In cooperation with the
U.S. NAVY

Hydrogeological Investigation at Site 5, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania

by Ronald A. Sloto

Water-Resources Investigations Report 01-4263

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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
cubic foot (ft^3)	0.02832	cubic meter
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second
gallon per day (gal/d)	0.003785	cubic meter per day
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram
	Density	
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter

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 concentration units used in report:

- cm, centimeter
- kg/ft^3, kilogram per cubic foot
- µg, microgram
- µg/kg, microgram per kilogram
- µg/L, microgram per liter

HYDROGEOLOGICAL INVESTIGATION AT SITE 5, WILLOW GROVE NAVAL AIR STATION/JOINT RESERVE BASE, HORSHAM TOWNSHIP, MONTGOMERY COUNTY, PENNSYLVANIA

by Ronald A. Sloto

ABSTRACT

The U.S. Geological Survey conducted borehole geophysical logging, collected and analyzed water-level data, and sampled sections of a rock core to determine the concentration of volatile organic compounds in the aquifer matrix of the Stockton Formation. Borehole geophysical logs were run in three monitor wells. At well 05MW04I, the vertical gradient was upward at depths above 42 feet below land surface (ft bls), downward between 42 and 82 ft bls, and upward below 82 ft bls. At well 05MW05I, a downward vertical gradient was present. At well 05MW12I, the vertical gradient was downward above 112 ft bls and upward below 112 ft bls.

Three water-bearing fractures in a 17-foot long rock core from 23.5 to 40.5 ft bls were identified and sampled. Three samples were analyzed from each water-bearing fracture—at the fracture face, 2 centimeters (cm) below the fracture, and 4 cm below the fracture. Fifteen compounds were detected; however, concentrations of seven compounds were less than 1 microgram per kilogram (µg/kg) when detected. Concentrations of benzene (from 0.39 to 3.3 µg/kg), 1,1-dichloroethene (1,1-DCE) (from 0.15 to 13 µg/kg), 1,1,1-trichloroethane (TCA) (from 0.17 to 22 µg/kg), and trichloroethylene (TCE) (from 0.092 to 9.6 µg/kg) were detected in all samples. The highest concentrations detected were for toluene, which was detected at a concentration of 32 and 86 µg/kg in the samples from unweathered sandstone at 2 and 4 cm below the fracture, respectively. Concentrations generally decreased with distance below the fracture in the mudstone samples. Concentrations of benzene and toluene increased with distance below the fractures in the unweathered sandstone samples. Concentrations of 1,1-DCE, TCA, and TCE were higher in the mudstone samples than in the samples from sandstone. Toluene concentrations were higher in unweathered sandstone than in weathered sandstone or mudstone.

The effect of the pumping of Horsham Water and Sewer Authority public supply well 26 (HWSA-26), 0.2 mile southwest of the base boundary, on ground-water levels on the base was determined by shutting the well down for 6 days to allow water levels to recover. Water levels in 22 nearby wells were measured. The only well (02MW01I) that showed an unambiguous response to the shutdown of well HWSA-26 is 1,350 feet directly along strike from well HWSA-26. The recovery of well 05MW11I in response to the shutdown of well HWSA-26 is masked by recharge from snowmelt but probably does not exceed about 0.2 feet on the basis of the water level in well 05MW11I, which showed a response to the pumping of well HWSA-26 that ranged from 0.5 to 0.15 foot.

Horizontal gradients differ with depth, and the rate and direction of ground-water flow and contaminant movement is depth dependent. The potentiometric-surface map for water levels measured in wells screened between 5 and 44 ft bls in the aquifer shows a ground-water mound that is the high point on a regional ground-water divide. From this divide, ground water flows both northwest toward Park Creek and southeast toward Pennypack Creek. The hydraulic gradient around this mound is relatively flat to the southeast and particularly flat to the northwest. The potentiometric-surface map for water levels measured in wells screened between 40 and 100 ft bls in the aquifer shows a very flat hydraulic gradient. Differences in the elevation of the potentiometric surface are less than 2 feet. The potentiometric-surface map for water levels measured in wells screened between 105 and 179 ft bls in the aquifer shows a steep hydraulic gradient between Sites 5 and 2 and a relatively flat hydraulic gradient between Sites 5 and 3. Water levels measured on October 7, 1999, showed downward vertical head gradients for all well clusters at Site 5. Vertical gradients ranged from 0.01 at well cluster 05MW10 to 0.2 at cluster 05MW11. Most gradients were between 0.01 and 0.026. Vertical head gradients vary with time. The variability is caused by a difference in the magnitude of water-level fluctuations between shallow and the deep fractures. The difference in the magnitude of water-level fluctuations is because of differences in lithology and aquifer storativity.

INTRODUCTION

The Willow Grove Naval Air Station/Joint Reserve Base (NAS/JRB) is in Horsham Township, Montgomery County, Pa., and is shown on the U.S. Geological Survey (USGS) Ambler 7.5-minute topographic quadrangle map (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 common facilities with the U.S. Navy.

Sites with possible contamination at the Willow Grove NAS/JRB (fig. 1), also referred to as the base in this report, were identified by the U.S. Navy as part of a preliminary assessment program (Halliburton NUS Environmental Corporation, 1993). A hydrogeological investigation is being conducted as part of the U.S. Navy's Installation Restoration Program to address ground-water contamination at these sites. The U.S. Navy requested the USGS provide technical assistance to their hydrogeological investigation. Specifically, the USGS was asked to conduct borehole geophysical logging, to collect and analyze water-level data, and to sample sections of a rock core to determine the concentration of volatile organic compounds (VOC's) in the aquifer matrix. This information is being used to further identify the sources and pathways of contamination and to evaluate management strategies for improving water quality. The USGS conducted this study during 1999-2001. This work is a continuation of the Phase I and II borehole geophysical logging by the USGS (Conger, 1997; 1999).

Purpose and Scope

This report presents an interpretation of borehole geophysical logs and heatpulse-flowmeter measurements for three monitor wells, provides an analysis of regional and site-specific water-level data, provides an analysis of water-level data from a shutdown test on Horsham Water and Sewer Authority (HWSA) supply well 26, and provides analytical data and interpretations from rock-core samples analyzed for VOC's. The USGS prepared this report as part of the hydrogeological investigations at the Willow Grove NAS/JRB in cooperation with the U.S. Navy.

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. The middle arkose member has a maximum thickness of 4,200 ft (Rima and others, 1962). Bedding in the Stockton Formation at the base generally 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 weathered zone moves through intergranular openings that have 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. Ground-water storage and movement within the unweathered part of the Stockton Formation primarily occurs through a network of interconnecting secondary openings such as fractures, bedding planes, and joints. Primary porosity that originally may have been present has been almost eliminated by compaction and cementation.

Wells greater than 100 ft deep may be multi-aquifer wells penetrating several major water-producing 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 are present among water-bearing

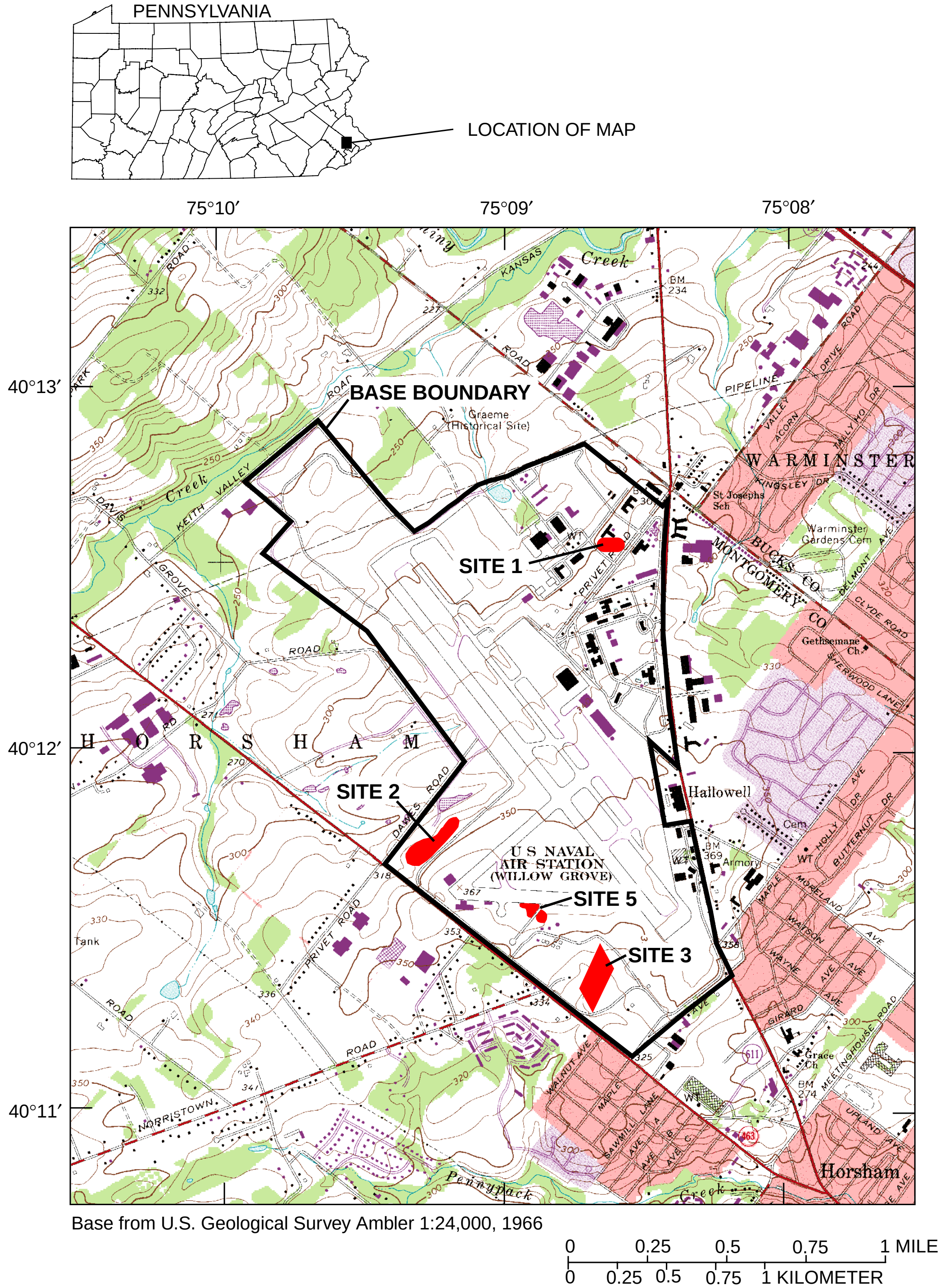


Figure 1. Location of the Willow Grove Naval Air Station/Joint Reserve Base and sites of possible ground-water contamination, Horsham Township, Montgomery County, Pennsylvania.

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 infiltration of local 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 nearby wells. Water in the upper 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 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. 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 05MW01S would indicate a shallow well in well cluster 1 at Site 5. The USGS well-identification number consists of a county-abbreviation prefix followed by a sequentially assigned number. The prefix MG denotes a well in Montgomery County. A cross-reference between site and USGS well-identification numbers is given in table 1. Locations of the wells are shown on figure 2.

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) describe the interpretation of borehole geophysical logs collected at the base. Sloto, Goode, and Way (2001) presented a potentiometric-surface map of the Willow Grove NAS/JRB and vicinity. Sloto, Goode, and Frasch (2002) describe a hydrogeologic investigation conducted at the base supply wells.

Acknowledgments

Borehole geophysical logging and borehole television surveys were done by Randall Conger and Philip Bird of the USGS Pennsylvania District. Water-level data for wells off the base were collected by Daniel Goode of the USGS Pennsylvania District and John Way of Lock Haven University. Most water-level data presented in this report were provided by TetraTech NUS, Inc. The use of these data are appreciated greatly. Daniel Goode conducted and collected data for the test of HWSA well 26. The cooperation of the HWSA for shutting down well 26 for a hydraulic test is appreciated greatly. Personnel from the Philadelphia Suburban Water Company assisted with the test. The cooperation of domestic well owners who allowed access to their wells for water-level measurements gratefully is acknowledged.

BOREHOLE GEOPHYSICAL LOGS

Caliper, natural-gamma, single-point-resistance, fluid-resistivity, and fluid-temperature borehole geophysical logs were collected in three monitor wells during August 2000. The logs were used to locate water-bearing fractures, determine zones of vertical borehole-water movement, and determine the depth to set well screens.

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 simply may 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 radio-

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

[Well depths given are for completed monitor wells. —, no data]

Site well-identification number	U.S. Geological Survey well-identification number	Well depth (feet)	Casing diameter (inches)	Open interval (feet below top of casing)
02MW01S	MG-1850	20	4	5-20
02MW01I	MG-1598	80	2	70-80
02MW02S	MG-1851	25	4	5-25
02MW03S	MG-1878	20	4	5-20
02MW03SI	MG-1852	55	2	40-55
02MW03I	MG-1628	150	2	140-150
02MW04S	MG-1593	44	2	34-44
02MW04I	MG-1594	115	2	105-115
03MW01S	MG-1853	32	4	12-32
03MW01SI	MG-1854	80	4	60-80
03MW01I	MG-1855	179	4	159-179
03MW02S	MG-1856	22.5	4	4.5-22.5
03MW02SI	MG-1857	65	4	55-65
03MW02I	MG-1629	144	2	134-144
03MW03S	MG-1858	20	4	5-20
03MW03I	MG-1859	168.5	4	148.5-168.5
03MW04S	MG-1860	35	4	5-35
03MW04SI	MG-1861	80	4	60-80
03MW04I	MG-1862	168	4	148-168
03MW05S	MG-1863	37	4	17-37
03MW05I	MG-1595	92	4	82-92
03MW06S	MG-1596	36	2	26-36
03MW06SI	MG-1877	85	2	75-85
03MW06I	MG-1597	150	2	140-150
03MW07S	MG-1630	44	2	34-44
05MW01S	MG-1599	32	4	12-32
05MW01SI	MG-1864	84.5	4	74.5-84.5
05MW01I	MG-1590	135	4	124-135
05MW02S	MG-1865	30	4	10-30
05MW03S	MG-1866	31	4	11-31
05MW03I	MG-1589	128	2	118-128
05MW04S	MG-1867	30	4	10-30
05MW04I	MG-1757	84.5	2	74.5-84.5
05MW05S	MG-1868	40	4	20-40
05MW05I	MG-1758	209.5	2	189.5-209.5
05MW06S	MG-1869	37.5	4	17.5-37.5
05MW06I	MG-1870	84	4	74-84
05MW07S	MG-1871	26	4	6-26
05MW07I	MG-1872	84	4	74-84
05MW08S	MG-1585	36	2	26-36
05MW08SI	MG-1873	65	2	55-65
05MW08I	MG-1586	99	2	89-99
05MW09S	MG-1588	32	2	27-32
05MW09SI	MG-1874	74	2	59-74
05MW09I	MG-1587	106	2	96-106

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

[Well depths given are for completed monitor wells. —, no data]

Site well-identification number	U.S. Geological Survey well-identification number	Well depth (feet)	Casing diameter (inches)	Open interval (feet below top of casing)
05MW10S	MG-1591	32	2	22-32
05MW10SI	MG-1875	94	2	79-94
05MW10I	MG-1592	126	2	116-126
05MW11S	MG-1634	25	2	20-25
05MW11SI	MG-1876	50	2	40-50
05MW11I	MG-1635	149	2	139-149
05MW12I	MG-1759	113.5	2	103.5-113.5
HWSA-26	MG-962	400	12	40-400
—	MG-1739	—	6	—
rock core	MG-1760	40.5	—	—

active elements may be 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 fluid filled, dry, cased, or uncased parts of the borehole. However, well casing reduces the gamma response. The gamma log is used to correlate lithologic 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. The 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 temperature of the water in the borehole. Fluid-temperture 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 temperature, and intervals of vertical borehole flow are identified by little or no temperature gradient.

Fluid-resistivity logs measure the electrical resistance of 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.

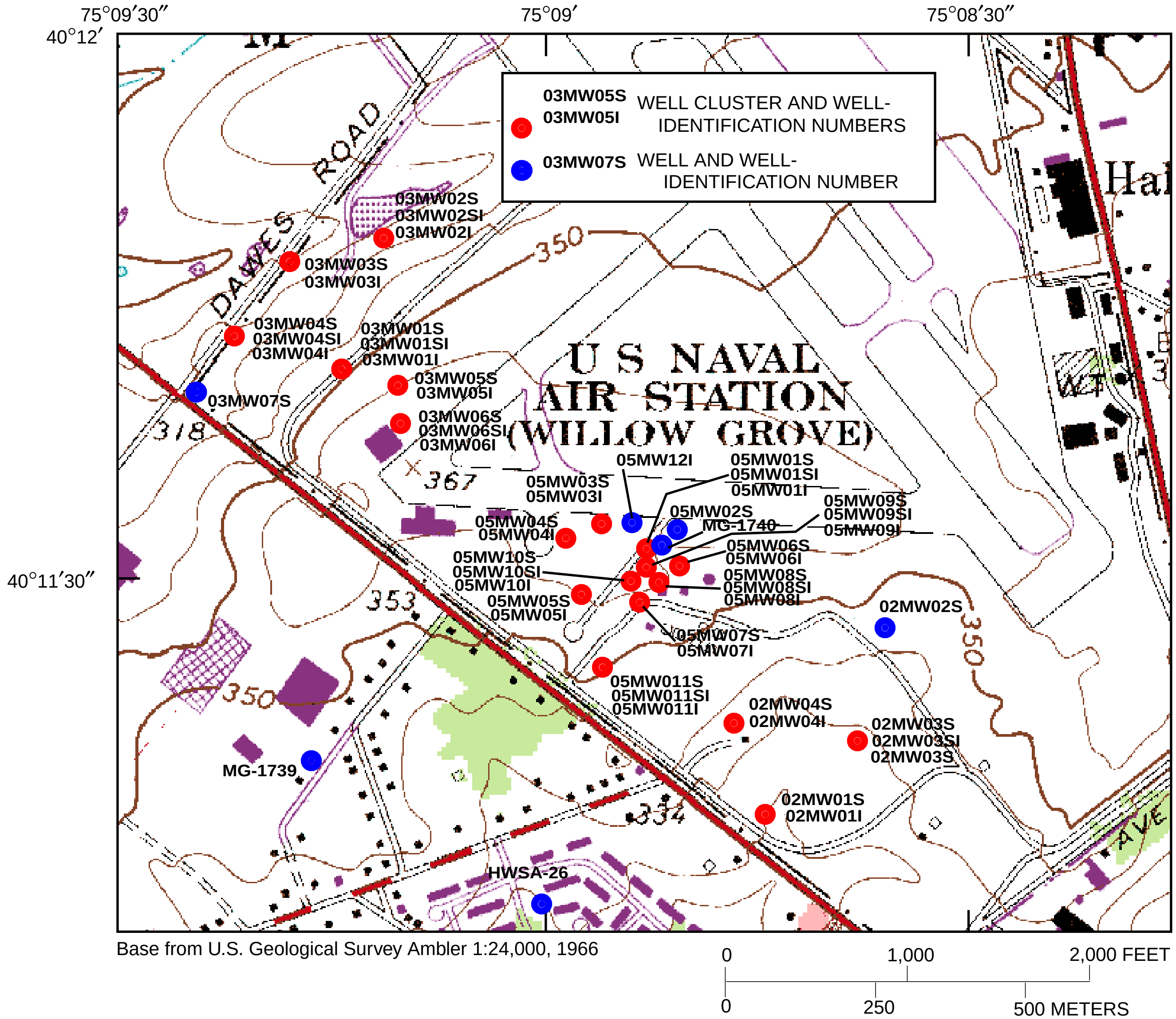


Figure 2. Locations of selected wells, Willow Grove Naval Air Station/Joint Reserve Base and vicinity, Horsham Township, Montgomery County, Pennsylvania.

Measurement of Vertical Borehole Flow

The direction and rate of borehole-water movement were measured with a high-resolution heatpulse flowmeter. The heatpulse flowmeter operates by diverting nearly all flow to the center of the tool where a heating grid slightly heats a thin zone of water. If vertical borehole flow is occurring, the water moves up or down the borehole to one of two sensitive thermistors (heat sensors). When a peak temperature is recorded by one of the thermistors, a measurement of direction and rate is calculated by the computer collecting the logging data. The range of flow measurement is about 0.01 to 1.5 gal/min in a 2- to 10-in. diameter borehole. Heatpulse-flowmeter measurements may be affected by poor seal integrity between the borehole and the flowmeter or contributions of water from storage within the borehole during pumping. 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 fluid-producing zones.

Borehole Television Surveys

Borehole television surveys were conducted by lowering a waterproof video camera down the borehole and recording the image on video tape. The depth indicated on the video image may not correspond exactly to the geophysical logs because of minor slippage (generally up to plus or minus 1 ft) of the video cable.

Interpretation of Borehole Geophysical Logs

Well 05MW04I (MG-1757)

A suite of borehole geophysical logs (fig. 3) was collected in well 05MW04I by the USGS on August 10, 2000. The caliper log shows the well is 151 ft deep and is cased to 28 ft below land surface (bls). The caliper log shows major fractures at 40-42, 56-60, 70-82, and 100 ft bls. The fluid-temperature and fluid-resistivity logs indicate borehole flow and possible water-bearing zones at about 36, 70, 106, 113, 124, 133, and 140 ft bls.

Heatpulse-flowmeter measurements were made under nonpumping conditions at 36, 46, 66, 95, 124, and 142 ft bls (table 2). The geophysical logs and heatpulse-flowmeter measurements indicate complex water circulation in the borehole. Water enters the upper part of the borehole at a rate of 0.93 gal/min through a horizontal fracture at 40-42 ft bls and flows upward and downward. Water flowing upward exits the borehole through a horizontal fracture at 32 ft bls. Additional water (0.14 gal/min) enters the borehole through a vertical fracture at 56-60 ft bls and flows downward. Water flowing downward in the upper part of the borehole exits through a large vertical fracture at 70-82 ft bls (fig. 4). Water enters the lower part of the borehole at a rate of 0.18 gal/min through a horizontal fracture at 148 ft bls and flows upward. Water flowing upward in the lower part of the borehole exits the borehole through horizontal fractures at 132 (0.04 gal/min) and 114 ft bls (0.02 gal/min) and through the large vertical fracture at 70-82 ft bls. A total of 0.89 gal/min exits the borehole through the fracture at 70-82 ft bls. The water-bearing fractures in well 05MW04I are at 32, 40-42, 56-60, 70-82, 114, 132, and 148 ft bls; the principal water-bearing fractures are at 40-42 and 70-82 ft bls. Well 05MW04I was screened later from 74.5 to 84.5 ft below top of casing (btoc) to monitor the principle water-bearing fracture at 70-82 ft bls.

The borehole geophysical logs indicate upward and downward vertical gradients are present in the Stockton Formation at well 05MW04I. The vertical gradient is upward above 42 ft bls, downward between 42 and 82 ft bls, and upward below 82 ft bls.

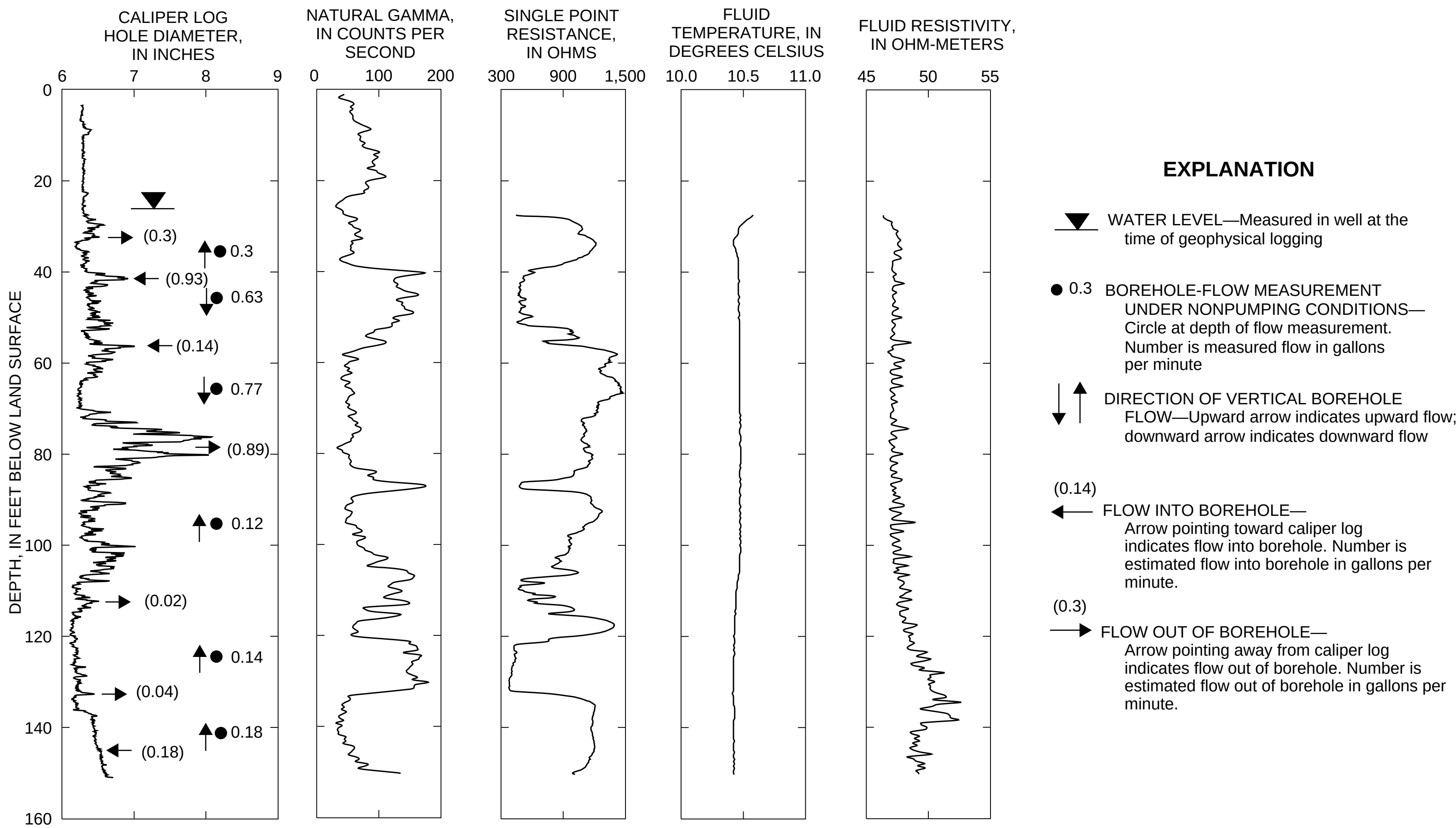


Figure 3. Borehole geophysical logs for well 05MW04I (MG-1757), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Table 2. *Heatpulse-flowmeter measurements made in well 05MW04I (MG-1757), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

Depth (feet below land surface)	Flow (gallons per minute)	Flow direction
36	0.30	Up
46	.63	Down
66	.77	Down
95	.12	Up
124	.14	Up
142	.18	Up

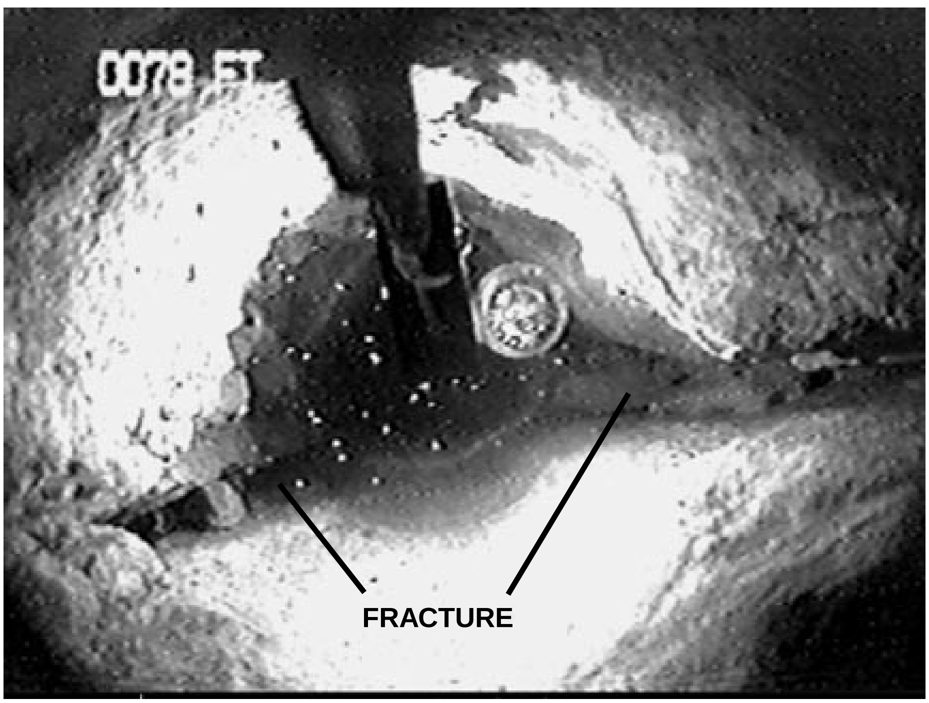


Figure 4. Image from borehole television survey showing vertical fracture at 78 feet below land surface in well 05MW04I (MG-1757), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Well 05MW05I (MG-1758)

A suite of borehole geophysical logs (fig. 5) was collected in well 05MW05I by the USGS on August 3, 2000. The caliper log shows the well is 250 ft deep and is cased to 18 ft bls. The caliper log shows major fractures at 52-58 and 142-148 ft bls. The fluid-temperature and fluid-resistivity logs indicate borehole flow and possible water-bearing zones at about 44, 68, 112, 174, and 190 ft bls.

Heatpulse-flowmeter measurements were made under nonpumping conditions at 30, 47, 65, 84, 100, 108, 124, 158, 180, 212, and 234 ft bls (table 3). On the basis of the geophysical logs and heatpulse-flowmeter measurements, water enters the upper part of the borehole through a large vertical fracture at 52-58 ft bls (0.1 gal/min) and flows downward. Water also enters the borehole through a horizontal fracture at 72 ft bls (0.3 gal/min) and a vertical fracture at 114 ft bls (0.1 gal/min) and flows downward. Some water exits the borehole through a large vertical fracture at 142-148 ft bls (0.2 gal/min) (fig. 6). Additional water enters the borehole through a horizontal fracture at 174 ft bls (0.2 gal/min) and flows downward. Water exits the borehole through horizontal fractures at 192 and 202-205 ft bls (0.3 gal/min) and 220-223 ft bls (0.2 gal/min). The water-bearing fractures in well 05WM05I are at 52-58, 72, 114, 142-148, 174, 192, 202-205, and 220-223 ft bls. The borehole geophysical logs indicate a downward vertical gradient is present in the Stockton Formation at well 05MW05I. Well 05MW05I was screened later from 189.5 to 209.5 ft btoc to monitor the water-bearing fractures at 192 and 202-205 ft bls.

Table 3. *Heatpulse-flowmeter measurements made in well 05MW05I (MG-1758), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

[—, no flow]

Depth (feet below land surface)	Flow (gallons per minute)	Flow direction
30	0	—
47	0	—
65	.1	Down
84	.4	Down
100	[1].3	Down
108	[1].2	Down
124	.5	Down
158	[1].3	Down
180	.5	Down
212	.2	Down
234	0	—

[1] Flow rate may be affected by nearby pumping.

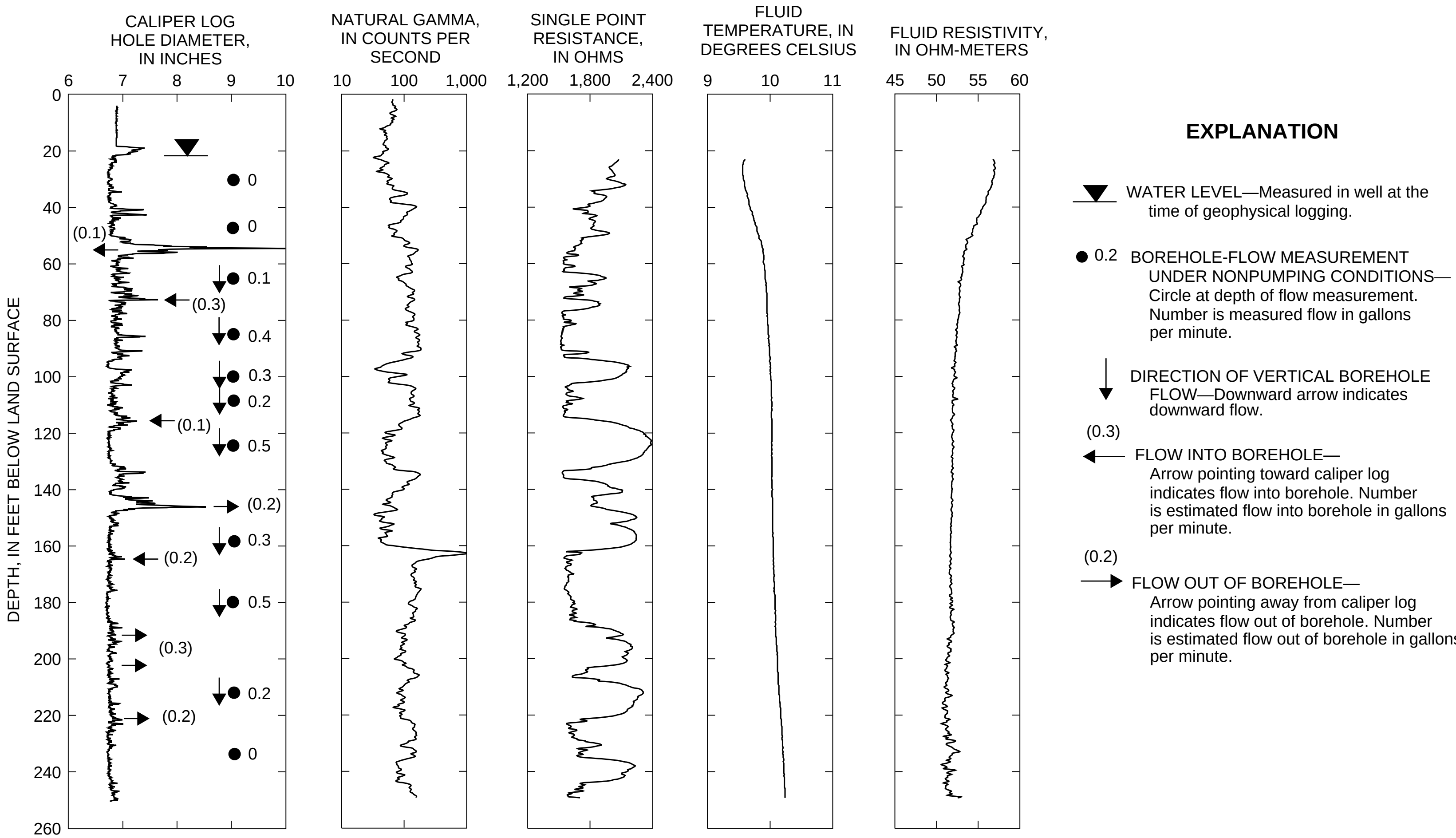


Figure 5. Borehole geophysical logs for well 05MW05I (MG-1758), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

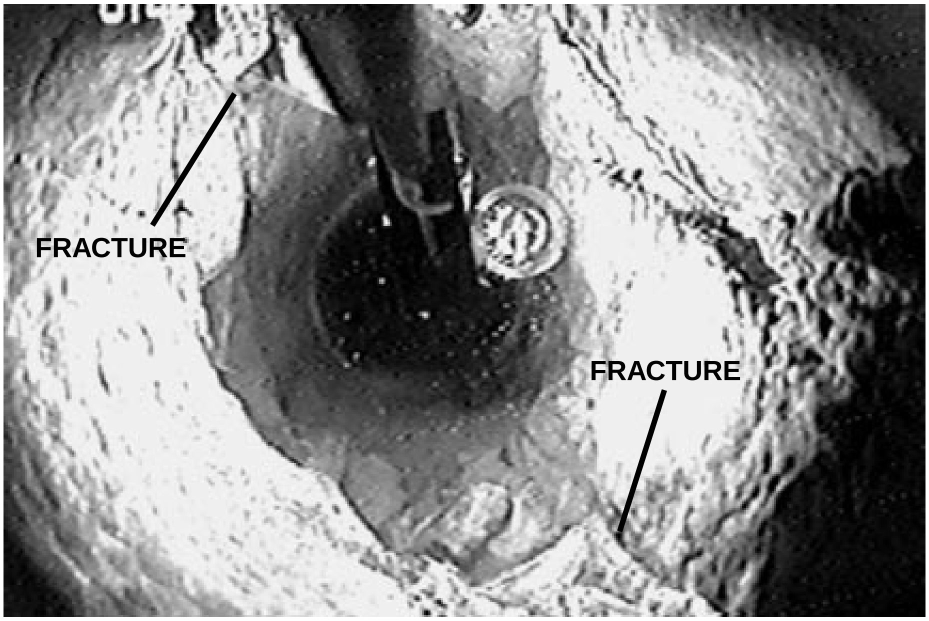


Figure 6. Image from borehole television survey showing vertical fracture at 142 feet below land surface in well 05MW05I (MG-1758), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Well 05MW12I (MG-1759)

A suite of borehole geophysical logs (fig. 7) was collected in well 05MW12I by the USGS on August 1, 2000. The caliper log shows the well is 149 ft deep and is cased to 28 ft bls. The caliper log shows major fractures at 88-92 and 109-112 ft bls. The fluid-temperature and fluid-resistivity logs indicate borehole flow and possible water-bearing zones at about 109, 120, and 129 ft bls.

Heatpulse-flowmeter measurements were made under nonpumping conditions at 49, 72, 81, 96, 100, 116, 132, 138, and 146 ft bls (table 4). On the basis of the geophysical logs and heatpulse-flowmeter measurements, water enters the upper part of the borehole at a rate of 1.48 gal/min through a vertical fracture at 36-38 ft bls (fig. 8) and flows downward. A minor quantity (less than 0.1 gal/min) of the water flowing downward exits the borehole, probably through fractures at 62 and 76 ft bls. Water also exits the borehole through the large vertical fracture at 88-92 ft bls (0.23 gal/min), but most water flowing downward exits the borehole through the large vertical fracture at 109-112 ft bls (1.42 gal/min total outflow). Water also enters the borehole near the bottom of the well (0.11 gal/min) and through a horizontal fracture at 140 ft bls (0.08 gal/min) and flows upward. About half the water flowing upward exits the borehole through a fracture at 119-126 ft bls (0.09 gal/min) and about half exits the borehole through the fracture at 109-112 ft bls (0.11 gal/min). The water-bearing fractures in well 05MW12I are at 36-38, 76, 88-92, 109-112, 119-123, 140, and 150 ft bls; the principal water-bearing fractures are at 109-112 and 119-123 ft bls. Well 05MW12I was screened later from 103.5 to 113.5 ft btoc to monitor the principle water-bearing fracture at 109-112 ft bls.

The borehole geophysical logs indicate upward and downward vertical gradients are present in the Stockton Formation at well 05MW12I. The vertical gradient is downward above 112 ft bls and upward below 112 ft bls.

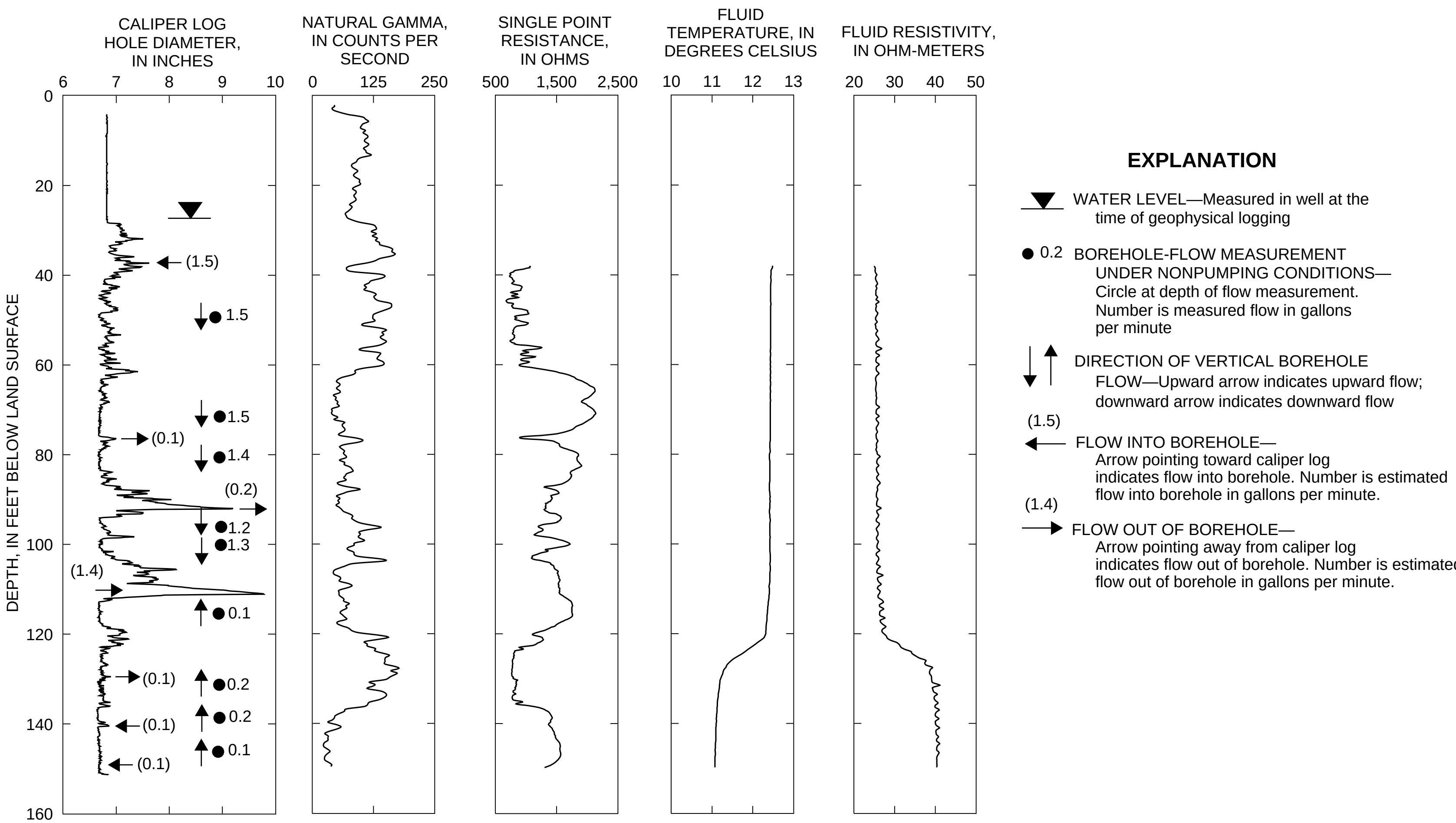


Figure 7. Borehole geophysical logs for well 05MW012I (MG-1759), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Table 4. *Heatpulse-flowmeter measurements made in well 05MW12I (MG-1759), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

Depth (feet below land surface)	Flow (gallons per minute)	Flow direction
49	1.5	Down
72	1.5	Down
81	1.4	Down
96	1.2	Down
100	1.3	Down
116	.1	Up
132	.2	Up
138	.2	Up
146	.1	Up

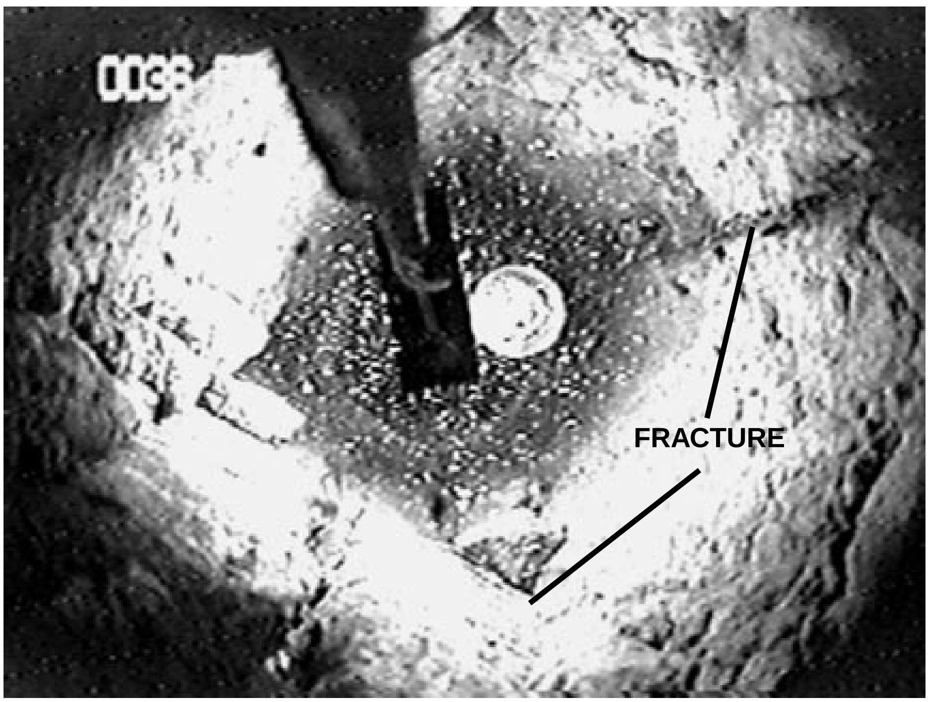


Figure 8. Image from borehole television survey showing vertical fracture at 36 feet below land surface in well 05MW12I (MG-1759), Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

ANALYSIS OF VOLATILE ORGANIC COMPOUNDS IN THE AQUIFER MATRIX

Ground water flows in fractures in the unweathered part of the Stockton Formation. If a chemical contaminant is released into the subsurface, water flowing in fractures may contain dissolved constituents from the release. A chemical concentration gradient is established between the water flowing in the fracture and immobile pore water in the aquifer matrix, causing a transfer of the contaminants from the fracture into the aquifer matrix by molecular diffusion (Parker and others, 1994; Parker and Sterling, 1999). To determine the extent of this transfer at Site 5, a rock core was obtained and sampled for VOC's.

On September 8, 2000, a driller contracted by the U.S. Navy drilled a core (MG-1760) at Site 5 between wells 05MW01S and 05MW01I. This is the area where analyses of soil and ground water showed the highest concentration of VOC's (Brown and Root Environmental, Inc., 1998, p. 7-9). The soil (weathered) zone extended from land surface to 23.5 ft bls. A 17-ft long core was recovered from 23.5 to 40.5 ft bls (fig. 9). Three water-bearing fractures in the core were identified by iron and manganese oxide staining on the fracture faces. One fracture was in mudstone at 30.8 ft bls, one fracture was at the contact between mudstone and weathered coarse-grained sandstone at 35.6 ft bls, and one fracture was in unweathered coarse-grained sandstone at 35.9 ft bls (fig. 10).

Three samples were obtained from each water-bearing fracture (fig. 10)—at the fracture face, 2 cm below the fracture, and 4 cm below the fracture. The rock was crushed, and approximately 5 grams of sample was placed into a 40-milliliter septum bottle with 1 gram of sodium bisulfate as a preservative. This procedure was done as quickly as possible to minimize volatilization. The bottle was sealed, weighed, packed in ice, and shipped to the USGS laboratory in Denver, Colo., for analysis. All samples were analyzed within 14 days of sample collection. Laboratory results are given in table 5.

All 15 compounds listed in table 5 were detected. However, concentrations of 1,2-dichloroethane; trans-1,2-dichloroethene; ethyl benzene; meta-, ortho-, and para-xylene; methylene chloride; and 1,1,2-trichloroethane were less than 1 µg/kg when detected. Concentrations of benzene (from 0.39 to 3.3 µg/kg), 1,1-dichloroethene (1,1-DCE) (from 0.15 to 13 µg/kg), 1,1,1-trichloroethane (TCA) (from 0.17 to 22 µg/kg), and trichloroethylene (TCE) (from 0.092 to 9.6 µg/kg) were

Table 5. *Analytical results for volatile organic compounds in samples from rock core MG-1760, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

[All concentrations are given in micrograms per kilogram; cm, centimeter; <, less than; E, estimated concentration]

Compound name	Mudstone			Weathered sandstone			Unweathered sandstone		
	Fracture face	2 cm below fracture	4 cm below fracture	Fracture face	2 cm below fracture	4 cm below fracture	Fracture face	2 cm below fracture	4 cm below fracture
Benzene	1.5	0.43	0.39	1.5	0.93	0.80	0.65	2.4	3.3
1,1-Dichloroethane	8.2	1.7	1.0	.64	.92	.63	.60	.56	<.07
1,2-Dichloroethane	.26	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1
1,1-Dichloroethene	13	3.0	2.4	.91	1.4	1.2	1.0	1.0	.15 E
cis-1,2-dichloroethene	3.0	.64	.50	.087 E	.12 E	.10 E	.095 E	.10 E	<.1
trans-1,2-dichloroethene	.069 E	<.053	<.053	<.053	<.053	<.053	<.053	<.053	<.053
Ethyl benzene	<.08	<.08	<.08	<.08	<.08	<.08	<.08	<.08	.090 E
meta- and para-Xylene	<.15	<.15	<.15	<.15	<.15	<.15	<.15	<.15	.10 E
Methylene chloride	.48	<.2	<.2	<.2	<.2	.084 E	<.2	<.2	<.2
ortho-Xylene	<.08	<.08	<.08	.19 E	<.08	<.08	<.08	.38	.74
Tetrachloroethene	1.6	.59	2.2	<.07	.092 E	<.07	<.07	<.07	<.07
1,1,1-Trichloroethane	22	4.9	4.7	1.2	1.8	1.3	1.2	1.2	.17 E
1,1,2-Trichloroethane	.65	.15 E	.13 E	<.07	<.07	<.07	<.07	<.07	<.07
Trichloroethene	9.6	2.4	5.7	.45	.77	.57	.55	.56	.092 E
Toluene	<.33	<.4	.50 E	14	4.4	5.9	3.0	32	86 E

MUDSTONE

SECTION OF CORE (MUDSTONE) SAMPLED FOR VOLATILE ORGANIC COMPOUNDS

SECTION OF CORE (WEATHERED SANDSTONE) SAMPLED FOR VOLATILE ORGANIC COMPOUNDS

WEATHERED SANDSTONE

UNWEATHERED SANDSTONE

SECTION OF CORE (UNWEATHERED SANDSTONE) SAMPLED FOR VOLATILE ORGANIC COMPOUNDS

Figure 9. Photographs of sections from rock core MG-1760, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

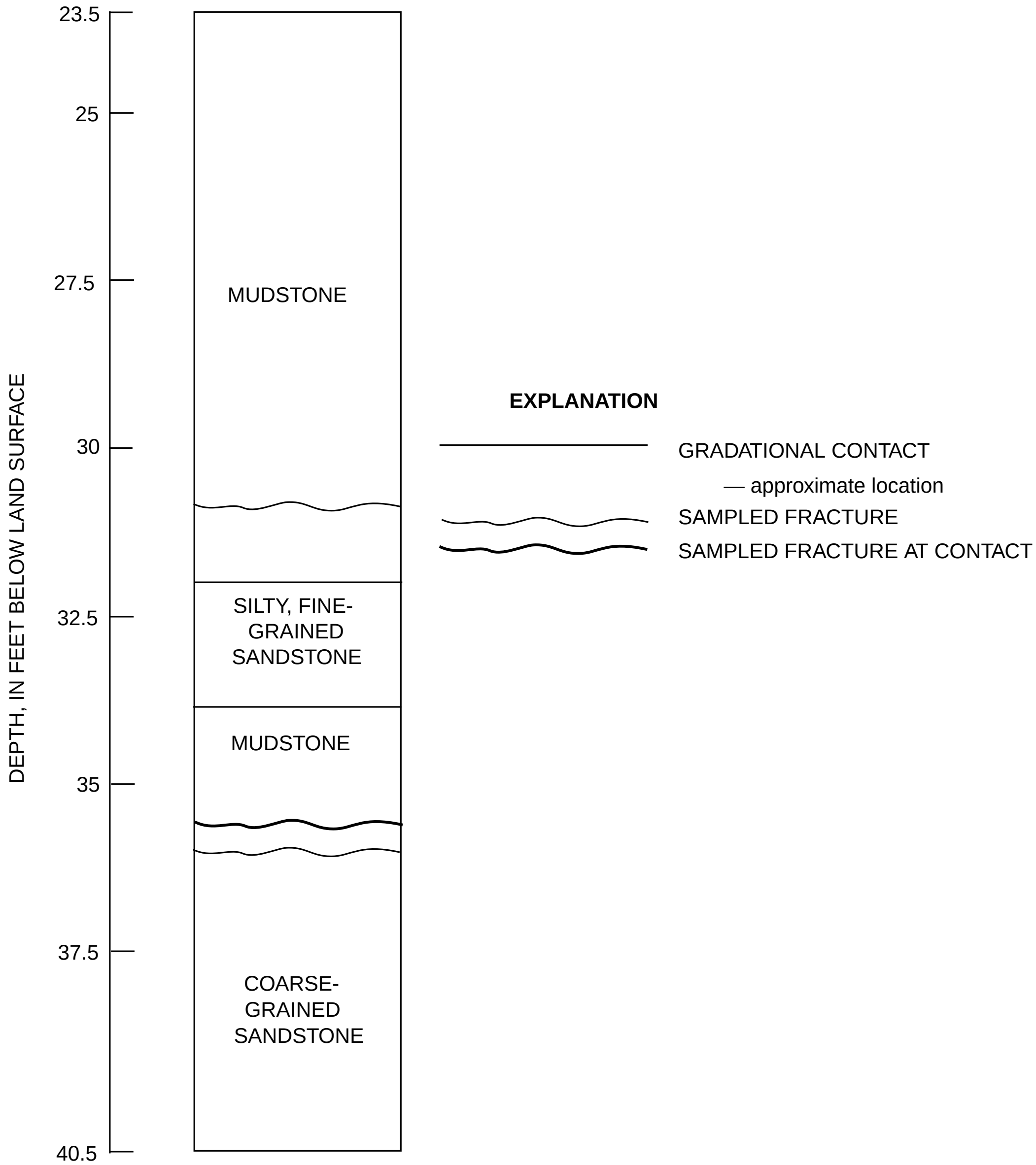


Figure 10. Geologic log of rock core MG-1760 and depths of sampled fractures, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

detected in all samples. The highest concentrations detected were for toluene, which was detected at a concentration of 32 and 86 µg/kg in the samples from unweathered sandstone at 2 and 4 cm below the fracture, respectively.

Concentrations of VOC's generally decreased with distance below the fracture in the mudstone samples. Concentrations of benzene and toluene increased with distance below the fractures in the unweathered sandstone samples. No pattern was evident in the weathered sandstone samples. Concentrations of 1,1-DCE, TCA, and TCE were higher in the mudstone samples than in the samples from the other rocks. Concentrations of toluene were higher in unweathered sandstone than in the other rocks. The distribution pattern may be related to the release history, which is unknown.

The volume of each compound per cubic foot of aquifer material (mudstone, weathered sandstone, and unweathered sandstone) can be determined by the following method. A representative section of the core was obtained with a diamond saw so that the top and bottom were parallel and were perpendicular to the sides. The diameter and length of each core section were measured, and the volume was calculated. Each core section was weighed, and its density was calculated (table 6). The mass of each compound per cubic foot of aquifer material can be calculated by multiplying the concentration in table 5 by the density in table 6 and then by the weight per volume of the compound to obtain the volume. For example, to determine the volume of TCE in 1 ft^3 of mudstone, the geometric mean concentration in mudstone (5.1 µg/kg) is multiplied by the density of mudstone (75 kg/ft^3) to obtain the mass of TCE, which is 382.5 µg. TCE weighs 1.46 kilograms per liter; therefore, 1 ft^3 of mudstone containing a mass of 382.5 µg of TCE contains 3.0×10^{-7} liters of TCE. The VOC concentration in the aquifer material is affected by spatial variability in concentration, matrix and fracture porosity, and partitioning between the free and dissolved phases.

The presence of contaminants in the aquifer matrix suggests that the contaminants cannot easily or rapidly be removed by water flowing in fractures. They may be a continuing source of low-level contamination to the ground-water system.

Table 6. *Density of rock types in rock core MG-1760, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

Rock type	Density	
	Kilograms per cubic foot	Pounds per cubic foot
Mudstone	75.0	165.3
Weathered sandstone	58.2	128.3
Unweathered sandstone	70.2	154.6

EFFECT OF PUMPING HORSHAM WATER AND SEWER AUTHORITY SUPPLY WELL 26 ON WATER LEVELS

The HWSA operates a public supply well (HWSA-26) 0.2 mi southwest of the base boundary (fig. 2). Well HWSA-26 is 400 ft deep and capable of producing 500 gal/min (Gilbert/Commonwealth, Inc., 1978). The well penetrates water-bearing zones at 160, 260, and below 260 ft bls, which is in the part of the Stockton Formation that is confined to semiconfined (Sloto and others, 1996). Well HWSA-26 pumps approximately 220,000 gal/d of water. The effect of pumping this well on ground-water levels on the base was unknown. To determine the effect of pumping well HWSA-26 on water levels, a hydraulic test was conducted.

Well HWSA-26 was shut down for 6 days to allow water levels to recover and then restarted. The well was removed from service at noon on January 25, 2000, and returned to service at 9 a.m. on January 31, 2000. Water levels in the vicinity of well HWSA-26 were measured for 1 week before the test, during the test, and for 1 week after the test. Water levels were measured by TetraTech NUS, Inc., in 10 wells using transducers and data-loggers and in 9 wells 3 times per day using electric water-level-measurement tapes. Water levels were measured by the USGS using transducers and dataloggers in well HWSA-26 after the pump was turned off and in well MG-1739, an operating domestic well near well HWSA-26. The transducer could not be placed lower than 51 ft btoc in well HWSA-26; therefore, no data could be collected until the water level rose to 51 ft btoc.

Wells measured during the test and the observed changes in water level during the shut-down period are listed in table 7. The only well that showed an unambiguous response to the shut-down of well HWSA-26 was well 02MW01I (fig. 11). Well 02MW01I is approximately 1,350 ft directly along strike from well HWSA-26. In the Stockton Formation, the effects of pumping a deep well are much more pronounced in the direction of strike than in the direction of dip (Sloto and others, 1996).

Four wells, 02MW01S, 02MW03I, 02MW04I, and 05MW11I, showed a rise in water level after well HWSA-26 was shut down. A comparison of climatic data (National Oceanic and Atmospheric Administration, 2000a; 2000b) with the hydrographs from these wells shows the rise in water level was most likely caused by recharge from snowmelt during a rise in temperature (fig. 12). Hydrographs from these wells and all the other wells, except well 02MW01I, showed no recovery in response to the shutdown of well HWSA-26 (figs. 13-17).

The hydrograph of well 05MW11I (fig. 12), however, does show a response to the pumping of well HWSA-26 and another well. While well HWSA-26 was pumping, the hydrograph of well 05MW11I shows two cycles of pumping and recovery each day, one ending around midnight and one ending around noon. While well HWSA-26 was not pumping, the hydrograph of well 05MW11I shows one cycle of pumping and recovery each day ending around midnight. It appears the pumping of well HWSA-26 contributes to both cycles of drawdown and recovery. Drawdown in well 05MW11I caused by the pumping of both wells ranged from 0.05 to 0.15 ft between January 18 and February 9. The recovery of well 05MW11I in response to the shutdown of well HWSA-26 is masked by recharge from snowmelt but probably does not exceed about 0.2 ft on the basis of fluctuations in the water level of well 05MW11I while well HWSA-26 is pumping. Well 05MW11I is in the well cluster nearest to the base boundary and is the well at Site 5 nearest to well HWSA-26. If extraction wells for remediation are drilled in this vicinity near the base boundary, off-base pumping possibly may cause some interference with the extraction wells.

Table 7. *Change in water level in wells measured January 25-31, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

[Data for Willow Grove monitor wells were provided by TetraTech NUS, Inc.; >, greater than; HWSA, Horsham Township Water and Sewer Authority; —, no data]

Site well-identification number	U.S. Geological Survey well-identification number	Frequency of measurement	Change in water level January 25-31, 2000 (feet)	Remarks
HWSA-26	MG-962	continuous	> 17.22	Pumped well
—	MG-1739	continuous	-.30	No effect
02MW01S	MG-1850	continuous	.60	Recharge from snowmelt
02MW01I	MG-1598	continuous	17.47	Affected by well HWSA-26
02MW04S	MG-1593	continuous	-.30	No effect
02MW04I	MG-1594	continuous	.38	Recharge from snowmelt
05MW01I	MG-1590	continuous	-.28	No effect
05MW03S	MG-1866	continuous	-.56	No effect
05MW03I	MG-1589	continuous	-.34	No effect
05MW06I	MG-1870	continuous	-.25	No effect
05MW011S	MG-1634	continuous	-.18	No effect
05MW11I	MG-1635	continuous	.60	Recharge from snowmelt and affected by well HWSA-26[1]
02MW03SI	MG-1852	3 times daily	-.10	No effect
02MW03I	MG-1628	3 times daily	.32	Recharge from snowmelt
03MW06S	MG-1596	3 times daily	-.36	No effect
03MW06SI	MG-1877	3 times daily	-.44	No effect
03MW06I	MG-1597	3 times daily	-.37	No effect
05MW01S	MG-1599	3 times daily	-.35	No effect
05MW01SI	MG-1864	3 times daily	-.30	No effect
05MW06S	MG-1869	3 times daily	-.65	No effect
05MW11SI	MG-1876	3 times daily	-.19	No effect

[1] Recovery in response to shutdown of well HWSA-26 is masked by recharge from snowmelt but probably is less than about 0.2 ft.

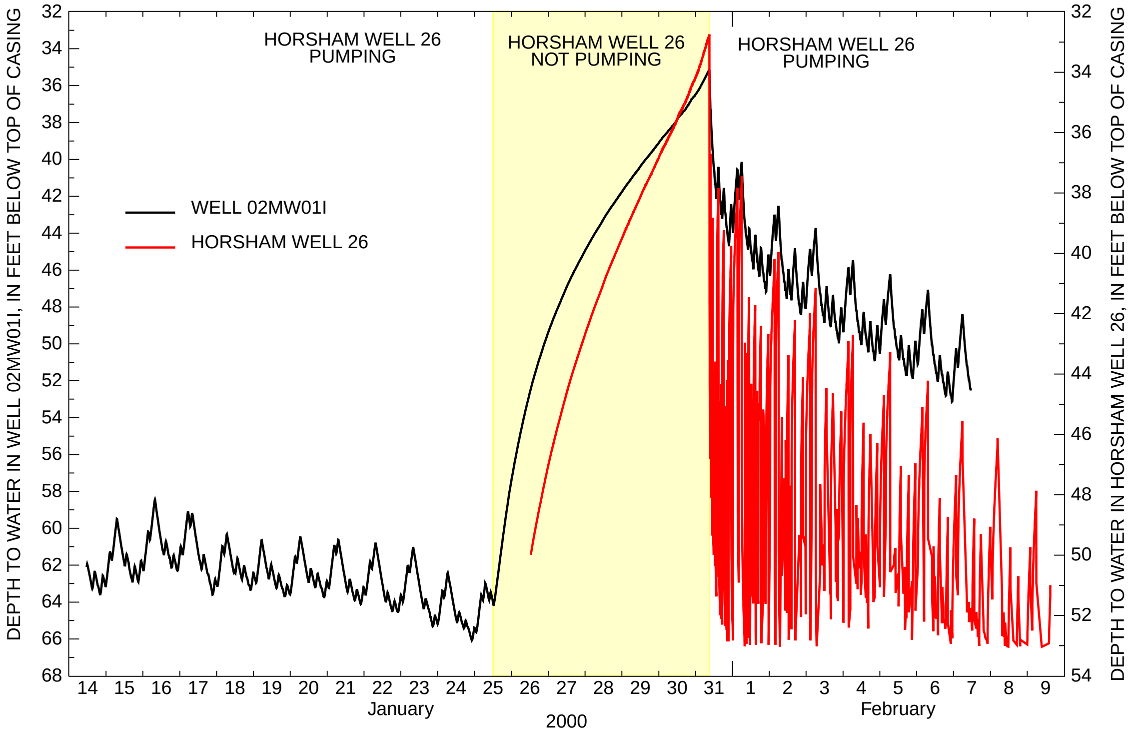


Figure 11. Hydrographs from Horsham Water and Sewer Authority well 26 and well 02MW01I, January 14 to February 9, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

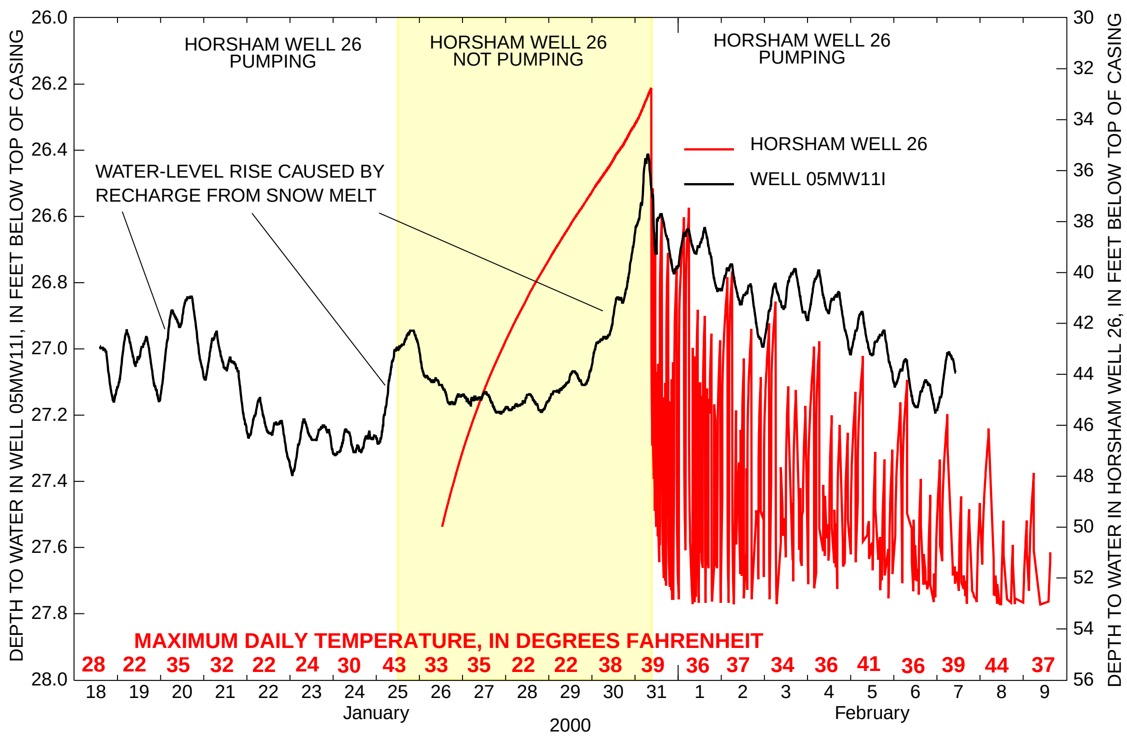


Figure 12. Hydrographs from Horsham Water and Sewer Authority well 26 and well 05MW11I, January 18 to February 9, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[Temperature data from the National Oceanic and Atmospheric Administration station at Neshaminy Falls, Pennsylvania.]

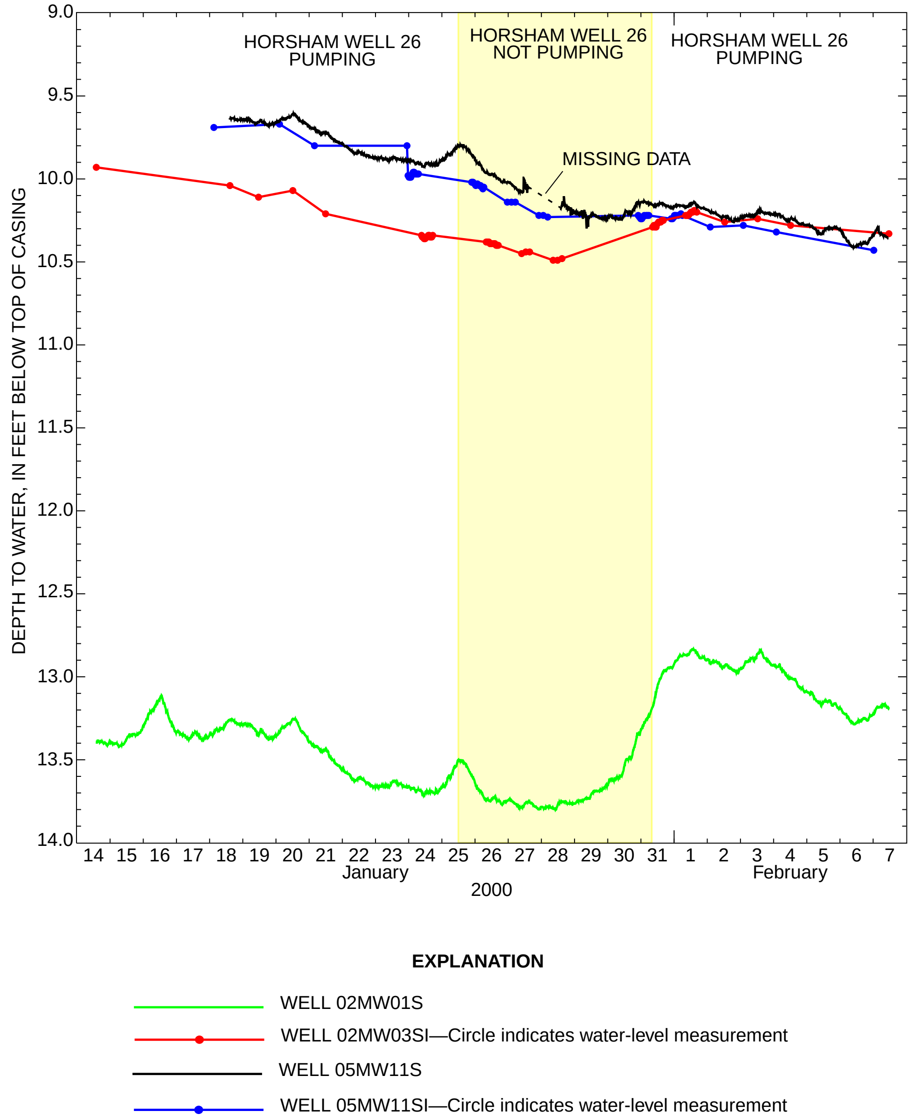


Figure 13. Hydrographs from wells 02MW01S, 02MW03SI, 05MW11S, and 05MW11SI, January 14 to February 7, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[Water-level data were provided by TetraTech NUS, Inc.]

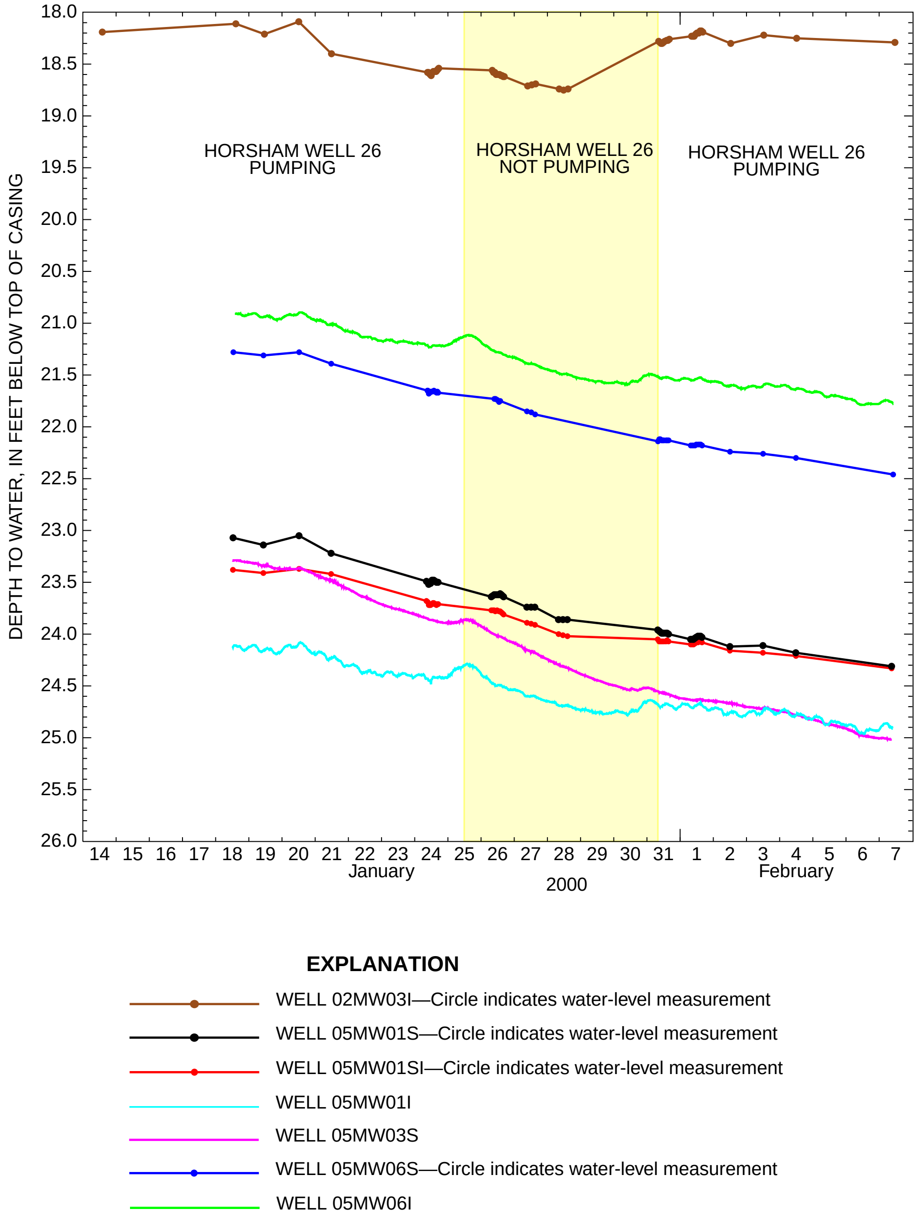


Figure 14. Hydrographs from wells 02MW03I, 05MW01S, 05MW01SI, 05MW01I, 05MW03S, 05MW06S, and 05MW06I, January 14 to February 7, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[Water-level data were provided by TetraTech NUS, Inc.]

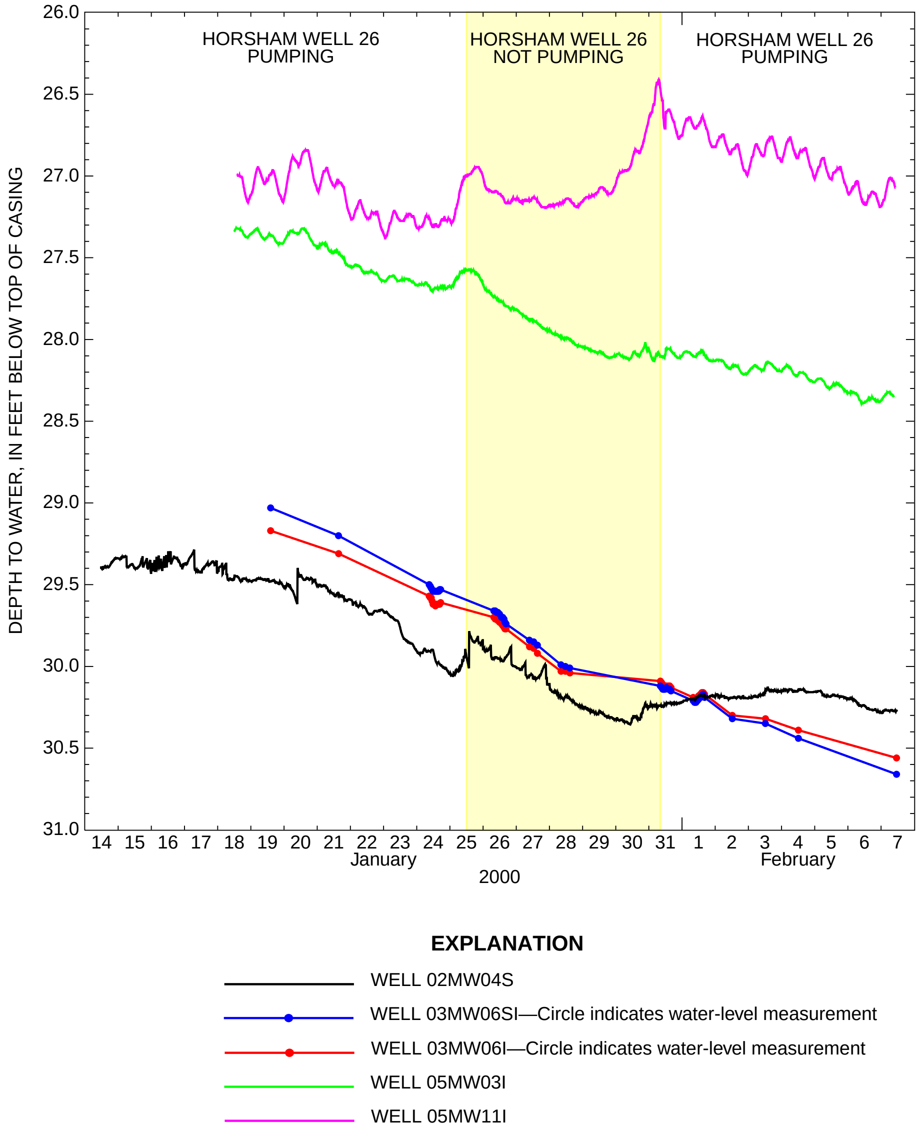


Figure 15. Hydrographs from wells 02MW04S, 03MW06SI, 03MW06I, 05MW03I, and 05MW11I, January 14 to February 7, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[Water-level data provided were by TetraTech NUS, Inc.]

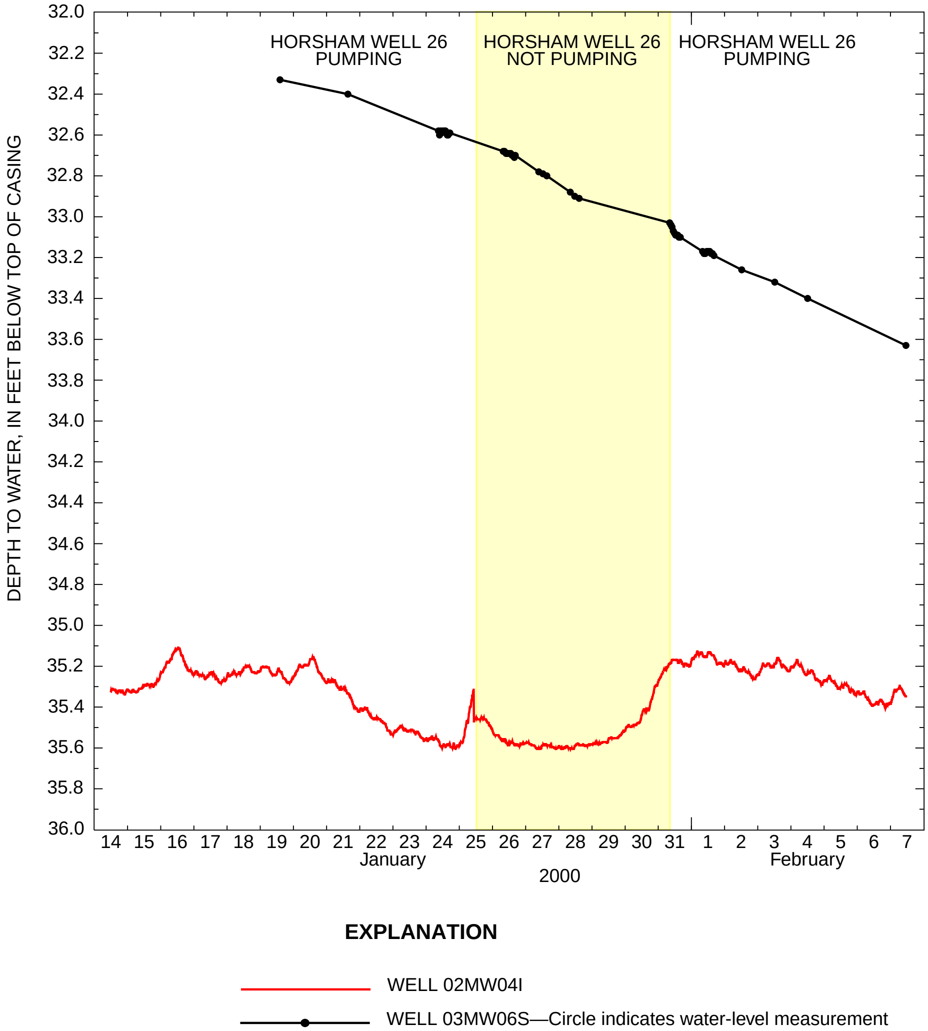


Figure 16. Hydrographs from wells 02MW04I and 03MW06S, January 14 to February 7, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

[Water-level data were provided by TetraTech NUS, Inc.]

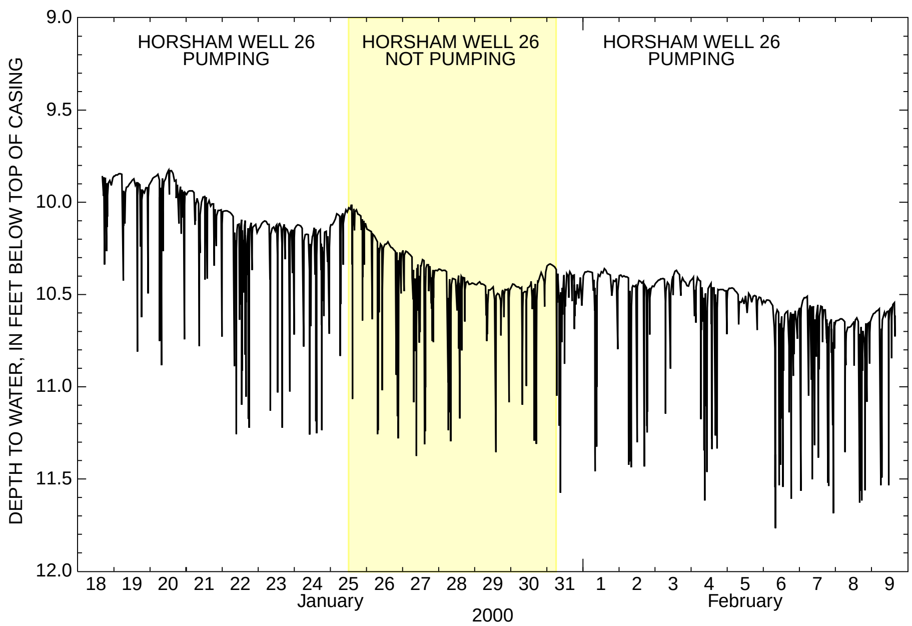


Figure 17. Hydrograph from well MG-1739, January 18 to February 9, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

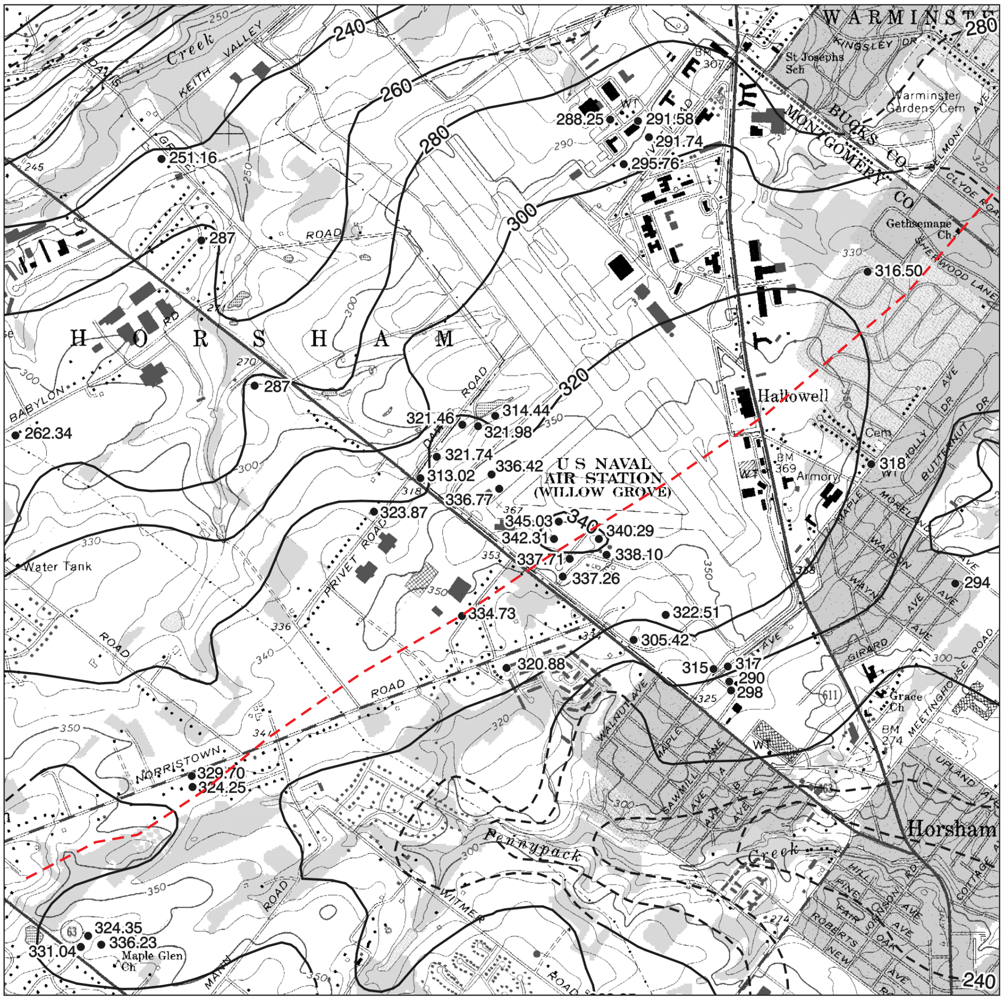
WATER LEVELS

Water-level data provide important information on the 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 gradients 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

To understand how horizontal ground-water flow at Site 5 fits into a regional perspective, it is necessary to utilize water-level data from wells on-base and off-base. A map showing the regional potentiometric surface in the Stockton Formation at and in the vicinity of the Willow Grove NAS/JRB was prepared by Sloto, Goode, and Way (2001). A part of the map, reproduced here as figure 18, shows a regional ground-water divide running northeast-southwest approximately through the center of Site 5. From this divide, ground water flows both northwest toward Park Creek, a tributary to Little Neshaminy Creek, and southeast toward Pennypack Creek. The presence of this ground-water divide helps to explain the contaminant distribution patterns observed at Site 5; ground water flows northwest and southeast from Site 5. The location of this divide may shift to the northwest or the southeast because of variations in aquifer recharge and discharge. A shift in the divide to the northwest would cause more ground water at Site 5 to flow southeast. Likewise, a shift in the divide to the southeast would cause more ground water at Site 5 to flow northwest.

The high point on the divide (water-level elevations greater than 340 ft above sea level) was centered around wells 05MW02S, 05MW03S, and 05MW04S (fig. 18) during the time of water-level measurements on October 7, 1999 (table 8). From this high point, which appears as a ground-water mound, ground-water flow follows a radial pattern; the steepest gradients, however, are to the northwest and southeast.



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, elevations of streams, and topography. Dashed where approximately located. Contour interval is 20 feet. Altitude 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 18. 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, Goode, and Way (2001).)

Table 8. *Water levels measured October 7, 1999, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania*

Site identification number	U.S. Geological Survey well-identification number	Depth of well screen (feet below land surface)	Elevation of top of casing (feet above sea level)	Depth to water (feet below top of casing)	Elevation of water level (feet above sea level)
02MW01S	MG-1850	5-20	323.76	18.34	305.42
02MW01I	MG-1598	70-80	325.28	82.27	243.01
02MW02S	MG-1851	5-25	349.37	13.15	336.22
02MW03SI	MG-1852	40-55	333.66	11.15	322.51
02MW03I	MG-1628	140-150	333.55	19.37	314.18
02MW04S	MG-1593	34-44	349.96	34.14	315.82
02MW04I	MG-1594	105-115	349.54	40.45	309.09
03MW01S	MG-1853	12-32	347.49	22.64	324.85
03MW01SI	MG-1854	60-80	346.98	23.81	323.17
03MW01I	MG-1855	159-179	346.57	10.15	336.42
03MW02S	MG-1856	4.5-22.5	326.15	11.01	315.14
03MW02SI	MG-1857	55-65	326.33	11.89	314.44
03MW02I	MG-1629	134-144	326.38	4.40	321.98
03MW03S	MG-1858	5-20	312.96	4.82	308.14
03MW03I	MG-1859	148.5-168.5	314.08	-7.38	321.46
03MW04S	MG-1860	5-35	324.49	2.75	321.74
03MW04SI	MG-1861	60-80	323.87	12.72	311.15
03MW04I	MG-1862	148-168	323.93	-8.00	331.93
03MW05S	MG-1863	17-37	361.98	25.95	336.03
03MW05I	MG-1595	82-92	360.93	25.34	335.59
03MW06S	MG-1596	26-36	367.00	30.91	336.09
03MW06SI	MG-1877	75-85	366.86	29.21	337.65
03MW06I	MG-1597	140-150	366.82	30.05	336.77
03MW07S	MG-1630	34-44	324.90	11.88	313.02
05MW01S	MG-1599	12-32	364.11	24.87	339.24
05MW01SI	MG-1694	74.5-84.5	363.99	25.33	338.66
05MW01I	MG-1590	125-135	363.99	26.28	337.71
05MW02S	MG-1865	10-30	365.48	25.19	340.29
05MW03S	MG-1866	11-31	367.18	22.15	345.03
05MW03I	MG-1589	118-128	367.35	29.12	338.23
05MW04S	MG-1867	10-30	365.62	23.31	342.31
05MW05S	MG-1868	20-40	359.92	21.71	338.21
05MW06S	MG-1869	17.5-37.5	362.38	23.15	339.23
05MW06I	MG-1870	74-84	361.08	22.98	338.10
05MW07S	MG-1871	6-26	360.73	22.18	338.55
05MW07I	MG-1872	74-84	360.20	22.94	337.26
05MW08S	MG-1585	26-36	360.88	22.13	338.75
05MW08SI	MG-1873	55-65	360.92	22.92	338.00
05MW08I	MG-1586	89-99	361.02	23.07	337.95
05MW09S	MG-1588	27-32	361.91	22.85	339.06
05MW09SI	MG-1874	59-74	361.74	23.61	338.13
05MW09I	MG-1587	96-106	362.11	24.37	337.74
05MW10S	MG-1591	22-32	362.54	23.70	338.84
05MW10SI	MG-1875	79-94	362.44	24.35	338.09
05MW10I	MG-1592	116-126	362.48	24.84	337.64
05MW11S	MG-1634	20-25	349.50	11.75	337.75
05MW11SI	MG-1876	40-50	349.51	11.79	337.72
05MW11I	MG-1635	139-149	348.96	30.74	318.22

Potentiometric Surface at Site 5

To prepare a map of the potentiometric surface at Site 5, it is necessary to use water-level data from Sites 2, 3, and 5 (fig. 1). Because of vertical head gradients at these sites, water-level data were grouped into three depth ranges for contouring. Hydrographs from wells in the same depth range are similar. For example, hydrographs for wells 05MW08I (screened 89-99 ft bls), 05MW09I (screened 96-106 ft bls), and 05MW12I (screened 103.5-113.5 ft bls) show identical water-level fluctuations (fig. 19). Horizontal gradients differ with depth, and the rate and direction of ground-water flow and contaminant movement is depth dependent.

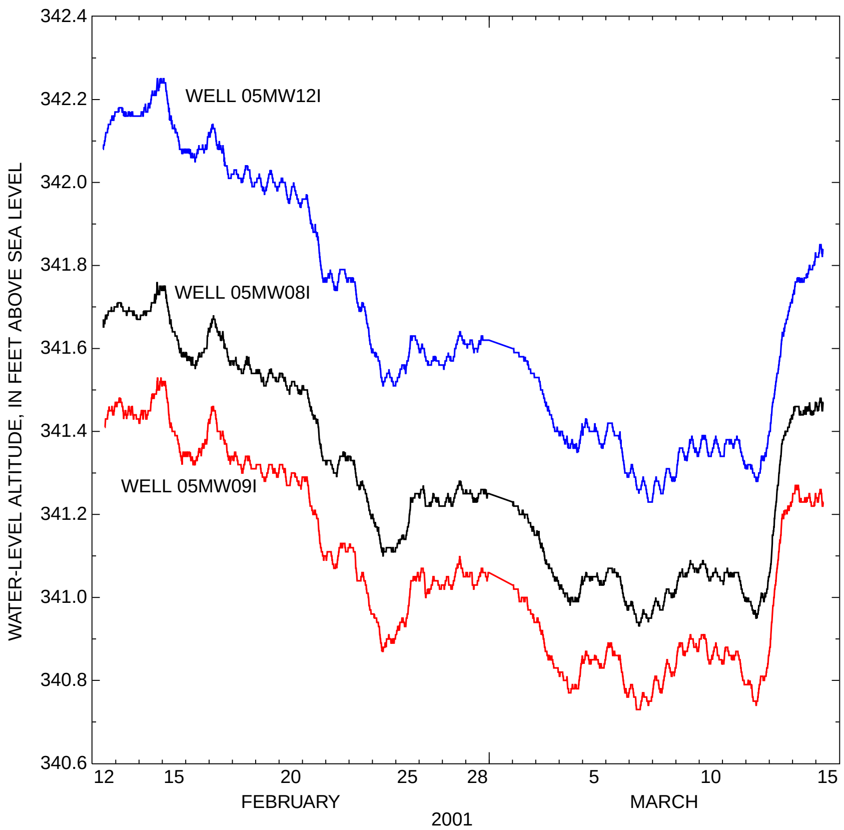
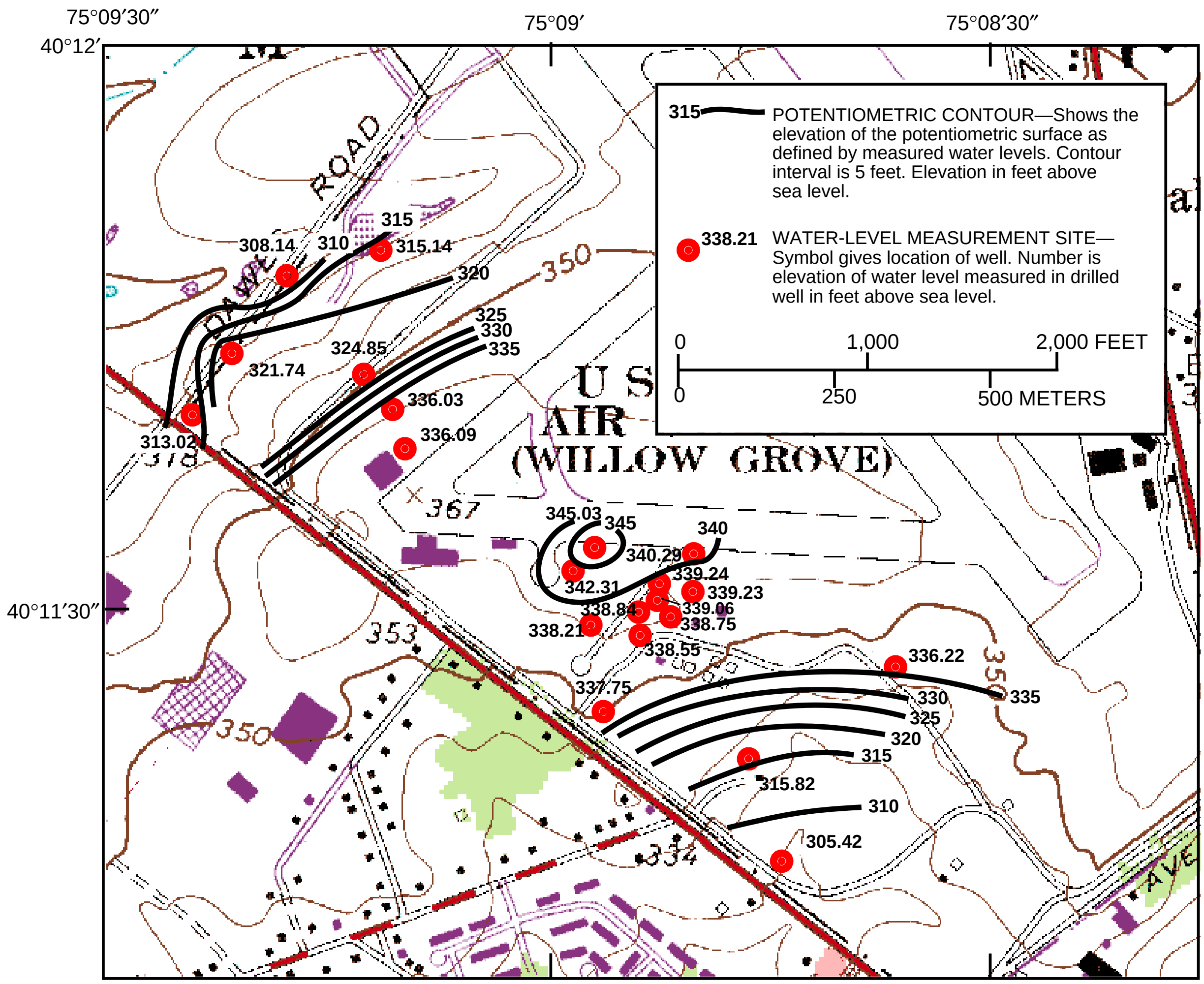


Figure 19. Hydrographs from wells 05MW08I, 05MW09I, and 05MW12I, February 12 to March 15, 2001, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

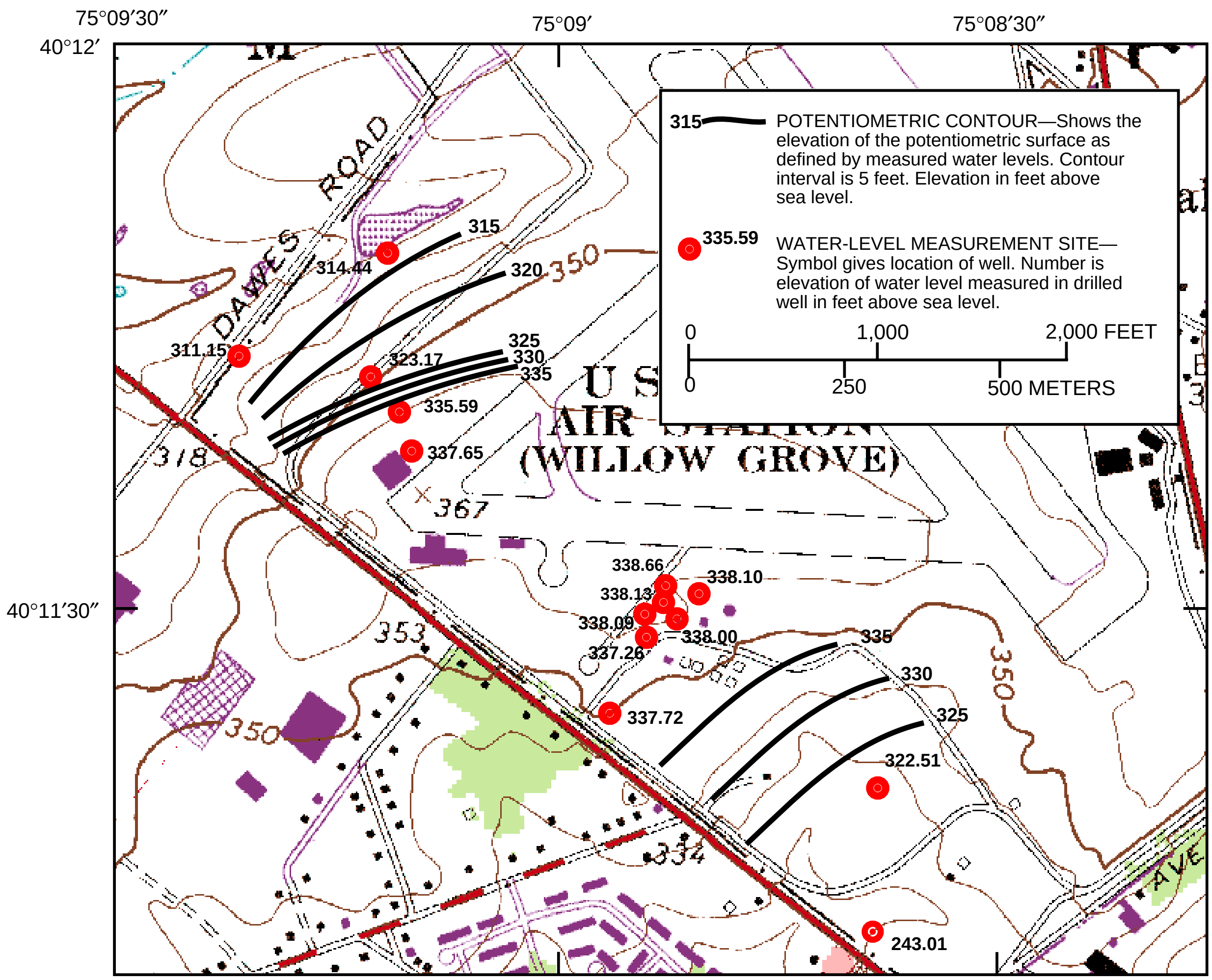
The potentiometric surface was mapped for each of the three depth ranges of the aquifer. The potentiometric surface as defined by water levels in wells screened between 5 and 44 ft bls is shown on figure 20. This interval is the shallowest of the three intervals, and the potentiometric surface represents the water table. The map shows a ground-water mound around wells 05MW02S, 05MW03S, and 05MW04S. This represents the high point on the regional ground-water divide. From this mound, the ground-water flow is radial. The hydraulic gradient around this mound is relatively flat to the southeast and particularly to the northwest.



Base from U.S. Geological Survey Ambler 1:24,000, 1966

Figure 20. Potentiometric surface defined by water levels in wells screened between 5 and 44 feet below land surface, October 7, 1999, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

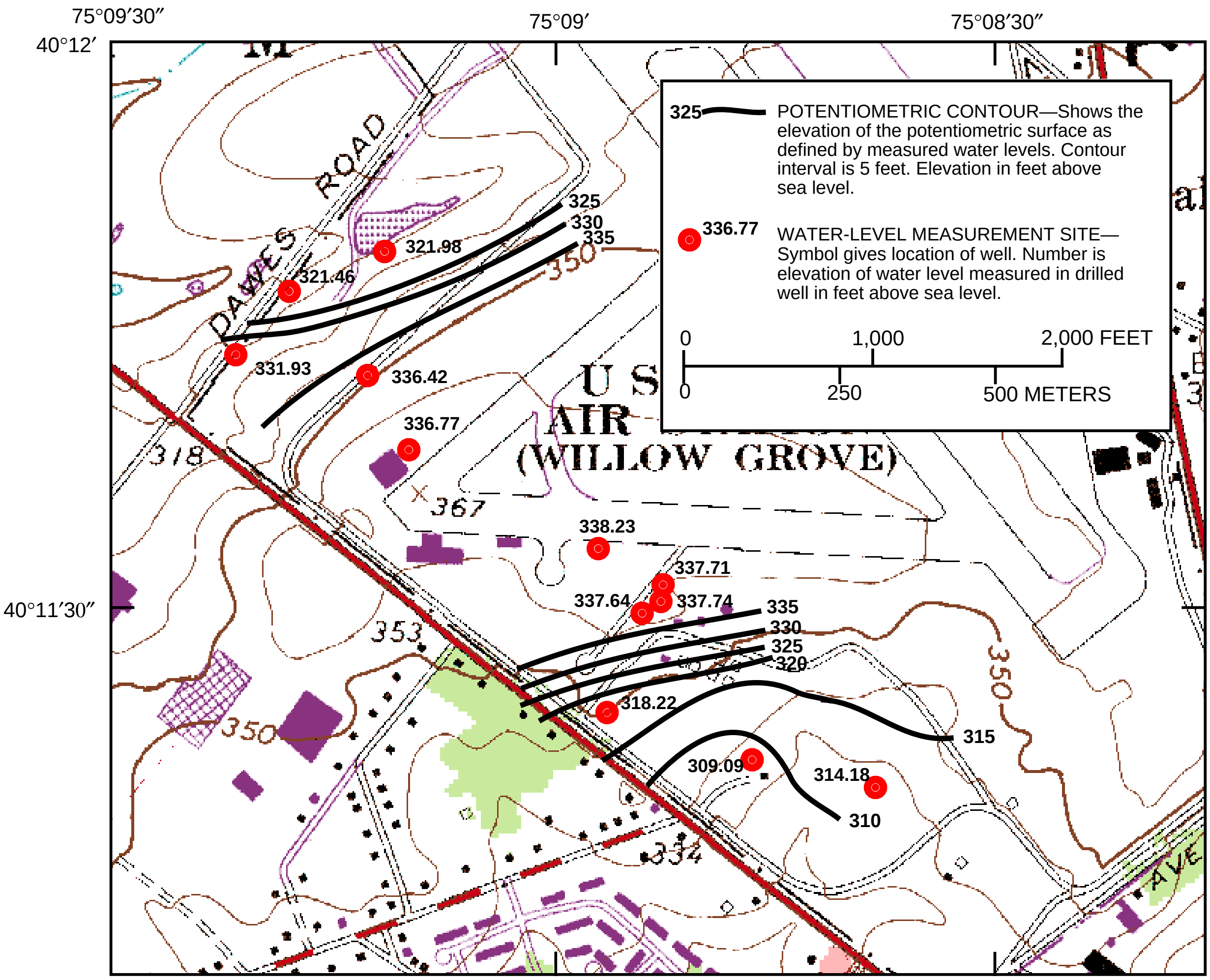
The potentiometric surface as defined by water levels in wells screened between 40 and 100 ft bls is shown on figure 21. The map shows a very flat hydraulic gradient at Site 5. Differences in the elevation of the potentiometric surface are less than 2 ft. The area of flat hydraulic gradient extends northwest to Site 3. The water level in well 02MW01I (elevation of 243.01) in the southeastern part of Site 2 is affected by the pumping of well HWSA-26 and is lower than water levels in other wells at Site 2.



Base from U.S. Geological Survey Ambler 1:24,000, 1966

Figure 21. Potentiometric surface defined by water levels in wells screened between 40 and 100 feet below land surface, October 7, 1999, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

The potentiometric surface defined by water levels in wells screened between 105 and 179 ft bls is shown on figure 22. The map shows a steep hydraulic gradient between Sites 5 and 2 and a relatively flat hydraulic gradient between Sites 5 and 3.



Base from U.S. Geological Survey Ambler 1:24,000 1966

Figure 22. Potentiometric surface defined by water levels in wells screened between 105 and 179 feet below land surface, October 7, 1999, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

Vertical Head Gradients

Water-level hydrographs for well cluster 05MW11 are shown on figure 23. The vertical flow gradient is downward from higher water levels (wells 05MW11S and 05MW11SI) to lower water levels (well 05MW11I). Wells 05MW11S (screened 20-25 ft bls) and 05MW11SI (screened 40-50 ft bls) are screened in the water table, and the water levels measured in these wells nearly are identical.

The vertical head gradient varies with time. The variability in the vertical head gradient is caused by a difference in the magnitude of water-level fluctuations between the shallow wells and the deep well. The difference in water level between August 9, 1999, and January 14, 2000, ranged from a difference of 27.93 ft on August 10, 1999, to a difference of 17.43 ft on January 14, 2000. The difference in the magnitude of water-level fluctuations is because of differences in lithology and aquifer storativity; the storativity at depth is less than the storativity in the shallow zone. The difference in response to recharge from Hurricane Floyd (September 16, 1999) is shown on figure 23. The maximum water-level rise was 7.92 ft in well 05MW11I and only 4.07 and 4.04 ft in wells 05MW11S and 05MW11SI, respectively.

Water levels measured on October 7, 1999 (table 8), showed downward vertical head gradients for all well clusters at Sites 5 and 2. These measurements are consistent with most heatpulse-flowmeter measurements made by Conger (1997), which showed downward flow. The downward vertical gradient at Site 5 is what would be expected in a ground-water divide/recharge area. Gradients ranged from 0.01 at well cluster 05MW10 to 0.2 at cluster 05MW11. Most gradients are between 0.01 and 0.026. The large downward gradient at well cluster 02MW01 at Site 2 (62.41 ft of water-level difference) is attributable to the pumping of well HWSA-26, which lowers the water level in well 02MW01I.

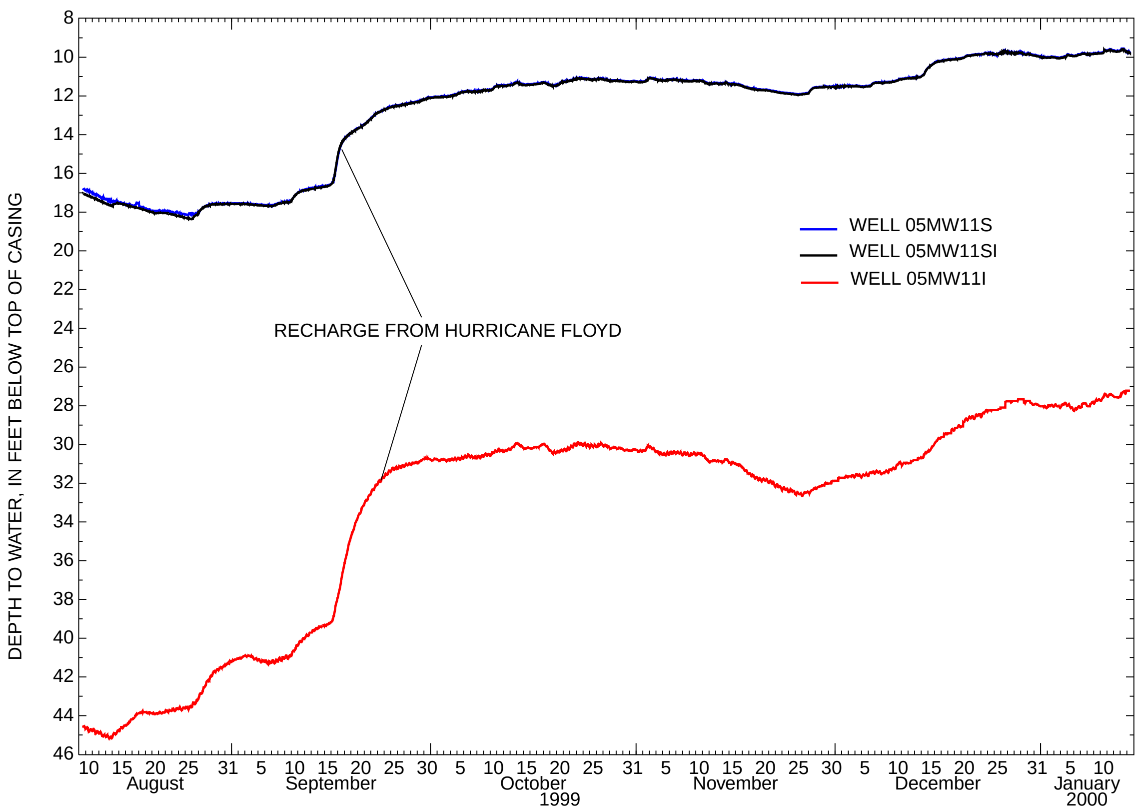


Figure 23. Hydrographs from wells 05MW11S, 05MW11SI, and 05MW11I, August 9, 1999, to January 14, 2000, Willow Grove Naval Air Station/Joint Reserve Base, Horsham Township, Montgomery County, Pennsylvania.

The same vertical gradient pattern was observed for all well clusters at Site 3 except for well cluster 03MW06. The vertical head gradient is downward from wells screened at shallow depths (screened 4.5 to 35 ft bls) to wells screened at an intermediate depth (55 to 80 ft bls) and upward from wells with deep screens (134 to 179 ft bls) to the intermediate and shallow screened wells. This pattern was observed for well clusters 03MW01, 03MW02, and 03MW04. At well cluster 03MW05, a downward vertical head gradient was observed from the shallow screened well to the intermediate depth screened well; the well cluster lacks a deep screened well. At well cluster 03MW03, an upward vertical head gradient was observed from the deep screened well to the shallow screened well; the well cluster lacks a well screened at an intermediate depth. The pattern at well cluster 03MW06, which is the well cluster in Site 3 closest to Site 5, is different than the others in Site 3. The vertical head gradient is upward and downward from the intermediate zone, which has a higher head than either the shallow or deep zones.

SUMMARY

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. Specifically, the USGS was asked to conduct borehole geophysical logging, to collect and analyze water-level data, and to sample sections of a rock core to determine the concentration of VOC's in the aquifer matrix. This information is being used to further identify the sources and pathways of contamination and to evaluate management strategies for improving water quality.

The Willow Grove NAS/JRB and surrounding area are underlain by the Stockton Formation, which forms 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.

Borehole geophysical logs were collected in three monitor wells. Well 05MW04I was logged to a depth of 151 ft. The principal water-bearing fractures are at 40-42 and 70-82 ft bls. The borehole geophysical logs indicate upward and downward vertical gradients are present; the vertical gradient is upward above 42 ft bls, downward between 42 and 82 ft bls, and upward below 82 ft bls. Well 05MW05I was logged to a depth of 250 ft. The water-bearing fractures in well 05WM05I are at 52-58, 72, 114, 142-148, 174, 192, 202-205, and 220-223 ft bls. The borehole geophysical logs indicate a downward vertical gradient is present. Well 05MW12I was logged to a depth of 149 ft. The principal water-bearing fracture is at 109-112 ft bls. The borehole geophysical logs indicate upward and downward vertical gradients are present; the vertical gradient is downward above 112 ft bls and upward below 112 ft bls.

Contaminants in ground water flowing in fractures may move by molecular diffusion into immobile aquifer pore water under a chemical concentration gradient. To determine the extent to which this occurred at Site 5, a 17-ft long rock core from 23.5 to 40.5 ft bls was obtained in the area where analyses of soil and ground water showed the highest concentration of VOC's. Three water-bearing fractures in the core were identified by iron and manganese oxide staining on the fracture faces. One fracture was in mudstone at 30.8 ft bls, one fracture was at the contact between mudstone and weathered coarse-grained sandstone at 35.6 ft bls, and one fracture was in unweathered coarse-grained sandstone at 35.9 ft bls. Three samples were analyzed from each water-bearing fracture—at the fracture face, 2 cm below the fracture, and 4 cm below the fracture. Fifteen VOC's were detected. However, concentrations of 1,2-dichloroethane; trans-1,2-dichloroethene; ethyl benzene; meta-, ortho-, and para-xylene; methylene chloride; and 1,1,2-trichloroethane were less than 1 µg/kg when detected. Concentrations of benzene (from 0.39 to 3.3 µg/kg), 1,1-DCE (from 0.15 to 13 µg/kg), TCA (from 0.17 to 22 µg/kg), and TCE (from 0.092 to 9.6 µg/kg) were detected in all samples. The highest concentrations detected were for toluene, which was detected at a concentration of 32 and 86 µg/kg in the samples from unweathered sandstone at 2 and 4 cm below the fracture, respectively.

Concentrations of VOC's generally decreased with distance below the fracture in the mudstone samples. Concentrations of benzene and toluene increased with distance below the fracture in the unweathered sandstone samples. No pattern was evident in the weathered sandstone samples. Concentrations of 1,1-DCE, TCA, and TCE were higher in the mudstone samples than in the samples from the other rocks. Toluene concentrations were

higher in unweathered sandstone than in the other rocks. The distribution pattern may be related to the release history, which is unknown.

The presence of contaminants in the aquifer matrix suggests that the contaminants cannot easily or rapidly be removed by water flowing in fractures. Contaminants in the matrix may be a continuing source of low-level contamination to the ground-water system.

The effect of the pumping of well HWSA-26, 0.2 mi southwest of the base boundary, on ground-water levels on the base was determined by conducting a hydraulic test. Well HWSA-26 was shut down for 6 days to allow water levels to recover and then restarted. Water levels in the vicinity of well HWSA-26 were measured for 1 week before the test, during the test, and for 1 week after the test. Water levels were measured in well HWSA-26 and 11 other wells using transducers and dataloggers and in 9 wells 3 times per day using electric water-level-measurement tapes.

The only well that showed an unambiguous response to the shutdown of well HWSA-26 was well 02MW01I, which is directly along strike from well HWSA-26. Four wells, 02MW01S, 02MW03I, 02MW04I, and 05MW11I, showed a rise in water level that occurred after well HWSA-26 was shut down. A comparison of climatic data with the hydrographs from these wells showed the rise in water level was most likely caused by recharge from snowmelt during a rise in temperature. The recovery of well 05MW11I in response to the shutdown of well HWSA-26 was masked by recharge from snowmelt but probably does not exceed about 0.2 ft. The water level in well 05MW11I showed a response to the pumping of well HWSA-26 that ranged from 0.5 to 0.15 ft. Well 05MW11I is in the well cluster nearest to the base boundary and is the well at Site 5 nearest to well HWSA-26. If extraction wells for remediation are drilled in this vicinity near the base boundary, off-base pumping possibly may cause some interference with the extraction wells.

A map of the regional potentiometric surface at and in the vicinity of the Willow Grove NAS/JRB shows a regional ground-water divide running northeast-southwest approximately through the center of Site 5. From this divide, ground water flows both northwest toward Park Creek and southeast toward Pennypack Creek. The high point on the divide was centered around wells 05MW02S, 05MW03S, and 05MW04S during the time of water-level measurements on October 7, 1999. From this high point, which appears as a ground-water mound, ground-water flow is radial; the steepest gradients, however, are to the northwest and southeast.

Three potentiometric-surface maps were prepared using water-level data from Sites 2, 3, and 5. Because of vertical head gradients at these sites, water-level data were grouped into three depth ranges for contouring. Horizontal gradients differ with depth, and the rate and direction of ground-water flow and contaminant movement varies with depth. The potentiometric-surface map based on water levels measured in wells screened between 5 and 44 ft bls shows a ground-water mound around wells 05MW02S, 05MW03S, and 05MW04S. This represents the high point on the regional ground-water divide. From this mound, horizontal ground-water flow follows a radial pattern. The hydraulic gradient around this mound is relatively flat to the southeast and particularly to the northwest. The potentiometric-surface map based on water levels measured in wells screened between 40 and 100 ft bls shows a very flat hydraulic gradient at Site 5. Differences in the elevation of the potentiometric surface are less than 2 ft. The area of flat hydraulic gradient extends northwest to Site 3. The water level in well 02MW01I (altitude of 243.01) in the southeastern part of Site 2 is affected by the pumping of well HWSA-26 and is much lower than water levels in other wells at Site 2. The potentiometric-surface map based on water levels measured in wells screened between 105 and 179 ft shows a steep hydraulic gradient between Sites 5 and 2 and a relatively flat hydraulic gradient between Sites 5 and 3.

Water levels measured on October 7, 1999, showed downward vertical head gradients for all well clusters at Sites 5 and 2. Gradients at Site 5 ranged from 0.01 at well cluster 05MW10 to 0.2 at well cluster 05MW11. Most gradients were between 0.01 and 0.026. The downward vertical gradient at Site 5 is what would be expected in a ground-water divide/recharge area.

Except for well cluster 03MW06, the same vertical gradient pattern was observed for all well clusters at Site 3. The vertical head gradient is downward from wells screened at shallow depths (screened 4.5 to 35 ft bls) to wells screened at an intermediate depth (55 to 80 ft bls) and upward from wells with deep screens (134 to 179 ft bls) to the intermediate and shallow screened wells. This pattern was observed for well clusters 03MW01, 03MW02, and 03MW04. At well cluster 03MW05, a downward vertical head gradient was observed from the shallow screened well to the intermediate depth screened well; the well cluster lacks a deep screened well. At well cluster 03MW03, an upward vertical head gradient was observed from the deep screened well to the shallow screened well; the well cluster lacks a well screened at an intermediate depth. The pattern at well cluster 03MW06, which is the well cluster in Site 3 closest to Site 5, is different than the others in Site 3. The vertical head gradient is upward and downward from the intermediate zone, which has a higher water level than either the shallow or deep zones.

The vertical head gradient varies with time. The variability is caused by a difference in the magnitude of water-level fluctuations between the shallow wells and deep fractures. The difference in the magnitude of water-level fluctuations is because of differences in lithology and aquifer storativity. The storativity at depth is less than the storativity in the shallow zone.

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