 J	2.2 J	39	8.3 J	ND	ND
8	345.3–389	4/20/2000	3.1 J	ND	21	8.3 J	ND	ND

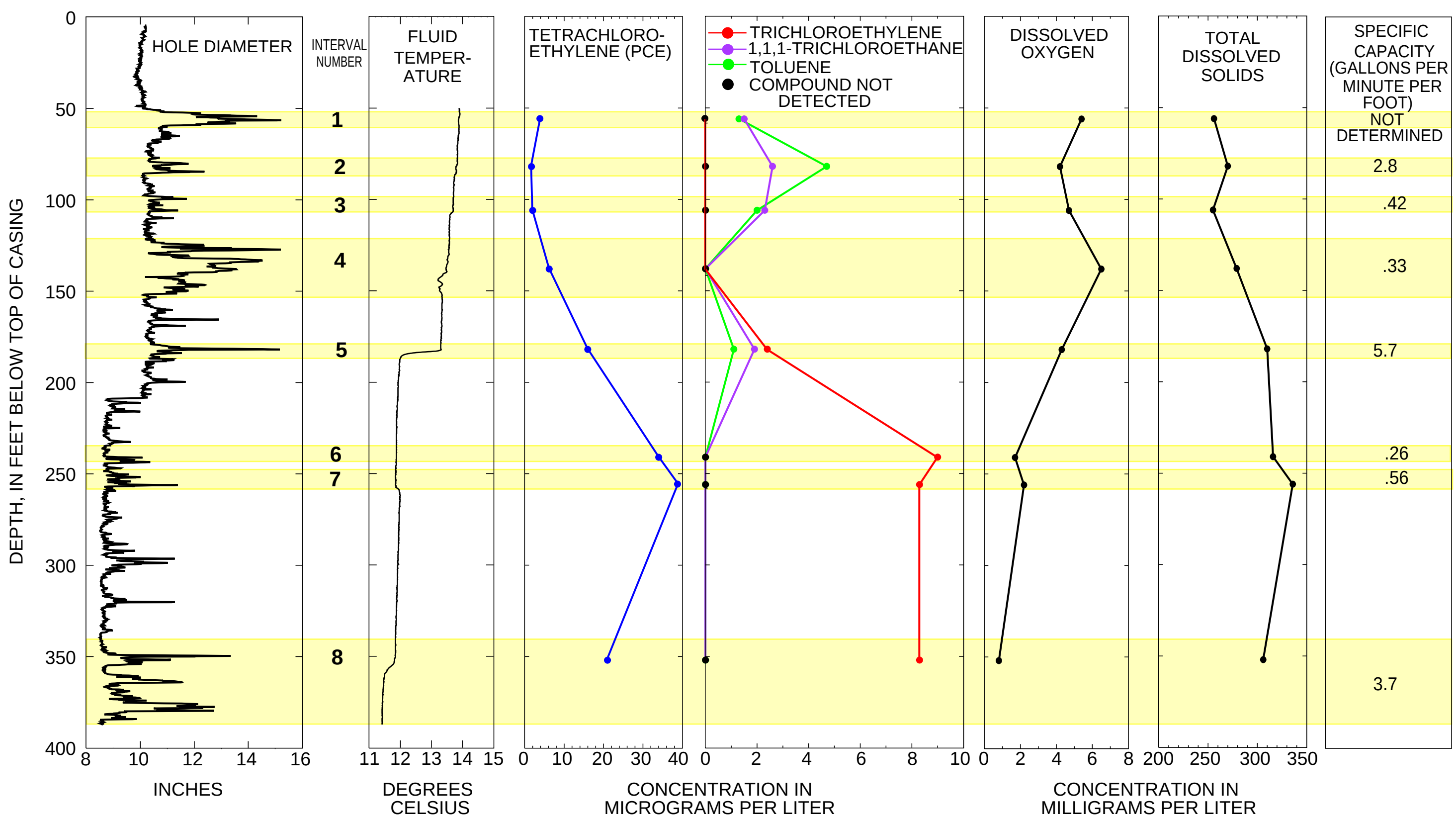


Figure 15. Concentration of tetrachloroethylene, trichloroethylene, 1,1,1-trichloroethane, toluene, dissolved oxygen, and total dissolved solids with depth in water samples from supply well 1 (MG–209), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Table 12. *Selected field determinations and concentrations of inorganic constituents in water samples collected during aquifer-isolation tests in supply well 1 (MG–209), April 17–21, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

[ft btoc, feet below top of casing; mg/L, milligrams per liter; µS/cm at 25°C, microsiemens per centimeter at 25 degrees Celsius; C, Celsius; µg/L, micrograms per liter; <, less than; J, estimated result less than reporting limit of 2.2 µg/L]

Interval	Depth of sample (ft btoc)	Date sampled	Dissolved oxygen (mg/L)	pH (standard units)	Specific conductance (µS/cm at 25°C)	Temperature (degrees C)	Calcium (mg/L)
1	51.8–60	4/17/2000	5.4	6.2	460	14.4	44
2	77.8–86	4/18/2000	4.2	6.1	461	15.3	45
3	98.8–107	4/19/2000	4.7	6.1	443	15	43
4	121–153.4	4/21/2000	6.5	6.6	496	14.3	51
5	179.8–188	4/19/2000	4.3	6.6	519	15.2	53
6	236.8–245	4/19/2000	1.7	7.3	553	14.1	52
7	249.8–258	4/20/2000	2.2	7.5	588	14.1	57
8	345.3–389	4/20/2000	.8	7.4	534	14.1	48

Interval	Magnesium (mg/L)	Potassium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)	Fluoride, dissolved (mg/L)	Silica, dissolved (mg/L)	Sulfate, dissolved (mg/L)
1	16	1.3	19	52	< 0.1	32	37
2	15	1.2	21	49	<.1	33	57
3	14	1.2	20	52	<.1	33	42
4	18	1.2	19	60	<.1	32	20
5	24	1.4	20	52	<.1	31	29
6	33	1	16	37	<.1	26	17
7	33	1.1	16	40	<.1	30	12
8	34	1.2	16	35	<.1	23	23

Interval	Barium, dissolved (µg/L)	Iron, dissolve d (µg/L)	Manganese, dissolved (µg/L)	Strontium, dissolved (µg/L)	Total dissolved solids (mg/L)
1	125	12	<2.2	141	256
2	75	280	13	115	270
3	92	260	7.2	121	255
4	209	56	7.2	156	279
5	480	59	4.8	235	310
6	266	38	<2.2	335	316
7	354	35	<2.2	215	336
8	171	43	1.6 J	510	306

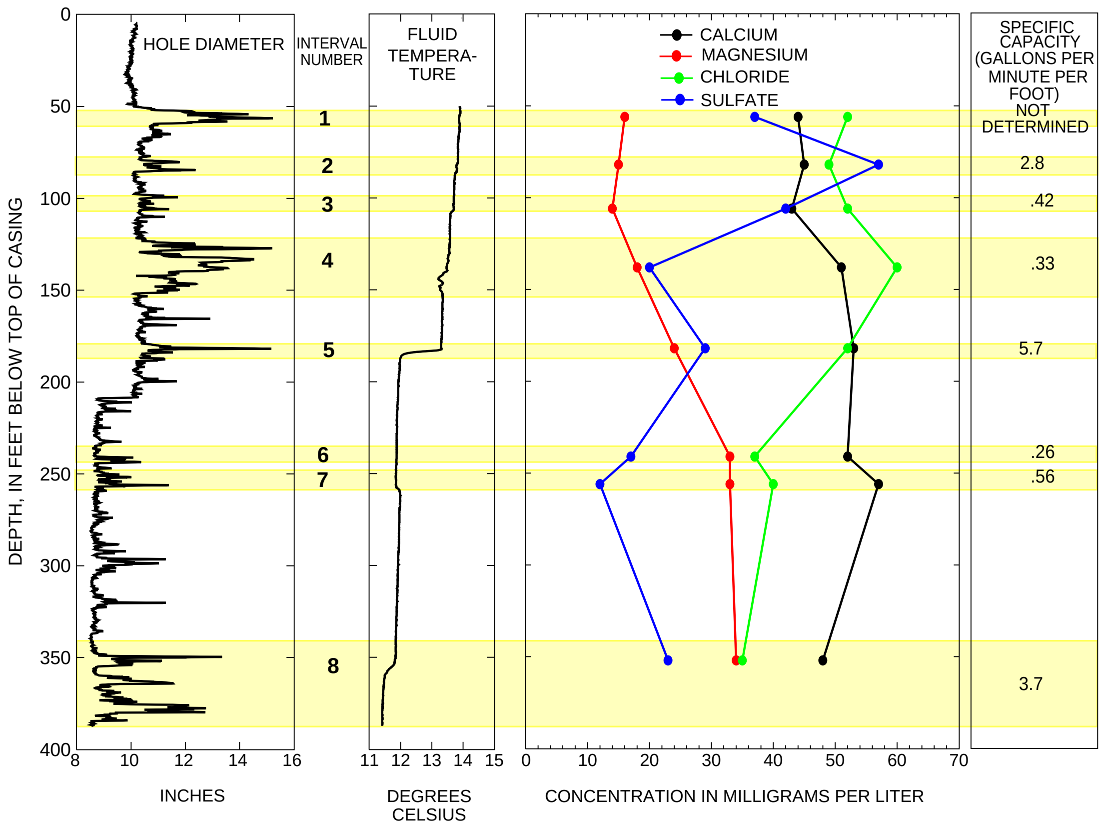


Figure 16. Concentration of calcium, chloride, magnesium, and sulfate with depth in water samples from supply well 1 (MG–209), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

SUPPLY WELL 2

Supply well 2 (MG–210) is one of two wells supplying the U.S. Navy part of the Willow Grove NAS/JRB with potable water. USGS records from 1947 indicate the well was drilled in 1942 to a depth of 351 ft and cased with 18 ft of 16-in.-diameter outer casing and 43 ft of 10-in.-diameter inner casing.

Interpretation of Borehole Geophysical Logs

A suite of borehole geophysical logs (fig. 17) was collected in supply well 2 by the USGS on March 17, 2000. At the time of geophysical logging, supply well 1 was pumping, and the water-level decline in the aquifer was nearing stabilization. The fluid-temperature and fluid-resistivity logs and heatpulse-flowmeter measurements are affected by the pumping of supply well 1 and reflect borehole conditions in supply well 2 during the pumping of supply well 1. The caliper log shows the well is 340 ft deep and is cased to 43 ft btoc. The well was drilled as a 10-in.-diameter borehole to 200 ft btoc and as an 8-in.-diameter borehole below 200 ft btoc. The caliper log shows major fractures and fracture zones at 43–53, 68–74, 93, 115, 162, 270, and 314 ft btoc. The fluid-temperature and fluid-resistivity logs indicate possible water-bearing zones at about 72, 113, 160, 205, 298, and 313 ft btoc.

Heatpulse-flowmeter measurements made under nonpumping conditions at 64, 85, 104, 132, 153, 184, 210, 238, 252, 282, 300, and 324 ft btoc (table 13) reveal a complicated pattern of borehole flow. On the basis of the geophysical logs and heatpulse-flowmeter measurements, water enters the upper part of the borehole through a vertical fracture at 68–74 ft btoc (1.2 gal/min) and flows downward. Water also enters the borehole through a horizontal fracture at 115 ft btoc (0.27 gal/min) (fig. 18) and flows downward. Water flowing downward exits the borehole through a large horizontal fracture at 162 ft btoc (1.53 gal/min total outflow). Water enters the borehole through a vertical fracture at 205 ft btoc (1.34 gal/min) and flows upward (0.1 gal/min) and downward (1.24 gal/min). The water flowing upward exits the borehole through the fracture at 162 ft btoc. Water flowing downward exits the borehole through a vertical fracture at 270 ft btoc (0.52 gal/min) (fig. 19) and a large horizontal fracture at 314 ft btoc (1.22 gal/min total outflow). A vertical fracture at 287 ft btoc (0.17 gal/min) contributes water to this downward flow. Water also enters the borehole through a vertical fracture at 331 ft btoc (0.1 gal/min) near the bottom of the borehole and flows upward. This water exits the borehole through the fracture at 314 ft btoc. The principal water-bearing fractures in supply well 2 are at 68–74, 115, 162, 205, 270, 287, 314, and 331 ft btoc. The fractures at 62–74, 115, 205, 287, and 331 ft btoc are water-producing fractures. The fractures at 162, 270, and 314 ft btoc are water-receiving fractures.

Table 13. *Heatpulse-flowmeter measurements made in supply well 2 (MG–210), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

Depth (feet below top of casing)	Flow (gallons per minute)	Flow direction
64	0	No flow
85	1.20	Down
104	1.18	Down
132	1.45	Down
153	1.43	Down
184	.10	Up
210	1.24	Down
238	1.47	Down
252	1.47	Down
282	.95	Down
300	1.12	Down
324	.10	Up

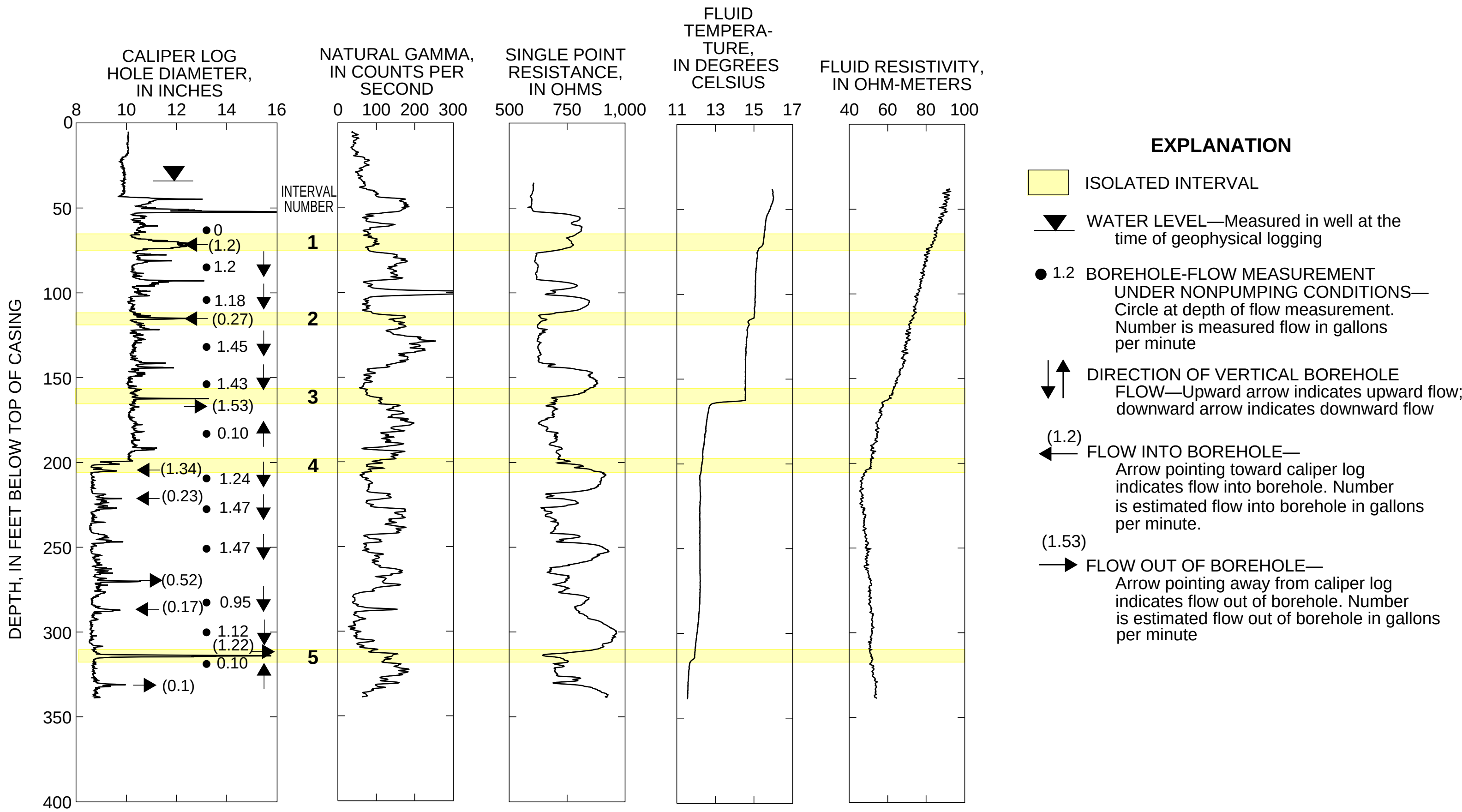


Figure 17. Borehole geophysical logs for supply well 2 (MG–210), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

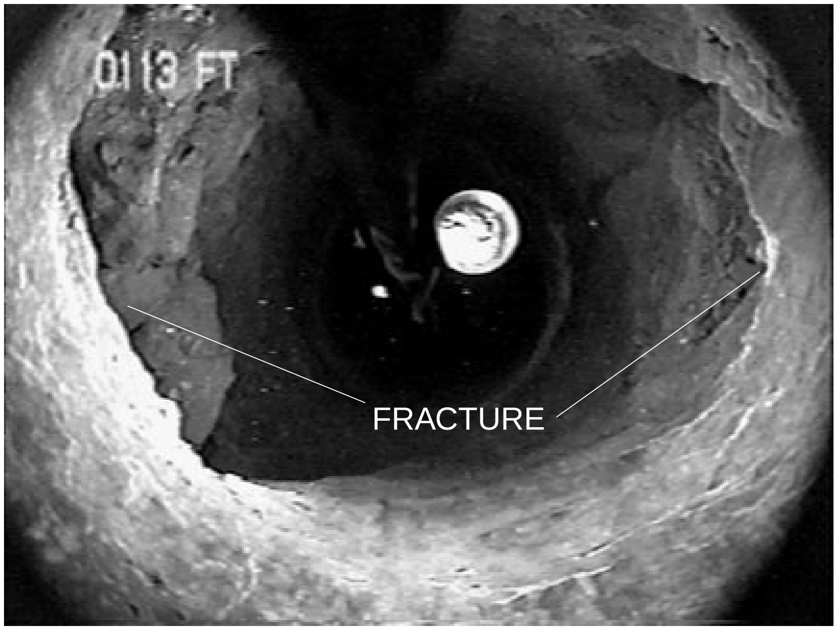


Figure 18. Borehole television survey showing horizontal fracture at 115 feet below top of casing in supply well 2 (MG–210), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

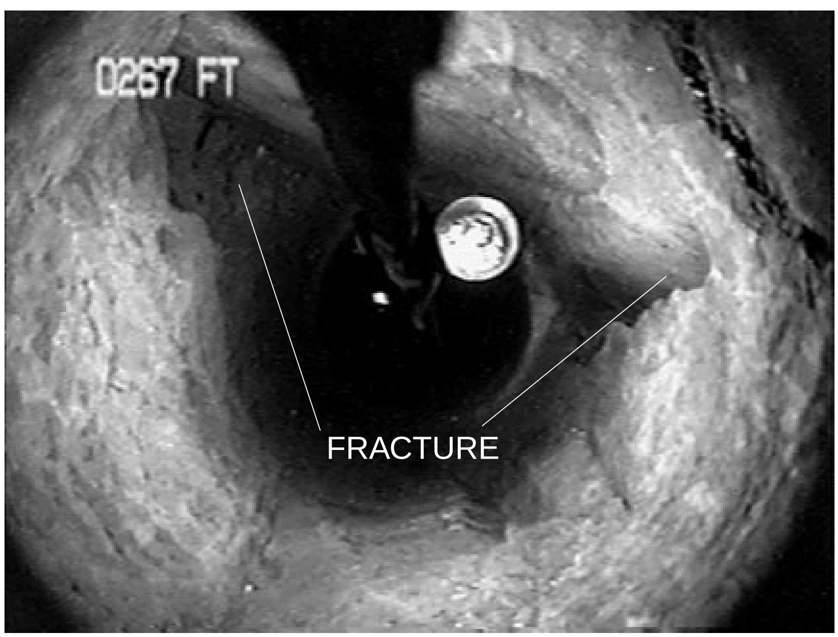


Figure 19. Borehole television survey showing vertical fracture at 270 feet below top of casing in supply well 2 (MG–210), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Aquifer-Isolation Tests

On the basis of the borehole geophysical measurements and borehole television survey, five intervals were selected for aquifer-isolation tests in supply well 2 (table 14). A straddle-packer assembly was used to isolate discrete fractures to determine depth-discrete specific capacity and to obtain depth-discrete water samples. For the test of all five intervals, the distance between the bottom of the upper packer and the top of the lower packer was 8.2 ft, and both packers were inflated. For the test of intervals 1, 2, and 5, supply well 1 was pumping, and drawdown in the aquifer was nearing stabilization; this stabilization was determined from the water level in well 01MW05I, which is affected by the pumping of supply well 1 (fig. 20). For the test of intervals 3 and 4, supply well 1 was not pumping.

Interval 1 (67–75.2 Feet Below Top of Casing)

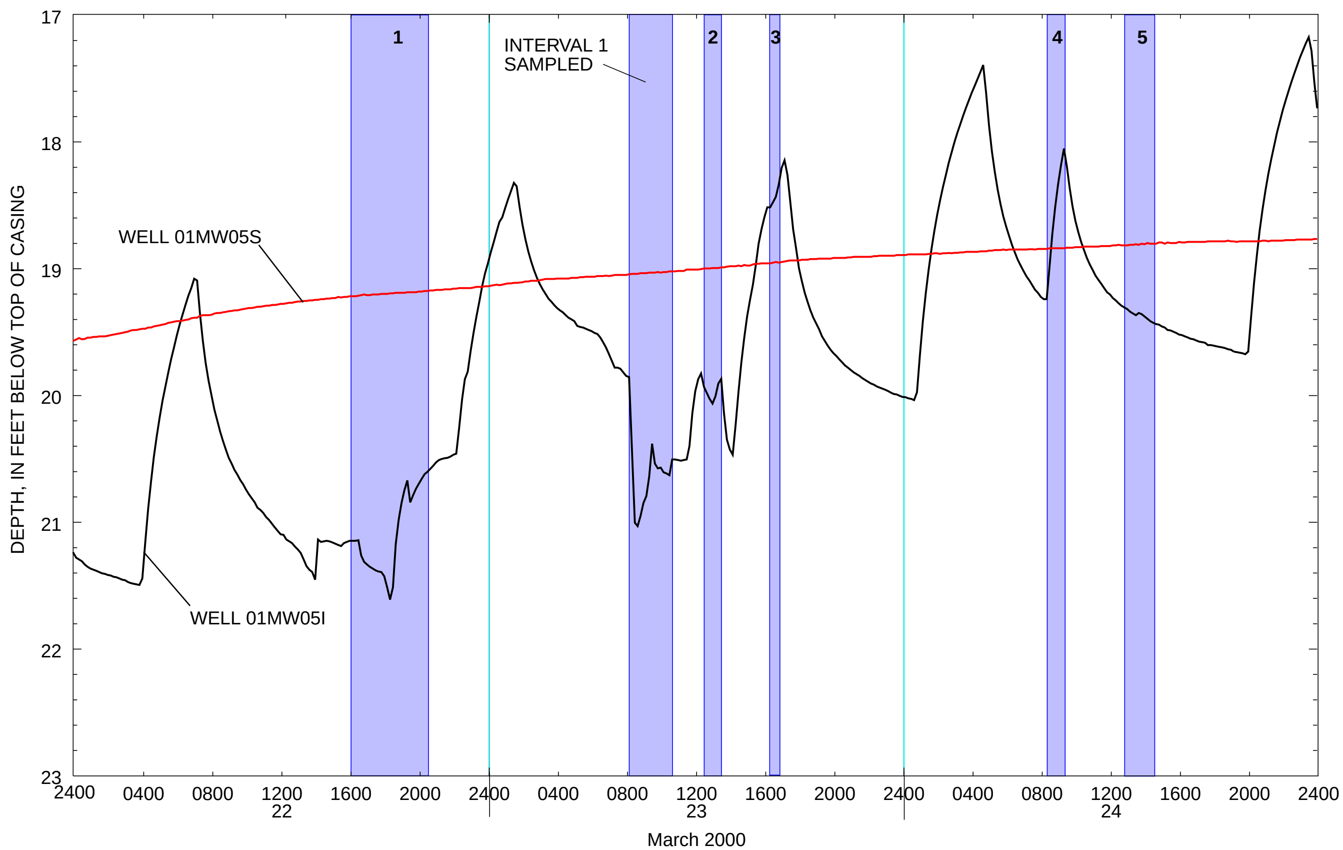
For the aquifer-isolation test of interval 1, the bottom of the upper packer and the top of the lower packer were set at 67 and 75.2 ft btoc, respectively, to isolate the fractures at 68–74 ft btoc. Before packer inflation, the depth to water in the open borehole was 33.11 ft btoc. Thirty-six minutes after packer inflation, the depth to water in the isolated interval was 33.41 ft btoc, a decrease of 0.30 ft; the depth to water in the interval below the packers was 33.39 ft btoc, a decrease of 0.28 ft; and the depth to water in the interval above the packers was 33.34 ft btoc, a decrease of 0.23 ft. The similar water levels probably resulted because the packers were not fully inflated.

Table 14. *Summary of intervals isolated during aquifer-isolation tests in supply well 2 (MG–210), March 22–24, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

[ft, feet; ft btoc, feet below top of casing; gal/min, gallons per minute; (gal/min)/ft, gallons per minute per foot of drawdown; <, less than; --, no data]

Interval	Depth of isolated fracture (ft btoc)	Bottom of top packer (ft btoc)	Top of bottom packer (ft btoc)	Final pumping rate (gal/min)	Drawdown (ft)	Specific capacity [(gal/min)/ft]
1	68–74	67	75.2	22	13.58	<1.6
2	115	111.5	119.7	10	11.17	.9
3	162	157	165.2	23	7.93	<2.9
4	205	197.7	205.9	6	54.43	--
5	314	310.5	318.7	4	47.14	.08
--	Open-hole test[1]	--	--	200	65	3

[1] From data provided by TetraTech NUS, Inc., from an 8-hour open-hole aquifer test conducted April 12, 2000.



EXPLANATION

1 TIME WHEN AQUIFER-ISOLATION TESTS WERE CONDUCTED IN SUPPLY WELL 2 AND INTERVAL NUMBER

Figure 20. Hydrographs from wells 01MW05S and 01MW05I showing the effect of pumping supply well 1, March 22–24, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Pumping began at 16:35 on March 22 at a rate of 22 gal/min (table 15). After 83 minutes, drawdown was similar in all three intervals. The pressure in the packers then was increased to achieve better separation of the intervals. After 32 additional minutes of pumping, total drawdown was 13.58 ft in the isolated interval, 3.50 ft in the interval below the packers, and 12.87 ft in the interval above the packers. The pump was shut down, but the packers were left inflated and the datalogger was left running overnight. The water level in the isolated interval still was declining rapidly when the test ended; therefore, the specific capacity of interval 1 is less than 1.6 (gal/min)/ft. The hydrographs for the interval above the packers, the isolated interval, and the interval below the packers (fig. 21) indicate either a poor seal between the upper packer and the borehole wall or a very strong hydraulic connection between the isolated interval and the interval above the packers and a strong hydraulic connection between the isolated interval and the interval below the packers.

Table 15. *Schedule for the aquifer-isolation test of interval 1 (67–75.2 feet below top of casing) in supply well 2 (MG–210), March 22–23, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

Date	Time	Activity
March 22	15:39	Start datalogger
-	16:00	Begin packer inflation
-	16:35	Start pump at 22 gallons per minute
-	17:58	Increase packer pressure
-	18:30	Pump off
-	22:15	Supply well 1 off
March 23	1:35	Supply well 1 on
-	9:30	Begin packer deflation
-	9:43	Stop datalogger

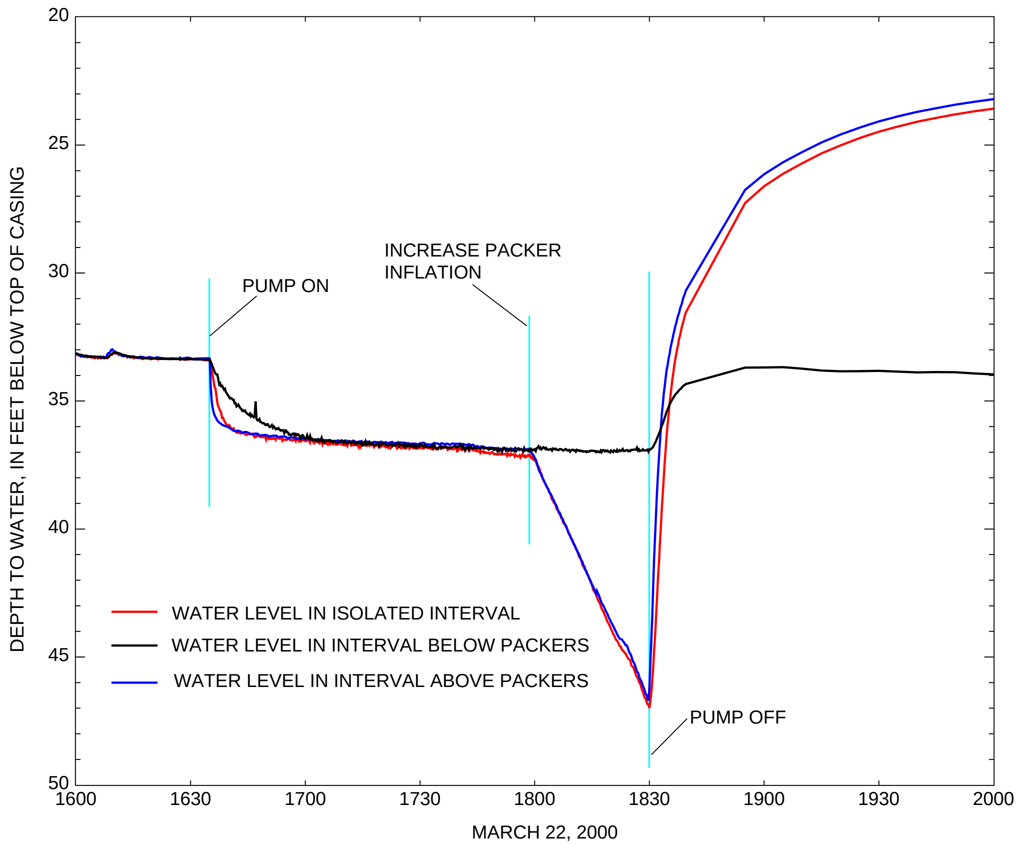


Figure 21. Hydrographs from aquifer-isolation test of interval 1 (67–75.2 feet below top of casing) in supply well 2 (MG–210), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

At approximately 22:15 on March 22, the pump in supply well 1 shut down. It restarted at approximately 1:35 on March 23. During this time, the water levels in the three intervals in supply well 2 recovered. The depth to water in the interval below the packers rose 10.13 ft, the depth to water in the isolated interval rose 2.51 ft, and the depth to water in the interval above the packers rose 2.49 ft (fig. 22). The pumping of supply well 1 caused more drawdown in the deeper (below 75.2 ft btoc) fractures than in the shallower (above 75.2 ft btoc) fractures.

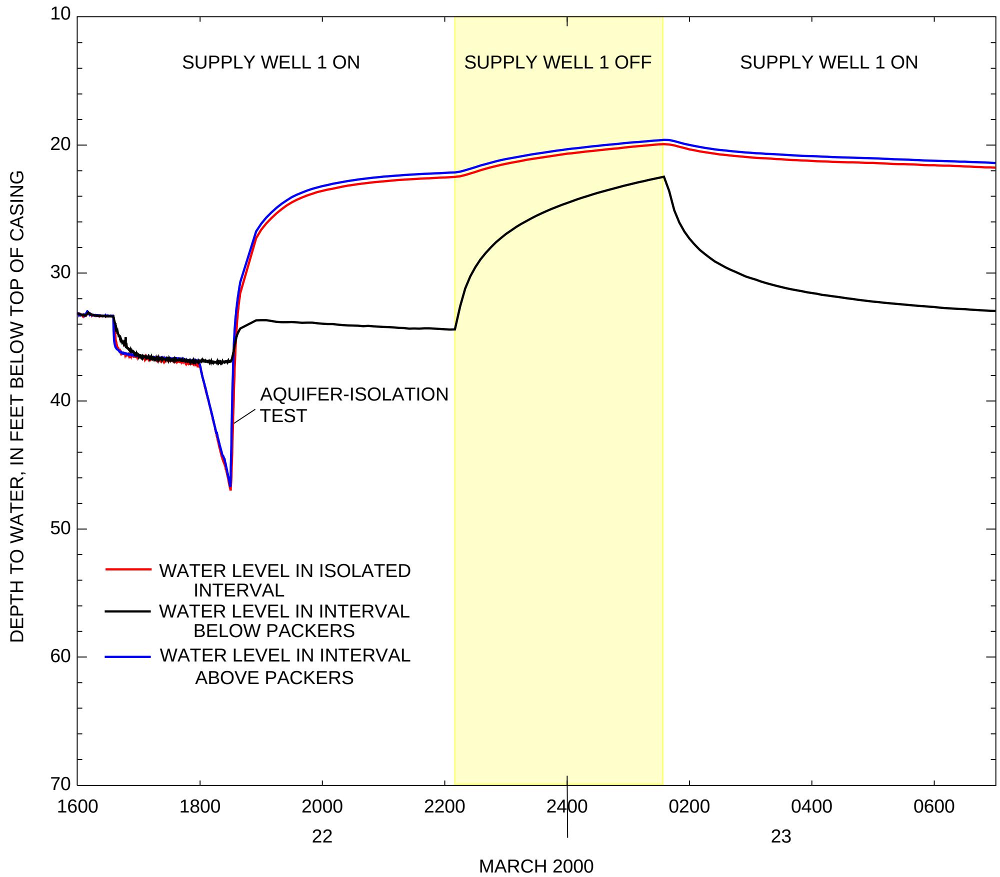


Figure 22. Hydrographs during and after the aquifer-isolation test of interval 1 (67–75.2 feet below top of casing) in supply well 2 (MG–210), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Interval 2
(111.5–119.7 Feet Below Top of Casing)

For the aquifer-isolation test of interval 2, the bottom of the upper packer and the top of lower packer were set at 111.5 and 119.7 ft btoc, respectively, to isolate the water-producing fracture at 115 ft btoc. Before packer inflation, the depth to water in the open borehole was 33.17 ft btoc. At 67 minutes after packer inflation, the depth to water in the isolated interval was 28.66 ft btoc, an increase in water level of 4.51 ft; the depth to water in the interval below the packers was 30.39 ft btoc, an increase in water level of 2.78 ft; and the depth to water in the interval above the packers was 33.95 ft btoc, a decrease in water level of 0.78 ft.

Pumping began at 12:30 at an initial rate of 24 gal/min (table 16). After 2 minutes, the pumping rate was decreased to 5 gal/min. After another 4 minutes, the pumping rate was increased to 10 gal/min. After 41 minutes of pumping, the total drawdown was 11.17 ft in the isolated interval. The water level declined 0.44 ft in the interval below the packers and 0.26 ft in the interval above the packers. The specific capacity of interval 2 is 0.9 (gal/min)/ft. The hydrographs for the interval above the packers, the isolated interval, and the interval below the packers (fig. 23) indicate a weak hydraulic connection among the three intervals. Missing data for the interval above the packers from 11:40 to 11:48 were caused by the water level rising above the range of the transducer. After the transducer was moved to a higher location in the borehole, data collection continued.

Table 16. *Schedule and pumping rates for the aquifer-isolation test of interval 2 (111.5–119.7 feet below top of casing) in supply well 2 (MG–210), March 23, 2000, Willow Grove Naval Air Station/ Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

Time	Activity
11:16	Start datalogger
11:24	Begin packer inflation
12:30	Start pump at 24 gallons per minute
12:32	Decrease pumping rate to 5 gallons per minute
12:36	Increase pumping rate to 10 gallons per minute
13:11	Pump off
13:32	Begin lower packer deflation
13:40	Begin upper packer deflation
13:53	Stop datalogger

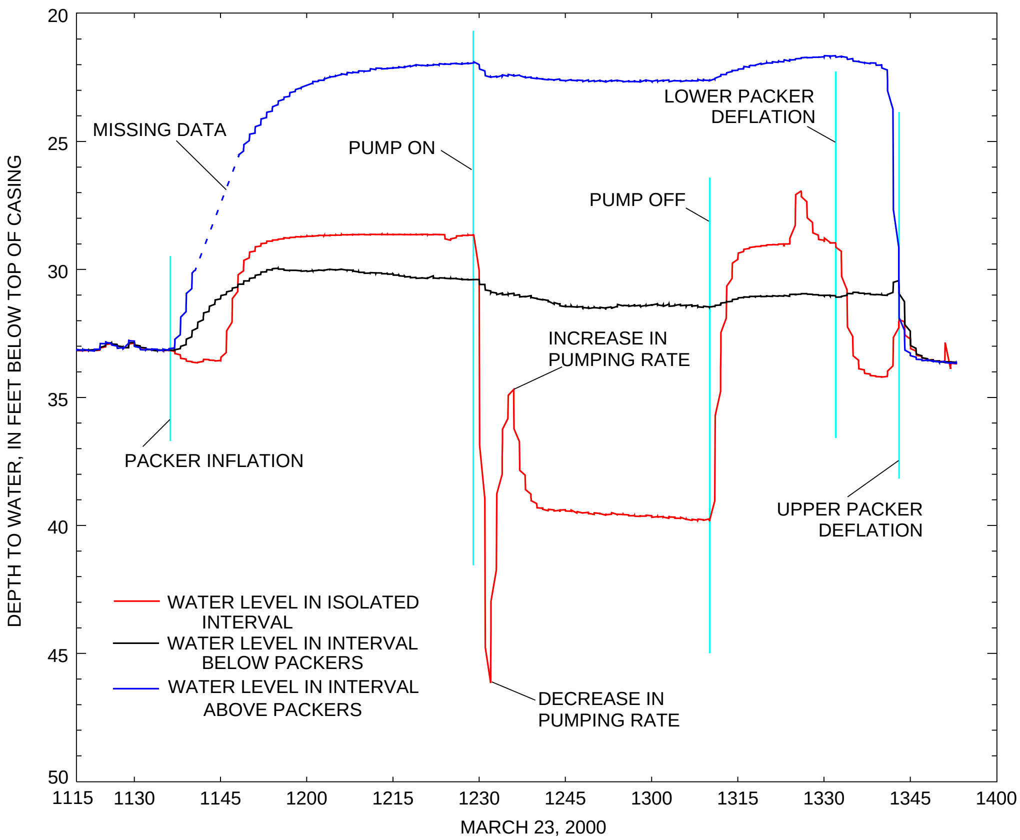


Figure 23. Hydrographs from aquifer-isolation test of interval 2 (111.5–119.7 feet below top of casing) in supply well 2 (MG–210), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Interval 3 (157–165.2 Feet Below Top of Casing)

The aquifer-isolation test of interval 3 took place while supply well 1 was not pumping and recovery of water levels in the aquifer was taking place (fig. 20). The bottom of the upper packer and the top of the lower packer were set at 157 and 165.2 ft btoc, respectively, to isolate the water-receiving fracture at 162 ft btoc. No data were collected between 15:36 and 15:41. Before packer inflation, the depth to water in the open borehole was 25.14 ft btoc. Forty-eight minutes after packer inflation, the depth to water in the isolated interval was 25.82 ft btoc, a decrease in water level of 0.68 ft; the depth to water in the interval below the packers was 22.73 ft btoc, an increase in water level of 2.41 ft; and the depth to water in the interval above the packers was 22.36 ft btoc, an increase in water level of 2.78 ft. This is consistent with the heatpulse-flowmeter measurements that showed downward flow from above the isolated interval and upward flow from below the isolated interval.

Pumping began at 16:13 at 23 gal/min (table 17). After 37 minutes of pumping, drawdown in the isolated interval was 7.93 ft, drawdown in the interval below the packers was 0.42 ft, and drawdown in the interval above the packers was 0.57 ft. Because water levels in the aquifer were recovering during the test (fig. 20), drawdown was less than it would have been if water levels were stable; therefore, the specific capacity of interval 3 is less than 2.9 (gal/min)/ft. The hydrographs for the interval above the packers, the isolated interval, and the interval below the packers (fig. 24) indicate a weak hydraulic connection among the three intervals.

Table 17. *Schedule for the aquifer-isolation test of interval 3 (157–165.2 feet below top of casing) in supply well 2 (MG–210), March 23, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

Time	Activity
14:10	Supply well 1 off
15:12	Start datalogger
15:25	Begin packer inflation
16:13	Start pump at 23 gallons per minute
16:50	Pump off
17:04	Begin packer deflation
17:10	Supply well 1 on
17:28	Stop datalogger

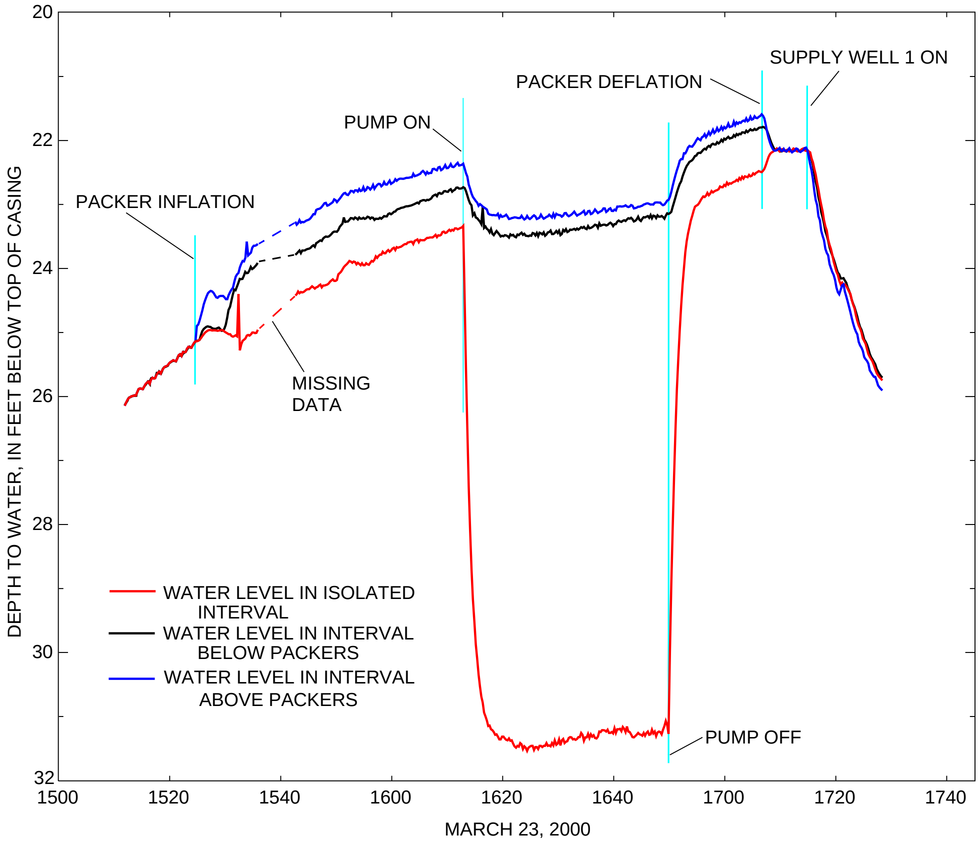


Figure 24. Hydrographs from aquifer-isolation test of interval 3 (157–165.2 feet below top of casing) in supply well 2 (MG–210), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Interval 4
(197.7–205.9 Feet Below Top of Casing)

For the aquifer-isolation test of interval 4, the bottom of the upper packer and the top of the lower packer were set at 197.7 and 205.9 ft btoc, respectively, to isolate the water-producing fracture at 205 ft btoc. On March 23 before packer inflation, the depth to water in the open borehole was 30.12 ft btoc. Fifteen minutes after packer inflation, the depth to water in the isolated interval was 26.38 ft btoc, an increase of 3.74 ft; the depth to water in the interval above the packers was 30.82 ft btoc, a decrease of 0.70 ft; and the depth to water in the interval below the packers was 30.95 ft btoc, a decrease of 0.83 ft. This is consistent with the heatpulse-flowmeter measurements that showed upward and downward flow from the isolated interval.

The packers were left inflated overnight, and the datalogger was left on. At approximately 0:40 on March 24, the pump in supply well 1 shut down; it restarted at approximately 4:45. During this time, the water levels in the three intervals of supply well 2 recovered. The water level in the isolated interval rose 8.61 ft, the water level in the interval below the packers rose 11.93 ft, and the water level in the interval above the packers rose 11.86 ft (fig. 25).

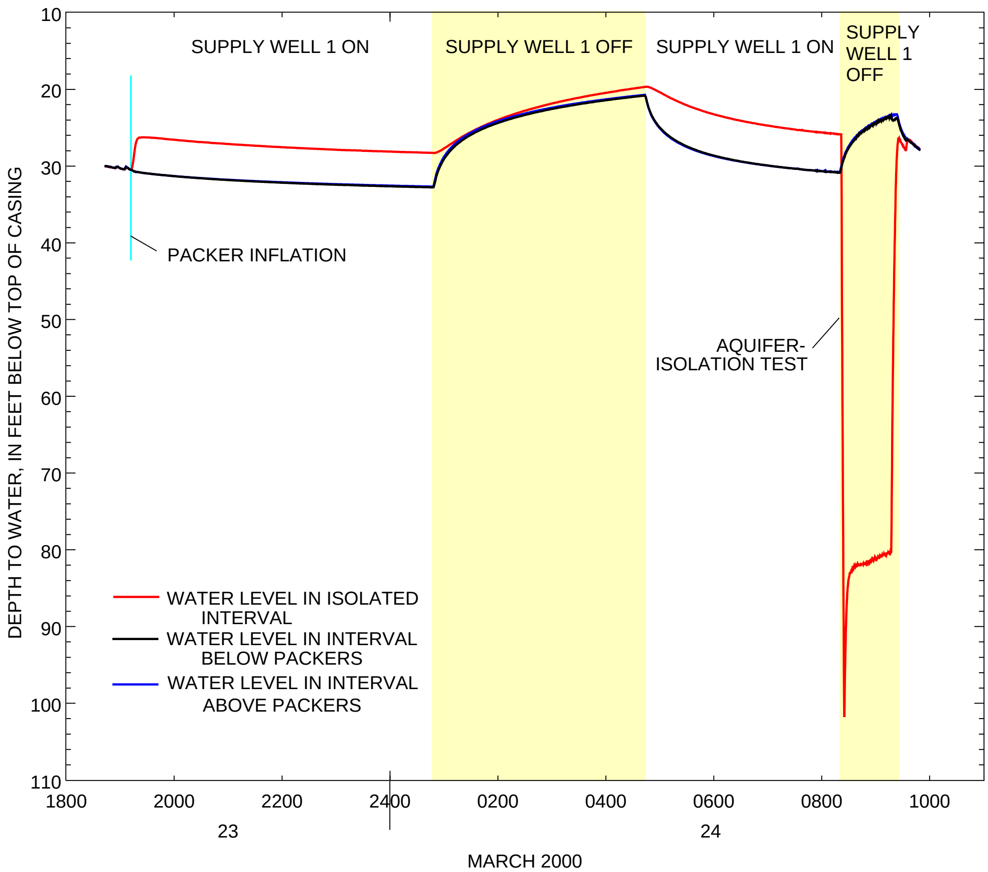


Figure 25. Hydrographs before and during the aquifer-isolation test of interval 4 (197.7–205.9 feet below top of casing) in supply well 2 (MG–210), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

On March 24 at 8:20, the water level in the interval below the packers was 30.99 ft btoc; the water level in the isolated interval was 25.95 ft btoc; and the water level in the interval above the packers was 30.83 ft btoc. At approximately 8:21, the pump in supply well 1 shut down. The pump in the isolated interval of well 2 was started at 8:22 at a rate of 20 gal/min (table 18). After 3 minutes, the water level in the isolated interval dropped to 101.86 ft btoc, and the pumping rate was decreased to 6 gal/min. After 51 additional minutes of pumping, drawdown in the isolated interval was 54.43 ft.

Because of water-level recovery from the shutdown of supply well 1, the water level in the intervals above and below the packers increased during the pumping of the isolated interval. The water level in the interval below the packers rose 6.86 ft, and the water level in the interval above the packers rose 6.77 ft. The specific capacity of interval 4 was not calculated because the water level was affected by recovery from the shutdown of supply well 1, and the water level in the isolated interval was rising during the latter part of the test because of the decrease in the pumping rate (fig. 25).

Table 18. *Schedule and pumping rates for the aquifer-isolation test of interval 4 (197.7–205.9 feet below top of casing) in supply well 2 (MG–210), March 23–24, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

Date	Time	Activity
March 23	18:42	Start datalogger
-	18:55	Begin packer inflation
March 24	0:40	Supply well 1 off
-	4:45	Supply well 1 on
-	8:21	Supply well 1 off
-	8:22	Start pump at 20 gallons per minute
-	8:25	Decrease pumping rate to 6 gallons per minute
-	9:17	Pump off
-	9:38	Begin packer deflation
-	9:50	Stop datalogger

Interval 5
(310.5–318.7 Feet Below Top of Casing)

For the aquifer-isolation test of interval 5, the bottom of the upper packer and the top of the lower packer were set at 310.5 and 318.7 ft btoc, respectively, to isolate the water-receiving fracture at 314 ft btoc. Before packer inflation, the depth to water in the open borehole was 30.96 ft btoc. Twenty-six minutes after packer inflation, the depth to water in the isolated interval was 34.44 ft btoc, a decrease in water level of 3.48 ft; the depth to water in the interval below the packers was 31.14 ft btoc, a decrease in water level of 0.18 ft; and the depth to water in the interval above the packers was 31.67 ft btoc, a decrease in water level of 0.71 ft. This is consistent with the heat-pulse-flowmeter measurements that showed downward flow from above the isolated interval and upward flow from below the isolated interval.

Pumping began at 12:56 at an initial rate of 5.2 gal/min (table 19), and the water level in the isolated interval quickly dropped to 68.18 ft btoc. The pumping rate was decreased to 2.6 gal/min at 12:58 and then increased to 4.4 gal/min at 13:01. Because of sediment partially clogging the filter, the pumping rate was unstable throughout the first 40 minutes of pumping. After this period of unstable pumping, the rate became more stable and was about 4 gal/min. Total drawdown was 47.14 ft in the isolated interval, 0.45 ft in the interval above the packers, and 0.41 ft in the interval below the packers, The specific capacity of interval 5 is 0.08 (gal/min)/ft. The hydrographs for the interval above the packers, the isolated interval, and the interval below the packers (fig. 26) indicate a weak hydraulic connection among the three intervals.

Table 19. *Schedule and pumping rates for the aquifer-isolation test of interval 5 (310.5–318.7 feet below top of casing) in supply well 2 (MG–210), March 24, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

Time	Activity
11:54	Start datalogger
12:19	Begin upper packer inflation
12:31	Begin lower packer inflation
12:56	Start pump at 5.2 gallons per minute
12:58	Decrease pumping rate to 2.6 gallons per minute
13:01	Increase pumping rate to 4.4 gallons per minute
14:13	Pump off
14:25	Begin deflating packers
14:47	Stop datalogger

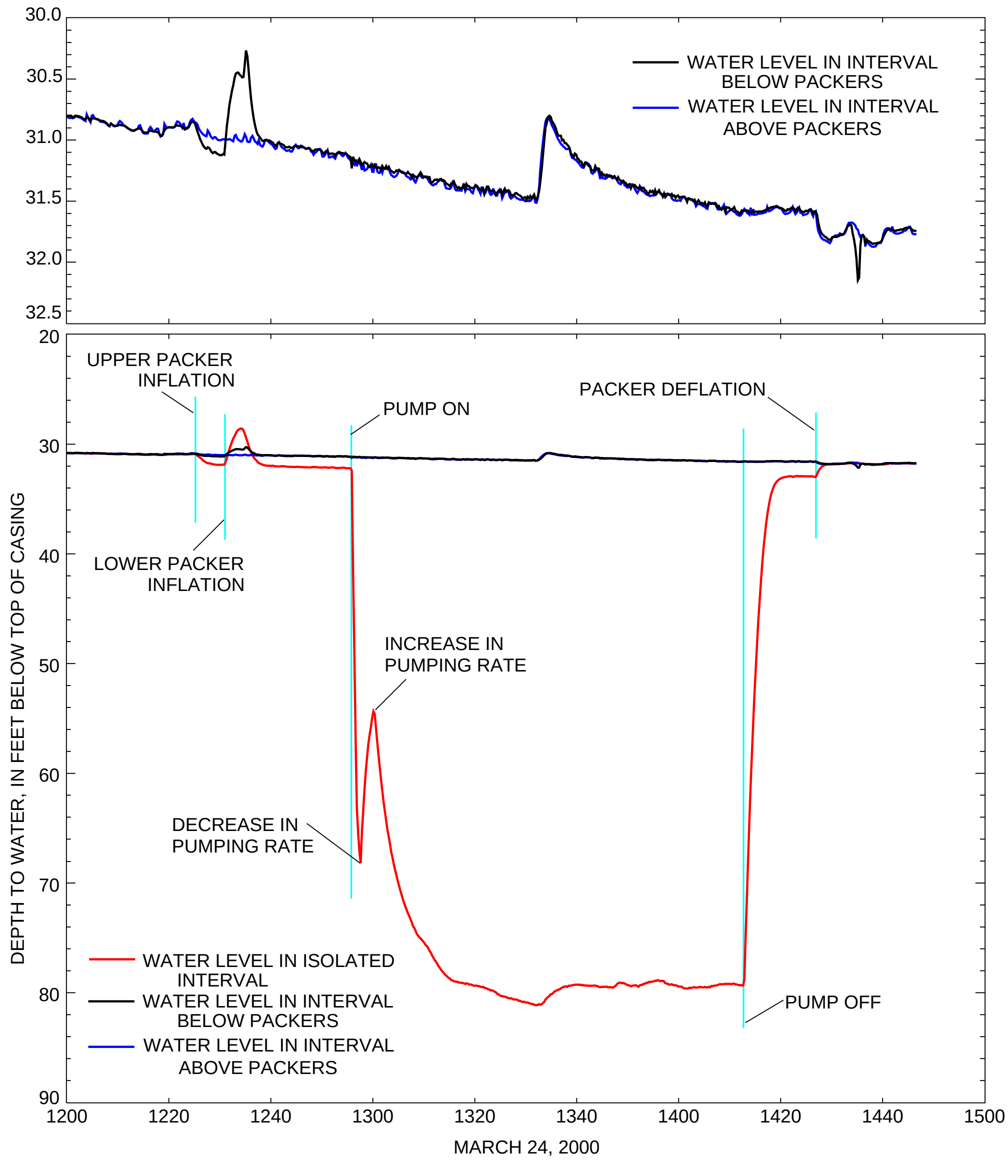


Figure 26. Hydrographs from aquifer-isolation test of interval 5 (310.5–318.7 feet below top of casing) in supply well 2 (MG–210), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Vertical Distribution of Water-Quality Constituents

During each aquifer-isolation test, water samples were collected by the USGS and analyzed for inorganic constituents and by TetraTech NUS, Inc., and analyzed for VOC's. Analytical results were used to determine change in concentration with depth. However, vertical mixing occurs in the aquifer and the well because of drawdown and recovery cycles in the supply wells, borehole flow when the supply wells are not pumping, and the pumping of one supply well affecting water levels (well interference) and borehole flow in the other supply well.

VOC's detected in water samples collected during aquifer-isolation tests and not attributable to laboratory contamination are listed in table 20. Concentrations of detected VOC's were estimated at 3.6 µg/L or less. Toluene was detected in every sample (table 20). PCE was detected only in samples from 197.7–205.9 and 310.5–318.7 ft btoc, and TCE was detected only in samples from 157–165.2 and 197.7–205.9 ft btoc (fig. 27). TCA, which was detected in water samples from supply well 1, was not detected in water samples from supply well 2.

Inorganic constituents in water samples collected during aquifer-isolation tests are listed in table 21. The concentrations of magnesium (fig. 28), barium, and strontium and pH generally increase with depth. Concentrations of dissolved oxygen (fig. 27), chloride, and sulfate generally decrease with depth (fig. 28).

Table 20. *Concentrations of selected volatile organic compounds in water samples collected during aquifer-isolation tests in supply well 2 (MG–210), March 23–24, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

[Laboratory results were provided by TetraTech NUS, Inc.; ft btoc, feet below top of casing; µg/L, micrograms per liter; ND, not detected; J, estimated result less than reporting limit of 10 micrograms per liter]

Interval	Depth of sample (ft btoc)	Date sampled	Acetone (µg/L)	2-Butanone (µg/L)	Chloroform (µg/L)	Tetrachloro-ethylene (µg/L)	Trichloro-ethylene (µg/L)	Toluene (µg/L)
1	67–75.2	3/23/2000	ND	ND	ND	ND	ND	3.5 J
2	111.5–119.7	3/23/2000	ND	ND	ND	ND	ND	2.1 J
3	157–165.2	3/23/2000	2.1 J	ND	ND	ND	1.6 J	2.2 J
4	197.7–205.9	3/24/2000	2.2 J	ND	1.6 J	3.6 J	1.1 J	2.2 J
5	310.5–318.7	3/24/2000	1.7 J	1.6 J	ND	1.8 J	ND	1.4 J

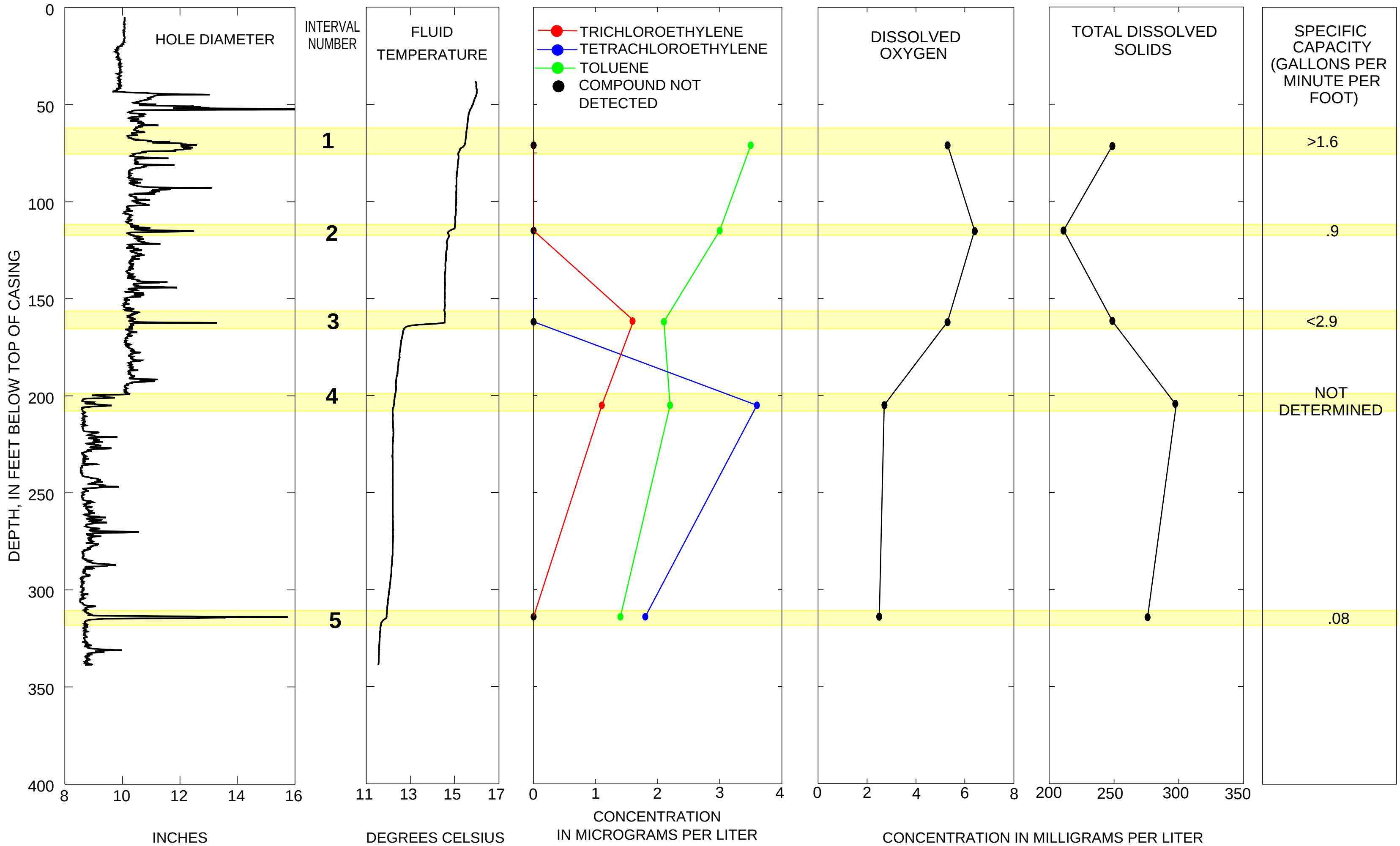


Figure 27. Concentration of tetrachloroethylene, trichloroethylene, toluene, dissolved oxygen, and total dissolved solids with depth in water samples from supply well 2 (MG–210), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Table 21. *Selected field determinations and concentrations of inorganic constituents in water samples collected during aquifer-isolation tests in supply well 2 (MG–210), March 23–24, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

[ft btoc, feet below top of casing; mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm at 25°C, microsiemens per centimeter at 25 degrees Celsius; C, Celsius; <, less than; J, estimated concentration below reporting limit]

Interval	Depth sampled (ft btoc)	Date sampled	Dissolved oxygen (mg/L)	pH (standard units)	Specific conductance (µS/cm at 25°C)	Temperature (degrees C)	Calcium (mg/L)
1	67–75.2	3/23/2000	5.3	6.5	401	15.3	38
2	111.5–119.7	3/23/2000	6.4	6.2	359	16.9	35
3	67–75.2	3/23/2000	5.3	6.6	429	15.6	46
4	111.5–119.7	3/24/2000	2.7	7.4	514	15.4	60
5	157–165.2	3/24/2000	2.5	7.4	477	15.6	51

Interval	Magnesium (mg/L)	Potassium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)	Fluoride, dissolved (mg/L)	Silica, dissolved (mg/L)	Sulfate, dissolved (mg/L)
1	9.6	1.4	19	39	< 0.1	32	38
2	9.6	1.3	19	40	<.1	36	25
3	14	1.4	17	39	<.1	34	24
4	21	.85	16	34	<.1	33	18
5	21	1.0	14	30	<.1	29	18

Interval	Barium, dissolved (µg/L)	Iron, dissolved (µg/L)	Manganese, dissolved (µg/L)	Strontium, dissolved (µg/L)	Total dissolved solids (mg/L)
1	146	96	4.0	87	249
2	202	110	2.4	100	211
3	251	44	1.6 J	118	249
4	333	47	1.6 J	135	298
5	412	30	8.8	371	276

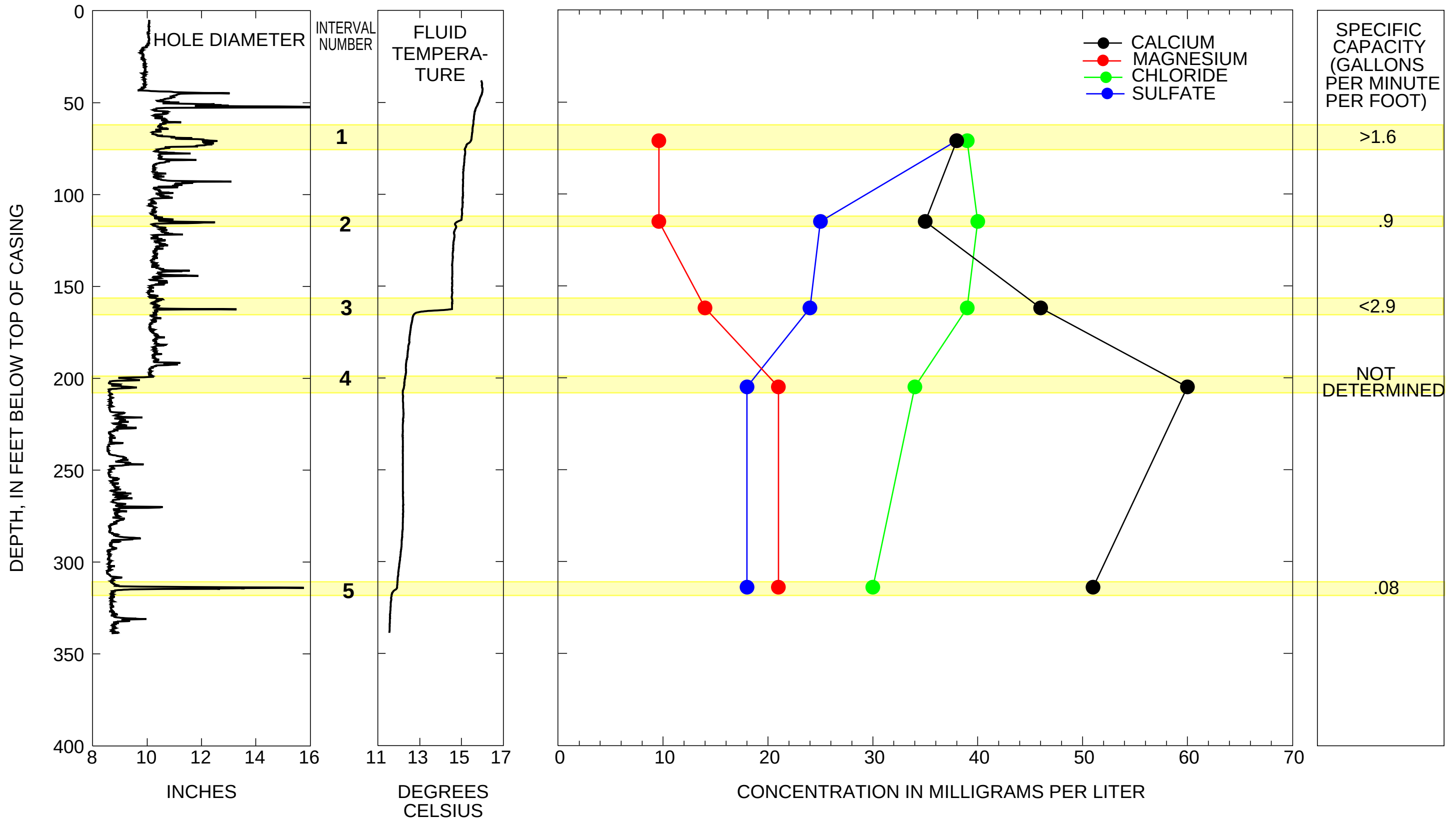


Figure 28. Concentration of calcium, chloride, magnesium, and sulfate with depth in water samples from supply well 2 (MG–210), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

CORRELATION OF BOREHOLE GEOPHYSICAL LOGS

Lithologic units penetrated by supply wells 1 and 2 were determined by correlating natural-gamma and single-point resistance logs (Sloto and others, 1996). Lithologic units A, C, E, G, I, K, and M are silty, finer-grained units and are either mudstone or siltstone (fig. 29). Lithologic units B, D, F, H, J, L, and N are sandstone or sandy, coarser-grained units. Water-bearing fractures are not necessarily present in the same lithologic units in both supply wells. Although the wells penetrate the same lithologic units (fig. 29), the location of only three water-bearing fractures are common to both wells. Common water-bearing fractures in both wells are in sandy lithologic unit H and at the contacts between lithologic units D and E and units L and M. For supply well 1, four water-bearing fractures are at the contact between silty and sandy lithologic units; three water-bearing fractures are in silty lithologic units A, C, and G; and two are in sandy lithologic units H and J. For supply well 2, four water-bearing fractures are at the contact between silty and sandy lithologic units; three water-bearing fractures are in silty lithologic units B, H, and L; and one is in sandy lithologic unit K.

The same lithologic unit may have different hydraulic properties in each supply well. The highest specific capacity (5.7 (gal/min)/ft) of the intervals tested in supply well 1 was at 179.8–188 ft btoc, which is at the top of sandy lithologic unit F. The highest specific capacity (less than 2.9 (gal/min)/ft) of the intervals tested in supply well 2 was at 157–165.2 ft btoc, which is at the bottom of sandy lithologic unit F. The second highest specific capacity (3.7 (gal/min)/ft) of the intervals tested in supply well 1 was at 345.3–389 ft btoc, which is at the top of lithologic unit M. The lowest specific capacity (0.08 (gal/min)/ft) of the intervals tested in supply well 2 was at 310.5–318.7 ft btoc, which also is at the top of lithologic unit M.

The highest concentrations of PCE in water samples from supply well 1 were from intervals 6 (236.8–245 ft btoc) and 7 (249.8–258 ft btoc). Interval 7 is in lithologic unit H, and interval 6 is just above lithologic unit H (fig. 29). The aquifer-isolation tests indicate these intervals are connected hydraulically. The highest concentrations of PCE in water samples from supply well 2 were from interval 4 (197.7–205.9 ft btoc). Interval 4 is in lithologic unit H (fig. 29). This lithologic unit appears to be the major source of contamination for both supply wells. Assuming a strike of N. 76° E. and a dip of 7° NW., the projected outcrop of lithologic unit H is approximately 2,300–2,450 ft southeast of supply well 1 and 1,850–2,050 ft southeast of supply well 2 (fig. 30). The projected outcrop is updip and hydraulically upgradient from the supply wells. The projected outcrop is approximately halfway between the supply wells and the regional ground-water divide running through the base (fig. 30), which is approximately 4,000 ft southeast of the supply wells.

DIRECTION OF GROUND-WATER FLOW

Water-level data provide important information on horizontal and vertical ground-water-flow directions and gradients. Water-level data from a monitor well cluster (wells drilled in close proximity) screened at different depths provide information on vertical head differences and the direction of vertical flow. Water-level data from monitor wells screened in the same depth interval provide information on horizontal gradients and the direction of horizontal flow.

Regional Potentiometric Surface

A map showing the regional potentiometric surface at and in the vicinity of the Willow Grove NAS/JRB was prepared by Sloto and others (2001). A part of the map, reproduced here as figure 31, shows a regional ground-water divide running northeast-southwest to the southeast of Site 1. From this divide, ground water flows northwest through Site 1 toward Park Creek, a tributary to Little Neshaminy Creek. This is the direction of regional ground-water flow.

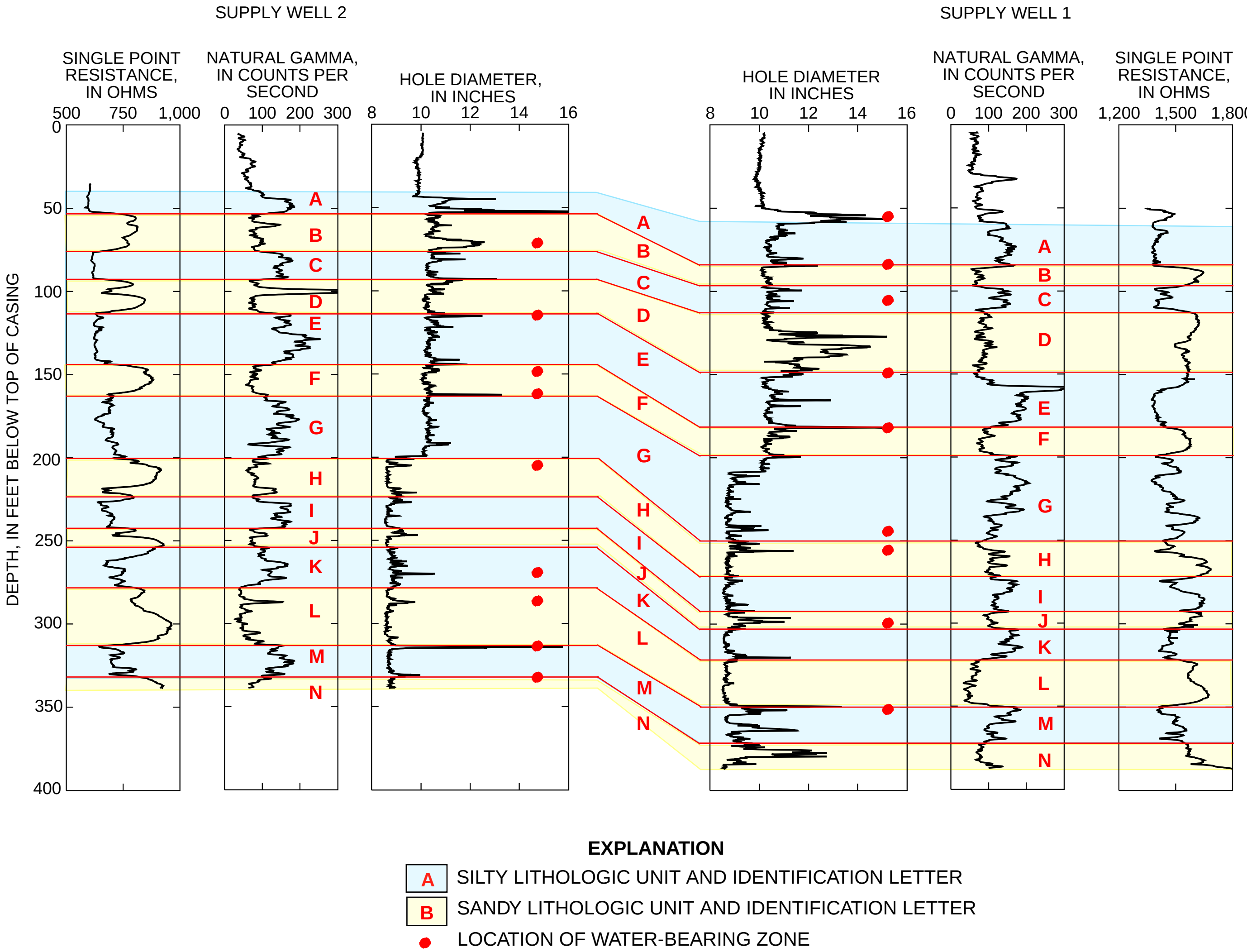


Figure 29. Correlation of borehole geophysical logs from supply wells 1 (MG–209) and 2 (MG–210), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

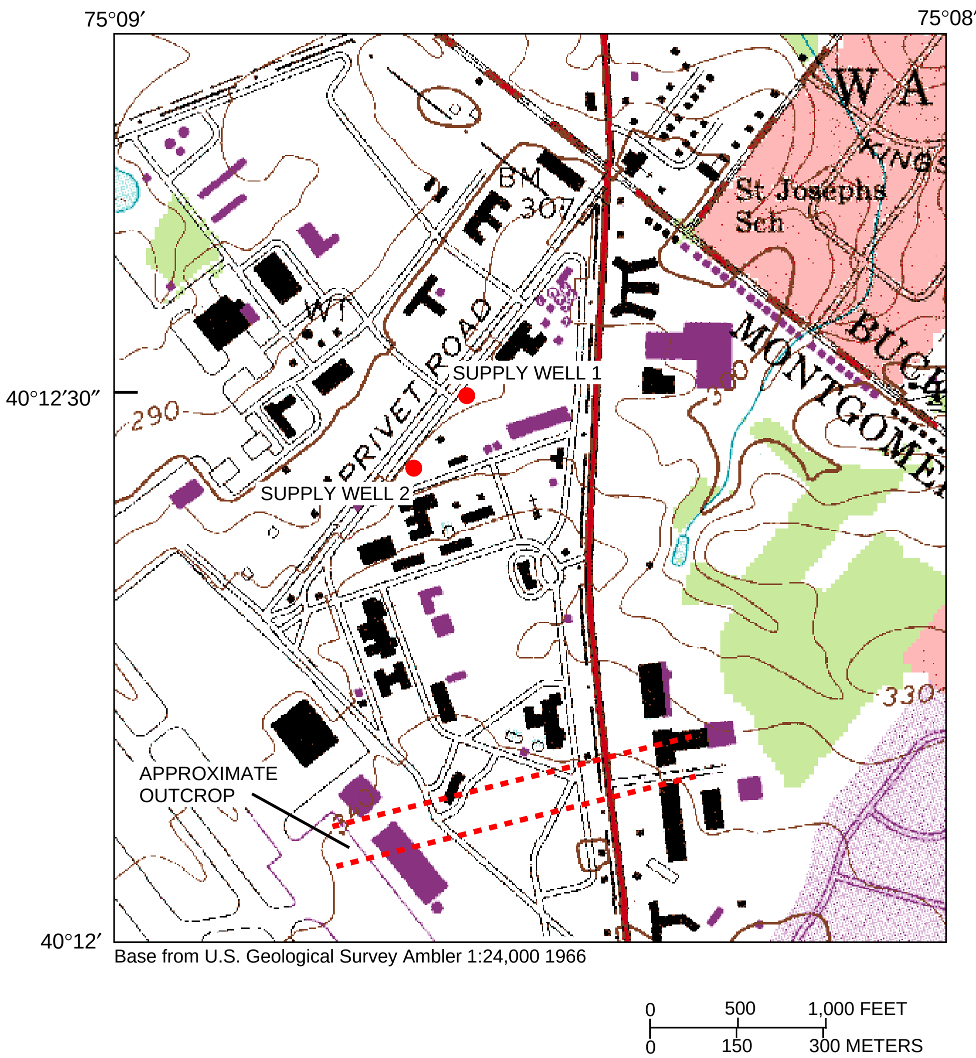
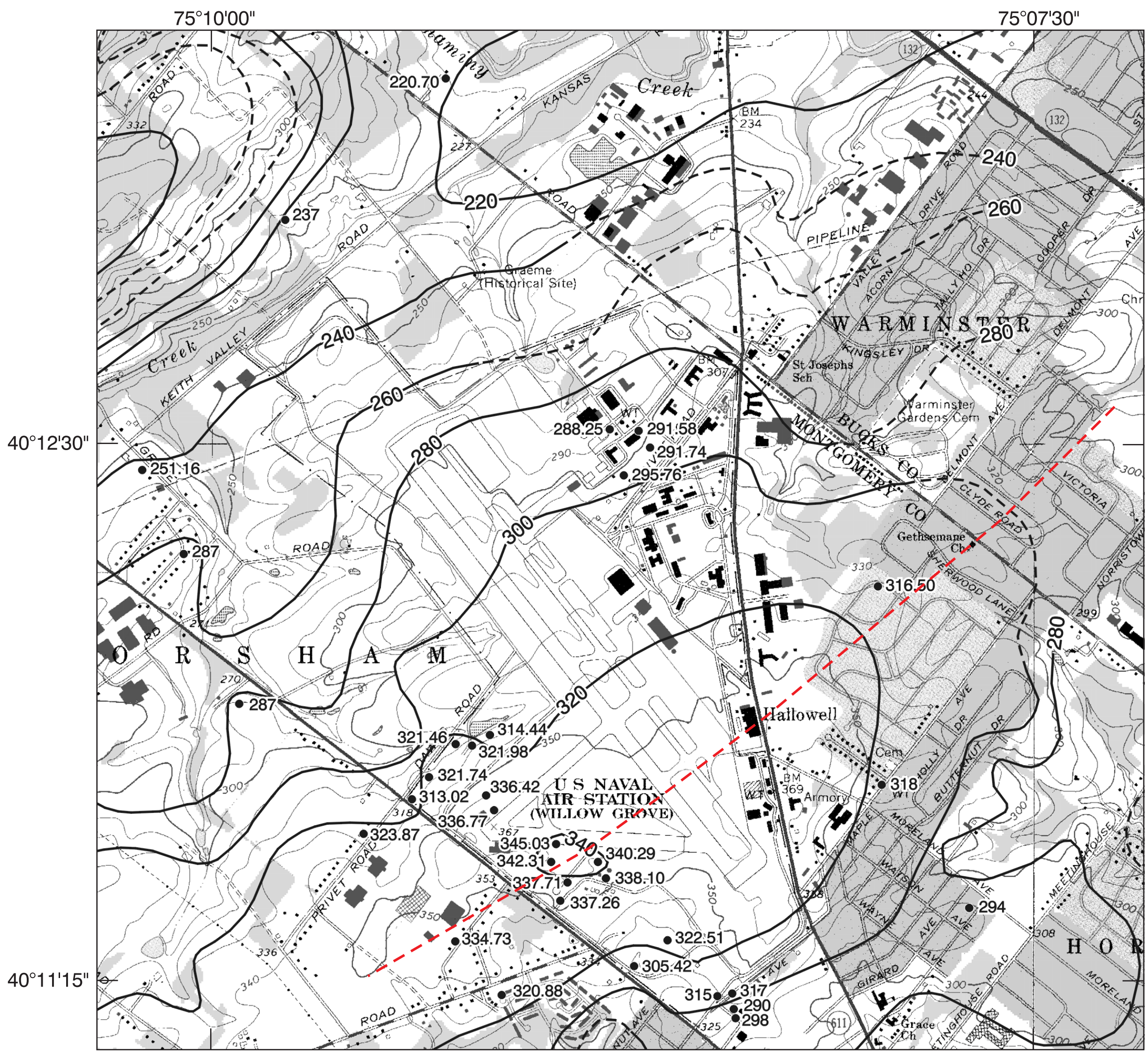


Figure 30. Approximate location of outcrop area for lithologic unit H, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.



Base from U.S. Geological Survey
Ambler 1:24,000, 1983
Hatboro 1:24,000, 1983

EXPLANATION

320 — POTENTIOMETRIC CONTOUR -- Shows elevation of the potentiometric surface as defined by measured water levels, altitudes of streams, and topography. Dashed where approximately located. Contour interval is 20 feet. Elevation in feet above sea level.

GROUND-WATER DIVIDE

352.02 WATER-LEVEL MEASUREMENT SITE -- Symbol gives location of site. Number is elevation of water level measured in a drilled well in feet above sea level.

0 1/2 1 MILE

0 1/2 1 KILOMETER

Figure 31. Potentiometric surface and regional ground-water divide, October 7–8, 1999, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania. (Modified from Sloto and others (2001))

Potentiometric Surface at Site 1

To map the potentiometric surface at Site 1, water-level data were grouped into two depth ranges (7–39 ft bls and 69–100 ft bls) for contouring. The potentiometric surface defined by water levels in wells screened between 7 and 39 ft bls is shown on figure 32. This interval is the shallower of the two intervals, and the potentiometric surface represents the water table. The map shows ground-water flow to the northwest. The hydraulic gradient is relatively low in the area around the supply wells.

The potentiometric surface defined by water levels in wells screened between 69 and 100 ft bls is shown on figure 33. The map shows a relatively high hydraulic gradient near supply well 2. The direction of ground-water flow near supply well 2 is to the north. To the northwest of supply well 2, the hydraulic gradient becomes lower, then higher again. In this vicinity, ground-water flow is toward the northwest.

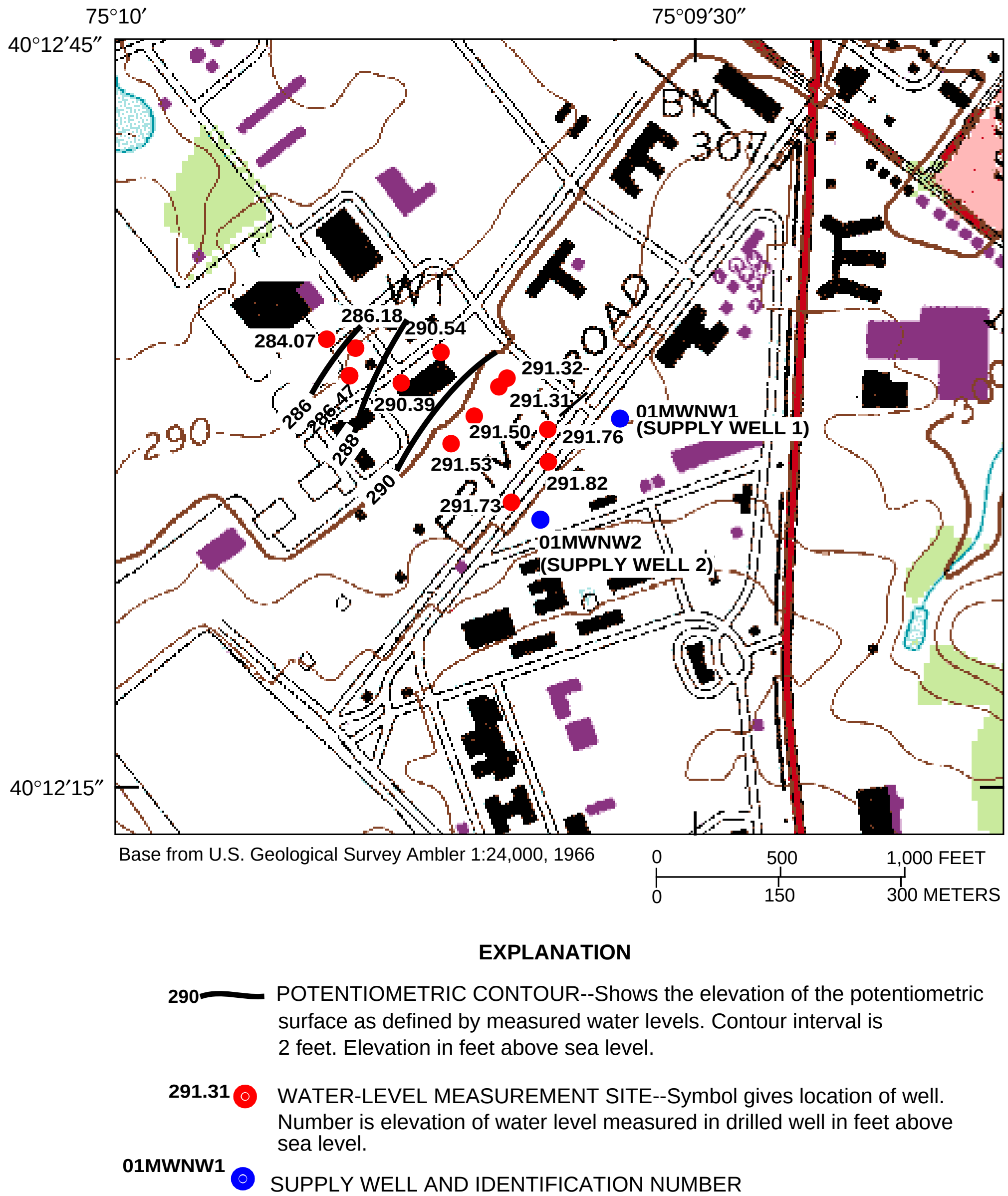
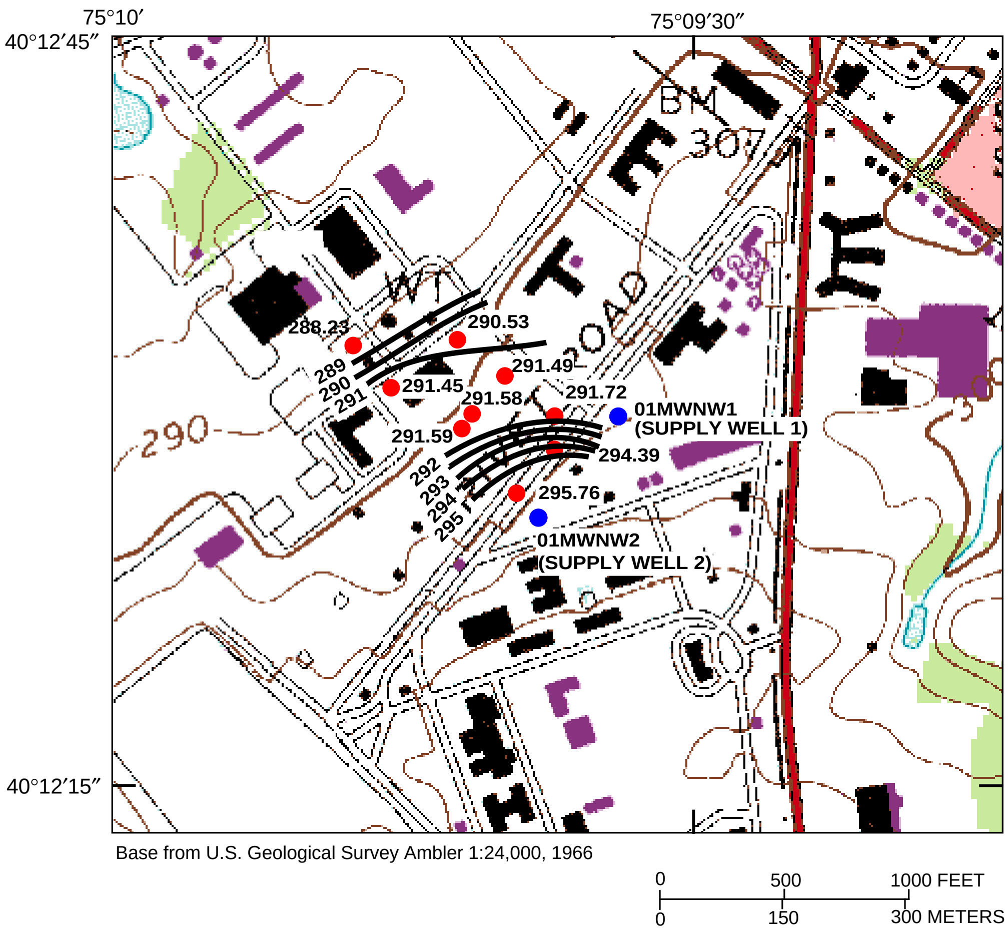


Figure 32. Potentiometric surface defined by water levels in wells screened between 7 and 39 feet below land surface, October 7, 1999, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.



EXPLANATION

291 — POTENTIOMETRIC CONTOUR--Shows the elevation of the potentiometric surface as defined by measured water levels. Contour interval is 1 foot. Elevation in feet above sea level.

291.49 ● WATER-LEVEL MEASUREMENT SITE--Symbol gives location of well. Number is elevation of water level measured in drillled well in feet above sea level.

01MWNW1 ● SUPPLY WELL AND IDENTIFICATION NUMBER.

Figure 33. Potentiometric surface defined by water levels in wells screened between 69 and 100 feet below land surface, October 7, 1999, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Vertical Head Gradients

For all monitor well clusters except 01MW06 and 01MW08, water-level measurements made on October 7, 1999 (table 1), show the vertical head direction was downward from the shallow to the deeper part of the aquifer. The vertical head gradient (0.001) was upward at well cluster 01MW08, and water levels were approximately the same in the shallow and deep wells in cluster 01MW06. Gradients were greatest near the supply wells (0.078 for well cluster 01MW05 and 0.054 for well cluster 01MW04). The vertical gradients to the northwest become less (0.001 for well clusters 01MW01 and 01MW03) and then greater (0.016 for well cluster 01MW07 and 0.029 for well cluster 01MWWW1). The vertical gradient pattern mimics the horizontal gradient defined by water levels in wells screened between 69 and 100 ft bls.

Pumping the supply wells at times causes the vertical gradient to reverse in wells 01MW05S and 01MW05I during pumping. Hydrographs for well cluster 01MW05 for March 16–27, 2000, are shown on figure 34. During this time, supply well 2 was pumping intermittently. Hydrographs for well cluster 01MW05 for April 11–25, 2000, are shown on figure 35. During this time, supply well 1 was pumping intermittently. During April 11–22, the water level was higher in well 01MW05S (screened 18.5–38.5 ft bls) than in well 01MW05I (screened 75–85 ft bls), and vertical flow was downward from the shallow to the deeper part of the aquifer (fig. 35). During March 19–27, the vertical flow direction reversed at times during the recovery cycle of supply well 2, and flow then was upward from the deeper to the shallow part of the aquifer (fig. 34). The vertical flow direction also reversed at times during April 23–25 during the recovery cycle of supply well 1; the vertical flow direction was upward from the deeper to the shallow part of the aquifer (fig. 35).

Pumping of the supply wells has a greater effect on water levels in the deeper (semiconfined to confined) part of the aquifer than in the shallow (water table) part of the aquifer (figs. 34 and 35). Pumping supply well 1 lowers the water level in well 01MW05I by more than 6 ft, and pumping supply well 2 lowers the water level in well 01MW05S by as much as 3 ft.

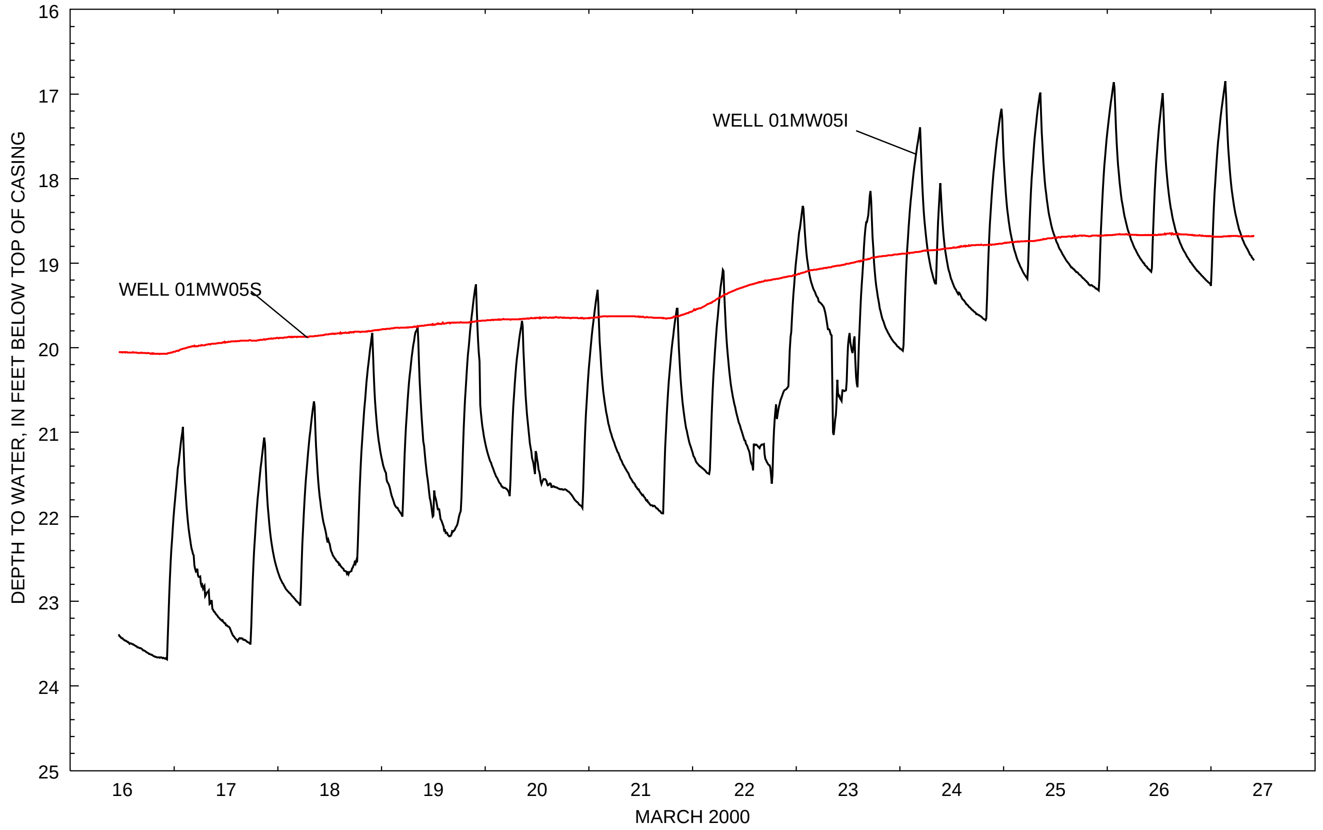


Figure 34. Hydrographs from wells 01MW05S and 01MW05I, March16–27, 2000, Willow Grove Naval Air Station/ Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.
[Supply well 1 is pumping intermittently. Data were provided by TetraTech NUS, Inc.]

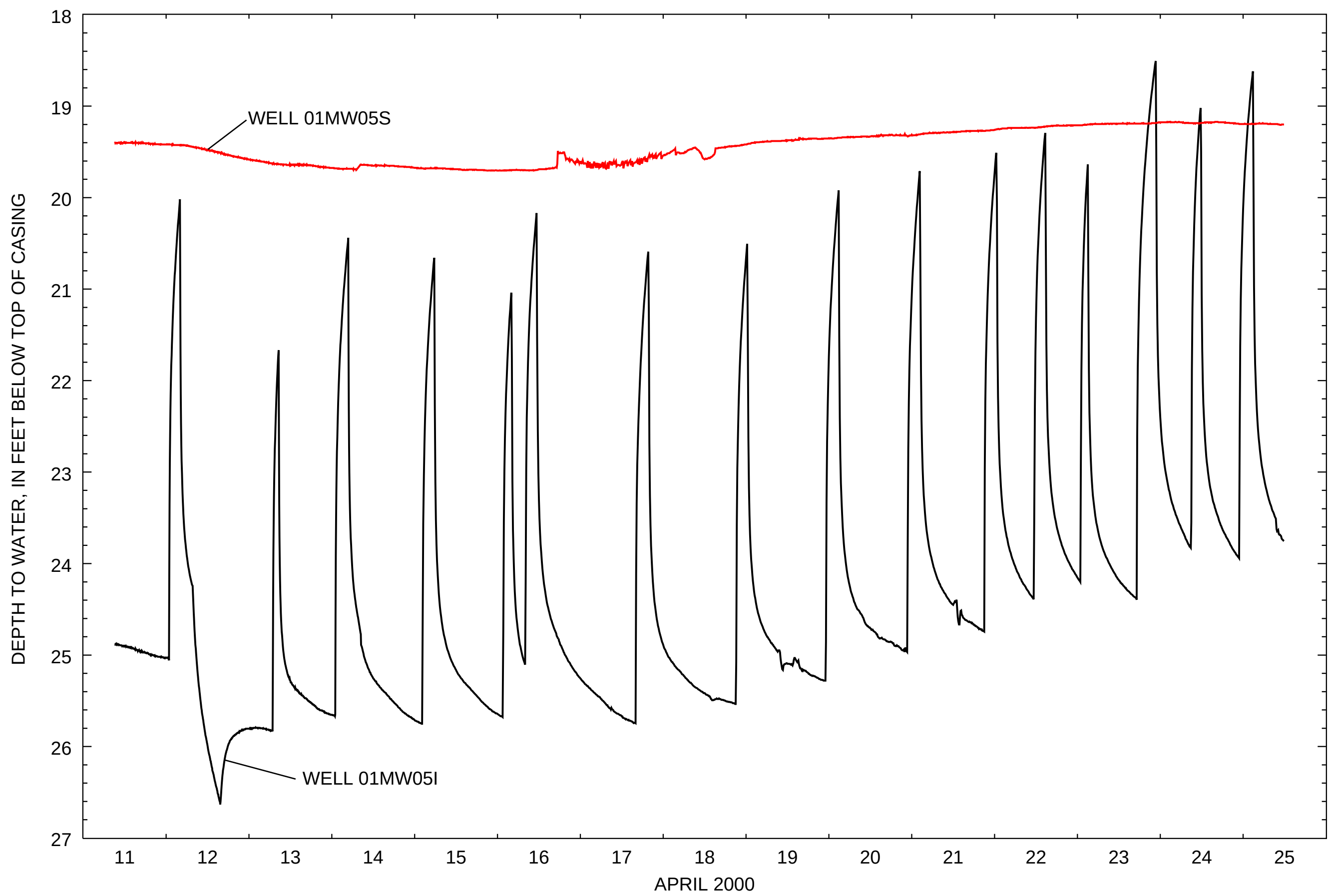


Figure 35. Hydrographs from wells 01MW05S and 01MW05I, April 11–25, 2000, Willow Grove Naval Air Station/ Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.
[Supply well 2 is pumping intermittently. Data were provided by TetraTech NUS, Inc.]

SUMMARY AND CONCLUSIONS

A hydrogeological investigation is being conducted as part of the U.S. Navy's Installation Restoration Program to address ground-water contamination at the Willow Grove NAS/JRB in Horsham Township, Montgomery County, Pa. The U.S. Navy requested the USGS provide technical assistance to their hydrogeological investigation. Specifically, the USGS was asked to conduct borehole geophysical logging and aquifer-isolation (packer) tests in supply wells 1 and 2 to characterize the geophysical and hydraulic properties, characterize the water quality of water-producing fractures, and collect and analyze water-level data. This information can be used to further identify the sources of contamination and to evaluate alternative management strategies for improving well efficiency and water quality.

Ground water pumped from supply wells 1 and 2 at the Willow Grove NAS/JRB provides water for use at the base, including potable water for drinking. The supply wells have been contaminated by VOC's, particularly TCE and PCE, and the water is treated to remove the VOC's. The Willow Grove NAS/JRB and surrounding area are underlain by the Stockton Formation, which forms a complex, heterogeneous aquifer.

The hydraulic and chemical characteristics of discrete water-bearing zones were characterized by isolating each water-bearing zone in the supply wells with straddle packers. Intervals selected for aquifer-isolation tests were based on interpretation of the borehole geophysical logs and borehole television surveys. Eight aquifer-isolation tests were conducted in supply well 1, and five aquifer-isolation tests were conducted in supply well 2. Specific capacity and depth of fracture in the wells were not related. During each aquifer-isolation test, water samples were collected and analyzed for VOC's and inorganic constituents.

A suite of borehole geophysical logs was collected in supply well 1 by the USGS. The caliper log shows the well is 389 ft deep and is cased to 50 ft btoc. On the basis of the interpretation of the borehole geophysical logs and heatpulse-flowmeter measurements for supply well 1, water enters the upper part of the borehole through fractures at 50–59 and 106 ft btoc and flows downward. Water flowing downward exits the borehole through a fracture at 182 ft btoc. Water also enters the borehole through fractures at 241–244, 256, and 350–355 ft btoc and flows upward. Water flowing upward exits the borehole through fractures at 182 and 199 ft btoc.

Eight intervals were selected for aquifer-isolation tests in supply well 1. Fractures at 50–59, 79–80, 106, 124–152, 182, 241–244, 256, and 350–354 ft btoc were isolated. A specific capacity could not be calculated for the fracture isolated at 50–59 ft btoc because the pump in supply well 2 shut off, and the water level in the isolated interval recovered faster than the drawdown from pumping throughout the test. For the other isolated intervals, specific capacities ranged from 0.26 to 5.7 (gal/min)/ft. The highest specific capacity was for the fracture isolated at 179.8–188 ft btoc.

The highest concentrations of PCE and TCE were in water samples collected from fractures isolated between 236.8 and 245 ft btoc (interval 6) and between 249.8 and 258 ft btoc (interval 7). Concentrations of PCE and TCE were similar in those samples as were concentrations of dissolved oxygen and total dissolved solids, which indicates these fractures are connected hydraulically. The concentration of PCE generally increased with depth to a maximum of 39 μg/L at a depth of 249.8–258 ft btoc and then decreased to 21 μg/L at a depth of 345.3–389 ft btoc.

A suite of borehole geophysical logs was collected in supply well 2 by the USGS. The caliper log shows the well is 340 ft deep and is cased to 43 ft btoc. On the basis of the borehole geophysical logs and heatpulse-flowmeter measurements, water enters the borehole through fractures at 68–74 and 115 ft btoc and flows downward. Water flowing downward exits the borehole through a fracture at 162 ft btoc. Water enters the borehole through a fracture at 205 ft btoc and flows upward and downward. The water flowing upward exits the borehole through the fracture at 162 ft btoc. Water flowing downward exits the borehole through fractures at 270 and 314 ft btoc. A fracture at 287 ft btoc contributes water to this downward flow. Water also enters the borehole through a fracture at 331 ft btoc near the bottom of the borehole and flows upward. This water exits the borehole through the fracture at 314 ft btoc.

Five intervals were selected for aquifer-isolation tests in well supply well 2. Fractures at 68–74, 115, 162, 205, and 314 ft btoc were isolated. A specific capacity could not be calculated for the fracture isolated at 205 ft btoc because the water level in the isolated fracture was rising during the latter part of the test. For the other isolated fractures, specific capacities ranged from 0.08 to less than 2.9 (gal/min)/ft. The highest specific capacity was for the fracture isolated at 157–165.2 ft btoc. Concentrations of detected VOC's in water samples were estimated at 3.6 µg/L or less. TCA, which was detected in water samples from supply well 1, was not detected in water samples from supply well 2.

Lithologic units penetrated by supply wells 1 and 2 were determined by correlating natural-gamma and single-point-resistance borehole geophysical logs. Water-bearing fractures are not necessarily present in the same lithologic units in both supply wells. Although the wells penetrate the same lithologic units, the lithologic location of only three water-bearing fractures are common to both wells.

The same lithologic unit may have different hydraulic properties in both wells. The highest specific capacity (5.7 (gal/min)/ft) of the intervals tested in supply well 1 was at 179.8–188 ft btoc, which is at the top of sandy lithologic unit F. The highest specific capacity (less than 2.9 (gal/min)/ft) of the intervals tested in supply well 2 was at 157–165.2 ft btoc, which is at the bottom of sandy lithologic unit F. The second highest specific capacity (3.7 (gal/min)/ft) of the intervals tested in supply well 1 was at 345.3–389 ft btoc, which is at the top of lithologic unit M. The lowest specific capacity (0.08 (gal/min)/ft) of the intervals tested in supply well 2 was at 310.5–318.7 ft btoc, which also is at the top of lithologic unit M.

The highest concentrations of PCE (34 and 39 µg/L) in water samples from supply well 1 were from intervals 6 (236.8–245 ft btoc) and 7 (249.8–259 ft btoc), respectively. Interval 7 is in lithologic unit H, and interval 6 is just above lithologic unit H. The aquifer-isolation tests indicate these intervals are connected hydraulically. The highest concentrations of PCE (3.6 µg/L) in water samples from supply well 2 were from interval 4 (197.7–205.9 ft btoc). Interval 4 is in lithologic unit H. Assuming a strike of N. 76° E. and a dip of 7° NW., the projected outcrop of lithologic unit H is approximately 2,300–2,450 ft southeast of supply well 1 and 1,850–2,050 ft southeast of supply well 2. The projected outcrop is updip and hydraulically upgradient from the supply wells.

A regional ground-water divide is present to the southeast of Site 1. From this divide, ground water flows northwest through Site 1 toward Park Creek, a tributary to Little Neshaminy Creek. This is the direction of regional ground-water flow. Two potentiometric-surface maps were prepared for Site 1. Water-level data were grouped into two depth ranges, one for shallow wells screened between 7 and 39 ft bls, and one for deeper wells screened between 69 and 100 ft. For both depth intervals, the direction of ground-water flow is toward the northwest.

For all monitor well clusters except 01MW06 and 01MW08, water-level measurements made on October 7, 1999, show the vertical head gradient was downward from the shallow to the deeper part of the aquifer. The vertical head gradients ranged from 0.001 to 0.078. The vertical gradient pattern mimics the horizontal gradient defined by water levels in wells screened between 69 and 100 ft bls.

During April 11–25, 2000, supply well 1 was pumping intermittently; the water level was higher in well 01MW05S (screened 18.5–38.5 ft bls) than in well 01MW05I (screened 75–85 ft bls), and vertical flow was downward from the shallow to the deeper part of the aquifer. During March 16–27, 2000, supply well 2 was pumping intermittently; the vertical flow direction reversed at times during the recovery cycle of supply well 2, and flow then was upward from the deeper to the shallow part of the aquifer. The vertical flow direction also reversed at times during April 23–25 during the recovery cycle of supply well 1; the vertical flow direction was upward from the deeper to the shallow part of the aquifer.

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