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

RESULTS OF BOREHOLE GEOPHYSICAL LOGGING AND HYDRAULIC TESTS CONDUCTED IN AREA D SUPPLY WELLS, FORMER U.S. NAVAL AIR WARFARE CENTER, WARMINSTER, PENNSYLVANIA

by Ronald A. Sloto and Kevin E. Grazul

Water-Resources Investigations Report 98-4129

prepared in cooperation with the

U.S. NAVY

Lemoyne, Pennsylvania
1998

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Thomas J. Casadevall, Acting Director

For additional information write to:

District Chief
U.S. Geological Survey
840 Market Street
Lemoyne, Pennsylvania 17043-1584

Copies of this report may be purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286
Denver, Colorado 80225-0286

CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
foot/minute (ft/min)	0.0051	meter per second
mile (mi)	1.609	kilometer
	Volume	
gallon (gal)	3.785	liter
	Flow	
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

Results of Borehole Geophysical Logging and Hydraulic Tests Conducted in Area D Supply Wells, Former U.S. Naval Air Warfare Center, Warminster, Pennsylvania

By Ronald A. Sloto and Kevin E. Grazul

ABSTRACT

Borehole geophysical logging, aquifer tests, and aquifer-isolation (packer) tests were conducted in four supply wells at the former U.S. Naval Air Warfare Center (NAWC) in Warminster, Pa., to identify the depth and yield of water-bearing zones, occurrence of borehole flow, and effect of pumping on nearby wells. The study was conducted as part of an ongoing evaluation of ground-water contamination at the NAWC. Caliper, natural-gamma, single-point-resistance, fluid-resistivity, and fluid-temperature logs and borehole television surveys were run in the supply wells, which range in depth from 242 to 560 ft (feet). Acoustic borehole televiewer and borehole deviation logs were run in two of the wells. The direction and rate of borehole-fluid movement under nonpumping conditions were measured with a high-resolution heatpulse flowmeter. The logs were used to locate water-bearing fractures, determine probable zones of vertical borehole-fluid movement, and determine the depth to set packers. An aquifer test was conducted in each well to determine open-hole specific capacity and the effect of pumping the open borehole on water levels in nearby wells. Specific capacities ranged from 0.21 to 1.7 (gal/min)/ft (gallons per minute per foot) of drawdown. Aquifer-isolation tests were conducted in each well to determine depth-discrete specific capacities and to determine the effect of pumping an individual fracture or fracture zone on water levels in nearby wells. Specific capacities of individual fractures and fracture zones ranged from 0 to 2.3 (gal/min)/ft. Most fractures identified as water-producing or water-receiving zones by borehole geophysical methods produced water when isolated and pumped. All hydrologically active fractures below 250 ft below land surface were identified as water-receiving zones and produced little water when isolated and pumped. In the two wells greater than 540 ft deep, downward borehole flow to the deep water-receiving fractures is caused by a large difference in head (as much as greater than 49 ft) between water-bearing fractures in the upper and lower part of the borehole. Vertical distribution of specific capacity between land surface and 250 ft below land surface is not related to depth.

INTRODUCTION

The U.S. Naval Air Warfare Center (NAWC) in Warminster, Pa. (fig. 1), was acquired by the U.S. Navy in 1944 to convert and modify newly produced Navy aircraft prior to delivery to the Naval Fleet. After World War II, the NAWC served as a research, development, testing, and evaluation center. In 1979, volatile organic compounds (VOC's) were detected in water from the Center's supply wells SW-1 and SW-2, which were removed from service in December of that year. These wells are now used only for fire protection. In 1980, the Navy implemented the Navy Assessment and Control of Installations Pollutants Program to identify and evaluate past hazardous materials disposal sites and to control the migration of hazardous material from such sites. The NAWC was listed as a National Priorities (Superfund) site in October 1989. Area D is a part of the NAWC that contains an identified disposal site. Supply wells SW-1, SW-2, SW-3, and SW-4 are located in Area D. Wells SW-3 and SW-4 are used as a source of drinking-water supply. The NAWC was closed on September 30, 1997, as part of the Base Realignment and Closure Act.

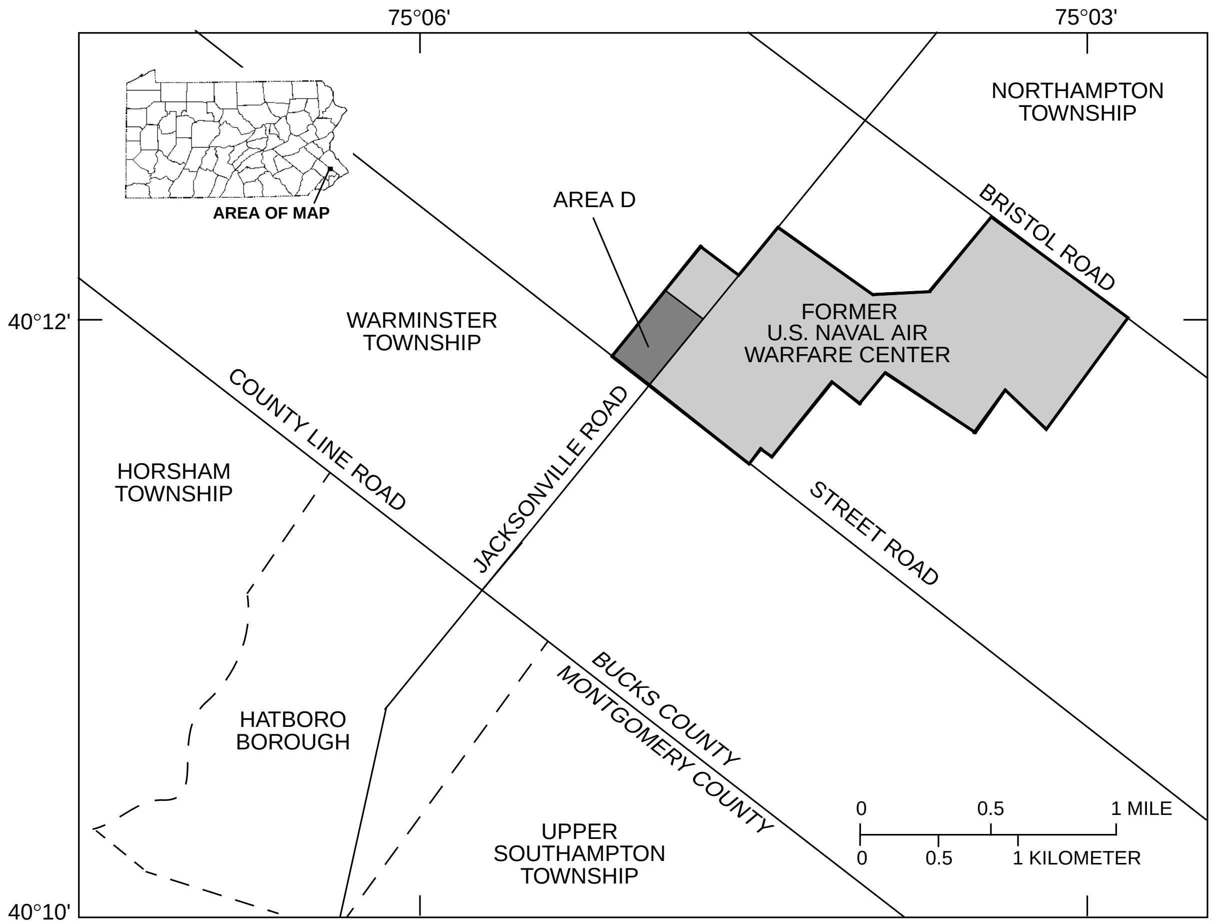


Figure 1. Location of the former U.S. Naval Air Warfare Center, Warminster, Pennsylvania.

Area D is to be included in ground-water remediation at the NAWC. However, the four deep, open-hole supply wells are present in Area D. The depth of water-bearing zones, occurrence of borehole flow in the wells, the chemical quality of water from discrete fracture zones, and the effect of pumping the wells on the hydrologic system were not known. To obtain that information, which is necessary for ongoing evaluation of ground-water contamination at the NAWC and for planning and design of remediation efforts, this study was initiated by the U.S. Geologi-cal Survey (USGS) in cooperation with the U.S. Navy.

Purpose and Scope

This report describes the results of borehole geophysical logging, aquifer tests, and aquifer-isolation tests (commonly known as packer tests) conducted by the USGS in supply wells SW-1, SW-2, SW-3, and SW-4 at the former NAWC. This report provides an interpretation of borehole geophysical logs and heatpulse-flowmeter measurements and describes drawdowns, water-level distributions, and specific capacities of isolated fracture zones. The USGS collected the data presented here and prepared this report as part of the environmental hydrogeological investigations conducted at the former NAWC in cooperation with the U.S. Navy.

Hydrogeological Setting and Physiography

The former NAWC is in the Triassic Lowlands Section of the Piedmont Physiographic Province and is underlain by sedimentary rocks of the Stockton Formation of Late Triassic age. The topography is flat to rolling. The rocks are chiefly arkosic sandstone and siltstone. In area D, the Stockton Formation strikes approximately N. 64° E. and dips approximately 7° NW. (Brown and Root Environmental, 1996a, p. 1-10).

The rocks of the Stockton Formation form a complex, heterogeneous, multiaquifer system. This aquifer system comprises a series of gently dipping lithologic units with different hydraulic properties. Each lithologic unit generally has different hydraulic properties, and permeability commonly differs from one lithologic unit to another.

In the Stockton Formation, 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 siltstone. Ground water in the unweathered zone mainly moves through a network of interconnecting secondary openings—fractures, bedding planes, and joints. Primary porosity that may have originally existed has been almost eliminated by compaction and cementation. Ground water is unconfined in the shallower part of the aquifer system and confined or semiconfined in the deeper part of the aquifer system.

Nearly all deep wells in the Stockton Formation are open to several water-bearing zones in different lithologic units and thus are multiaquifer wells. Each water-bearing zone usually has a different hydraulic head. The hydraulic head in a deep, openhole well is the composite of the heads in the several water-bearing zones penetrated. This can cause water levels in some wells to be different than water levels in adjacent wells of different depths. Where differences in hydraulic head exist between water-bearing zones, water in the well bore flows under nonpumping conditions in the direction of decreasing head. Wells that connect several water-bearing zones may act as conduits for the transport of contaminants (Sloto, Macchiaroli, and Towle, 1996).

Previous Investigations

The geology and hydrology of the Stockton Formation in southeastern Pennsylvania were described by Rima and others (1962). Sloto, Macchiaroli, and Towle (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 Hatboro Borough and Warminster Township.

Previous studies of the supply wells were conducted by the Earth Technology Corporation for wells SW-1 and SW-2 (Earth Technology Corporation, 1985a), well SW-3 (Earth Technology Corporation, 1988), and well SW-4 (Earth Technology Corporation,1985b). Ground-water studies in Area D by Brown and Root Environmental include a draft feasibility study (Brown and Root Environmental, 1996a) and a focused feasibility study (Brown and Root Environmental, 1996b). Water-quality data for the supply wells and water-level data for observation wells collected as part of this investigation are presented by Brown and Root Environmental (1998).

Well-Numbering System

Two well-identification numbering systems are used in this report to maintain consistency with previous studies. USGS well-identification numbers consist of a county abbreviation prefix followed by a sequentially-assigned number. The prefix BK denotes a well in Bucks County. U.S. Navy well-identification numbers are used for wells at the NAWC. U.S. Navy well-identification numbers begin with the prefix SW. Data for each well are given in table 1, and locations of the wells are shown on figure 2.

Acknowledgments

The authors thank Brown and Root Environmental for providing coordination and field support for pumped water discharge. Charles Meyer of Brown and Root Environmental was especially helpful in the field. Borehole geophysical logging was done by Randall Conger, Kim Moyer, and Philip Bird of the USGS Pennsylvania District. Borehole television surveys were done by Philip Bird. Robert Rosman, Nicholas Smith, and Timothy Oden of the USGS New Jersey District assisted with construction and placement of the straddle packer assembly; their assistance is greatly appreciated.

Table 1. *Construction characteristics of Area D supply wells, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania*

U.S. Navy well-identification number	U.S. Geological Survey well-identification number	Depth drilled (feet)	Depth logged (feet)	Depth of casing (feet)	Estimated land-surface elevation[1] (feet above mean sea level)
SW-1	BK-373	250	242	28	318
SW-2	BK-374	250	242	36	320
SW-3	BK-376	600	560	30	331
SW-4	BK-375	600	542	52	336

[1] Estimated from topographic map.

METHODS OF INVESTIGATION

Borehole Geophysical Methods

Caliper, natural-gamma, single-point-resistance, fluid-resistivity, and fluid-temperature logs were run in the four supply wells in Area D. Borehole television surveys also were run in all four supply wells. Acoustic borehole televiewer and borehole deviation logs were run in supply wells SW-3 and SW-4. No data on depth to water-bearing zones or yield of water-bearing zones were available for the supply wells. The logs were used to locate water-bearing fractures, determine probable zones of vertical borehole-fluid movement, and determine the depth to set packers.

Caliper logs provide a continuous record of average borehole diameter, which is related to fractures, lithology, and drilling technique. Caliper logs were used to help correlate lithostratigraphy and 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.

Natural-gamma logs, also called gamma-ray logs, record the natural-gamma radiation emitted from rocks penetrated by the borehole. Gamma radiation can be measured through casing, but the gamma response is dampened. 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 may be concentrated in clay by adsorption and ion exchange; therefore, fine-grained sedimentary rocks (siltstone units) usually emit more gamma radiation than do coarse-grained sedimentary rocks (sandstone units). Natural-gamma logs were used to differentiate between sandstone (sandy) and siltstone (silty) units and for lithostratigraphic correlation.

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 fluid (Keys, 1990). A fluid-filled borehole is required for single-point-resistance logs, and they are run only for the saturated part of the formation below the casing. Single-point-resistance logs sometimes help to identify the location of water-bearing zones because a fluid-filled fracture is less resistive than solid rock.

Fluid-temperature logs provide a continuous record of the temperature of the fluid 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 were identified by sharp changes in temperature, and intervals of vertical borehole flow were identified by little or no temperature gradient.

Fluid-resistivity logs measure the electrical resistance of fluid in the borehole. Resistivity is the reciprocal of fluid conductivity, and fluid-resistivity logs reflect changes in the dissolved-solids concentration of the borehole fluid. Fluid-resistivity 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 were identified by sharp changes

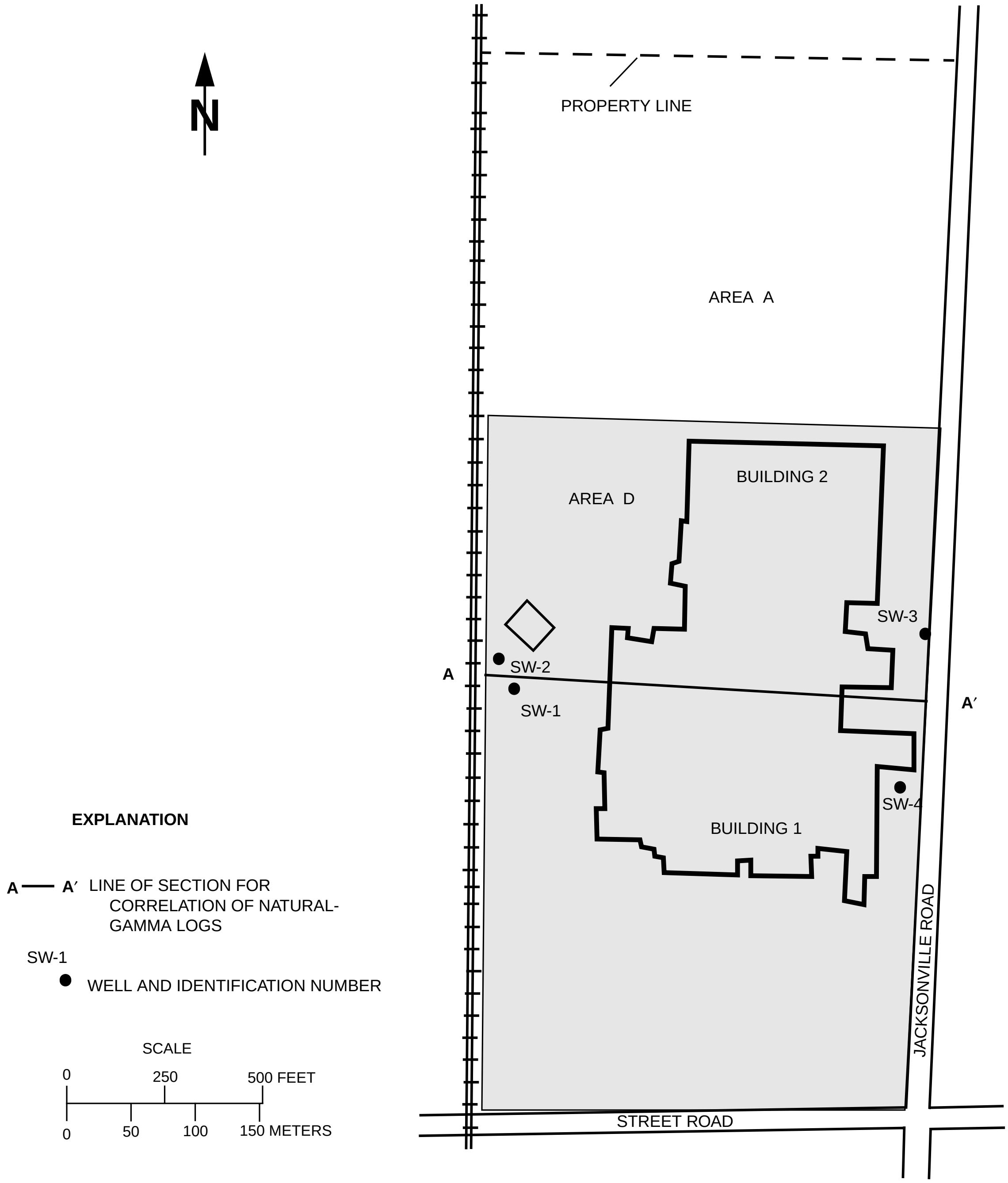


Figure 2. Location of Area D supply wells, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania.

in resistivity, and intervals of borehole flow were identified by a low resistivity gradient between water-producing and water-receiving zones.

The acoustic borehole televiewer log is a magnetically oriented, 360-degree, photograph-like image of the acoustic reflectivity of the borehole wall. The acoustic televiewer is an ultrasonic imaging tool operating at a frequency of about 1 megahertz that scans the borehole wall with an acoustic beam generated by a rapidly pulsed piezoelectric source rotating at about 3 revolutions per second as the tool is moved up the borehole. Digital images from the televiewer are recorded by the computer collecting logging data. A smooth and hard borehole wall produces a uniform pattern of reflectivity. The intersection of a fracture with the borehole wall scatters the acoustic waves, producing a dark, linear feature on the image. Because the image is magnetically oriented, the dip and strike of the fracture can be determined.

Borehole deviation logs, also called dipmeter logs, record the deviation of a borehole from true vertical. Deviation of boreholes from the vertical is common, and deviation logs are used to calculate true vertical depth of features of interest and to correct the strike and dip of fractures or bedding obtained from acoustic televiewer logs.

Borehole television surveys produce a 360-degree, color optical image of the borehole wall recorded on video tape. The borehole television survey is made by lowering a waterproof camera down the borehole. The borehole television survey allows direct viewing of fractures, bedding, grain size, texture, and other features. The borehole television surveys were used to locate smooth sections of borehole for setting packers.

Measurement of Vertical Borehole Flow

The direction and rate of borehole-fluid movement were measured with a high-resolution heatpulse flowmeter. The heatpulse flowmeter operates by diverting nearly all flow to the center of the tool where a heating grid slightly heats a thin zone of water. If vertical borehole flow is occurring, the water moves up or down the borehole to one of two sensitive thermistors (heat sensors). When a peak temperature is recorded by one of the thermistors, a measurement of direction and rate is calculated by the computer collecting the logging data. The range of flow measurement is about 0.01-1.5 gal/min in a 2- to 8-in.-diameter borehole. Heatpulse-flowmeter measurements may be influenced 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 fluid-producing zones.

Hydraulic Tests

An aquifer test and several aquifer-isolation tests were conducted in each supply well. Prior to borehole geophysical logging and hydraulic tests, pumps were removed by contractors for Brown and Root Environmental. Pumps were first removed from wells SW-1 and SW-2 and replaced on completion of all tests. Pumps were then removed from wells SW-3 and SW-4. Water samples were collected from the supply wells for chemical analysis, and water levels in nearby wells were monitored by Brown and Root Environmental. The water-quality and water-level data are presented by Brown and Root Environmental (1998).

Water levels for aquifer tests and aquifer-isolation tests were initially determined by electric measuring tapes. Land-surface datum is used as a reference for all water-level measurements in this report. During hydraulic tests, measurements of water levels and barometric pressure were made by calibrated pressure transducers and recorded by a digital data logger. The transducers were set in measurement tubes open to the intervals being monitored. The accuracy of the transducer in the isolated interval was ± 0.06 ft. The accuracy of the transducers used in the intervals above and below the isolated interval and in the observation well was ± 0.03 ft.

Water levels were recorded in linear time increments for pre-test trends, packer inflation and deflation, and post-test trends. Water levels were recorded in logarithmic time increments at the beginning of pumping, when discharge rates were changed during stepped tests, and for recovery when pumping stopped. Water-level data were collected before, during, and after aquifer and aquifer-isolation tests. Calibrated, in-line flowmeters were used to measure discharge.

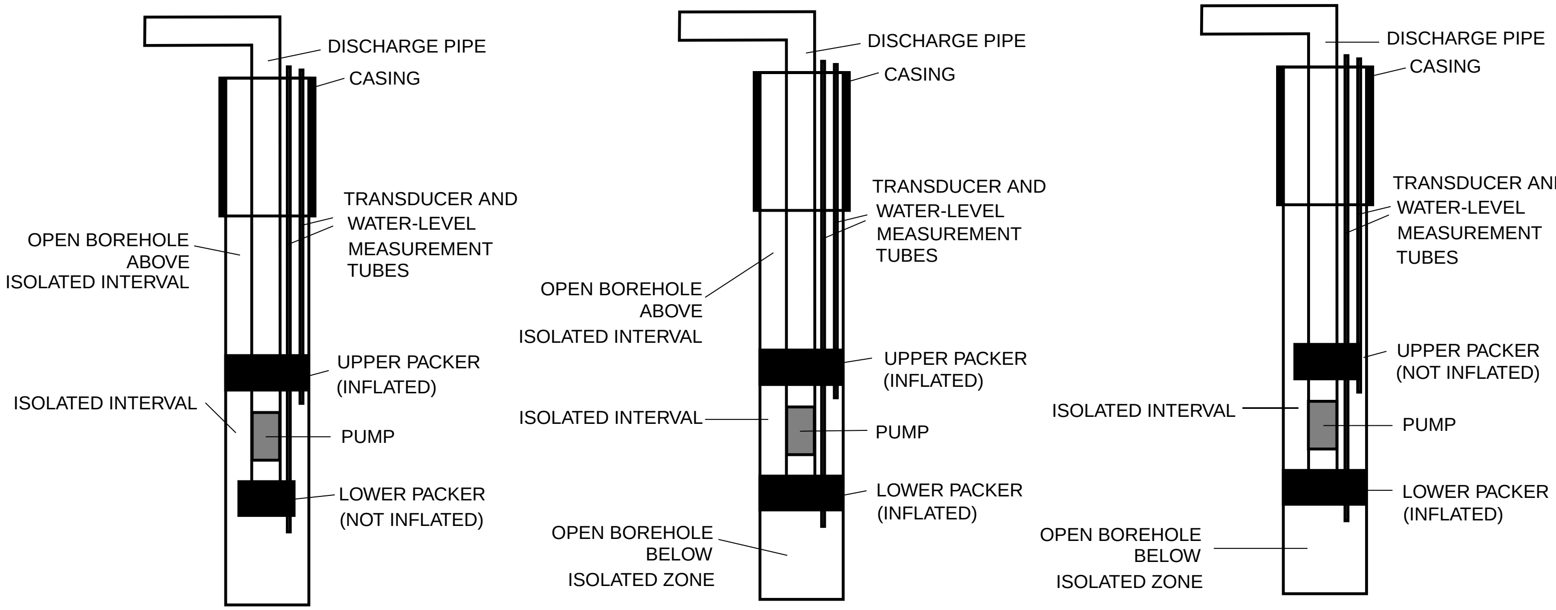
An aquifer test was conducted in each supply well to determine the effect of pumping the open borehole on water levels in nearby wells and to obtain a water sample for chemical analysis. For the aquifer tests, wells SW-1 and SW-2 were pumped by use of a 5-horsepower pump at the maximum possible discharge rate for 6 hours. Well SW-3 was pumped at a rate of 15.3 gal/min for 164 minutes. A stepped test was conducted for well SW-4, which was pumped for 6.1 hours at rates up to 58.4 gal/min, the maximum pump discharge. The maximum pumping rate varied for each well because of differences in discharge pipe length and equipment assembly. For the tests of wells SW-1 and SW-2, pumped water was piped 0.3 mi to the existing treatment plant. For the tests of wells SW-3 and SW-4, pumped water was discharged to a nearby storm sewer.

Aquifer-isolation tests, commonly known as packer tests, were conducted in each supply well. Because ground water in the Stockton Formation moves through discrete fractures or fracture zones, the hydraulic characteristics and chemical quality of water in each fracture or fracture zone can differ. These differences were characterized by isolating discrete fractures or fracture zones by use of a straddle-packer assembly to determine depth-discrete specific capacities, obtain depth-discrete water samples, and to determine the effect of pumping an individual fracture or fracture zone on water levels in nearby wells. The packer assembly consisted of two inflatable rubber bladders (packers) about 4 ft long set on a 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 was varied between 20 and 30 ft. Packer settings given in this report are from the center of the top packer to the center of the bottom packer. Generally, the lowermost interval was tested first, and isolated intervals are numbered in order from the bottom to the top of the well.

On the basis of the borehole geophysical logs, heatpulse-flowmeter measurements, and borehole television surveys, intervals were selected for aquifer-isolation tests. 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 the borehole television surveys. For the test of the lowermost isolated interval (except for well SW-3), only the upper packer was inflated (fig. 3A). For the test of the uppermost isolated interval, only the lower packer was inflated (fig. 3C). For the test of the other intervals, both packers were 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 continuously monitored so that the packers always remained at maximum inflation. Water levels in each interval were measured throughout the tests. Three pressure transducers were used to measure depth to water in the upper, lower, and isolated intervals.

After the packers were inflated, water levels in each interval were allowed to stabilize for approximately 1 hour unless static levels were reached in a shorter amount of time. After water levels stabilized, a step-drawdown test was run. Each isolated interval that produced sufficient water was pumped at two or three pumping rates. During the step-drawdown tests, water levels were recorded above, below, and in the isolated interval. After the pump was shut off, water levels were allowed to recover for approximately 1 hour to collect recovery water-level data before packer deflation.

The specific capacity of each isolated interval was determined by the following method (Sloto, 1997, p. 5). The specific capacity for each step was calculated by dividing the average pumping rate during the step by the total drawdown at the end of the step. The specific capacity of the isolated interval is the mean of the specific capacities of each step in the test of the isolated interval. The aquifer-isolation test for interval 4 in well SW-4 consisted of only one step, and the specific capacity was calculated 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.



A. UPPER PACKER INFLATED **B. BOTH PACKERS INFLATED** **C. LOWER PACKER INFLATED**

NOT TO SCALE

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

SUPPLY WELL SW-1

USGS records dated October 8, 1946, indicated that well SW-1 (USGS well BK-373) was drilled to a depth of 250 ft. Drawdown in the well was 78 ft after pumping at a rate of 176 gal/min for 3 hours; the specific capacity was 2.5 (gal/min)/ft of drawdown.

Interpretation of Borehole Geophysical Logs

A suite of borehole geophysical logs (fig. 4) was run in well SW-1 by the USGS. The caliper log shows that the well is 242 ft deep, 8 in. in diameter, and cased to 28 ft below land surface (bls). The natural-gamma log was used to help correlate lithostratigraphy across the site (fig. 5). Beds on figure 5 are lettered to enable tracing of the beds across the site. The fluid-resistivity log shows a change in resistivity at 34 ft bls. The fluid-temperature log shows changes in temperature at 38, 174, and 230 ft bls. A heatpulse flowmeter was used to measure vertical fluid movement in the well under nonpumping conditions (table 2). The heatpulse-flowmeter measurements showed upward flow at 46, 92, 124, 150, 164, and 233 ft bls and downward flow at 204 and 220 ft bls. The suite of borehole geophysical logs, borehole television survey, and heatpulse-flowmeter measurements indicate that water enters the well through a near-vertical fracture in silty unit C at 170-174 ft bls and flows both upward and downward. Water flows upward at a rate of 0.27 gal/min and exits the borehole through a very large near-vertical fracture in the same unit at 159-164 ft bls (0.1 gal/ min) and through bedding plane fractures in silty unit A at 33-42 ft bls (0.17 gal/min). Water flows downward from the fracture at 170-174 ft bls and a bedding-plane fracture in sandy unit D at 212 ft bls and exits the borehole through a near-vertical fracture in the same unit at 227 ft bls. Water also enters the well from a fracture in silty unit E at 239 ft bls and flows upward where it exits the well through the fracture at 227 ft bls (fig. 4). Water exits the borehole through the fracture at 227 ft bls at a rate of 0.75 gal/min.

Table 2. *Summary of heatpulse-flowmeter measurements made in well SW-1, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania*

Depth (feet below land surface)	Flow rate (gallons per minute)	Flow direction
46	0.15	Up
92	.17	Up
124	.17	Up
150	.17	Up
164	.27	Up
204	.10	Down
220	.30	Down
233	.45	Up

Aquifer Test

An aquifer test was conducted on well SW-1 by the USGS on October 17, 1997. Well SW-1 was pumped at a rate of 53.3 gal/min for 6 hours. On the basis of data from this test, the specific capacity of well SW-1 is 1.5 (gal/min)/ft. Water levels in wells SW-1 and SW-2, which are approximately 90 ft apart, were measured (fig. 6). Drawdown at the end of the test was 36.23 ft for well SW-1 and 12.82 ft for well SW-2, indicating that the wells are hydraulically connected.

Aquifer-Isolation Tests

On the basis of the borehole geophysical logs and heatpulse-flowmeter measurements, five intervals were selected for aquifer-isolation tests (table 3). For the test of the lowermost isolated interval (interval 1), only the upper packer was inflated (fig. 3A). For the test of the uppermost isolated interval (interval 5), only the lower packer was inflated (fig. 3C). For the test of intervals 2, 3, and 4, both packers were inflated (fig. 3B). The quantity of water pumped and specific capacity calculated for each isolated interval are summarized in table 3.

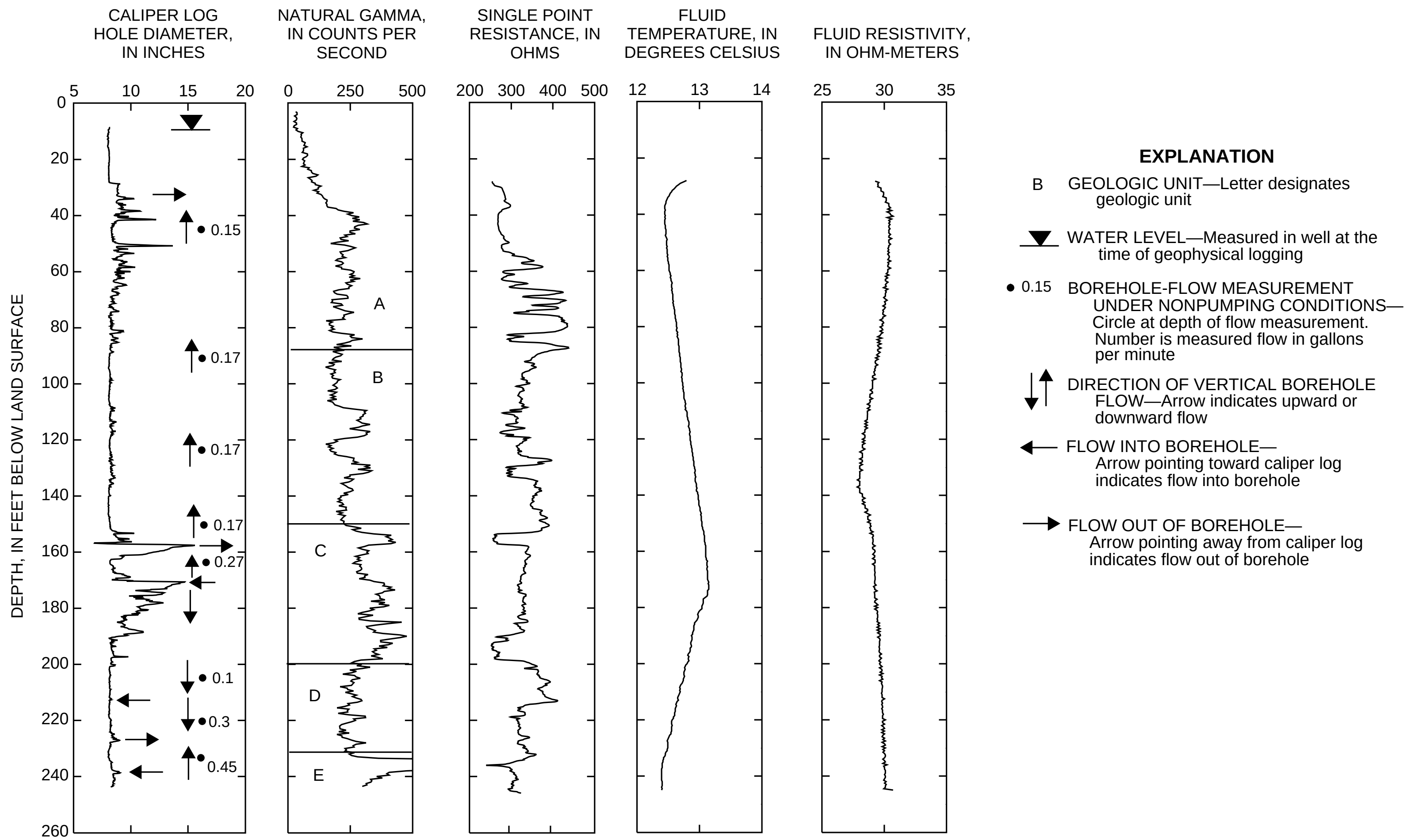


Figure 4. Borehole geophysical logs from well SW-1, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania.

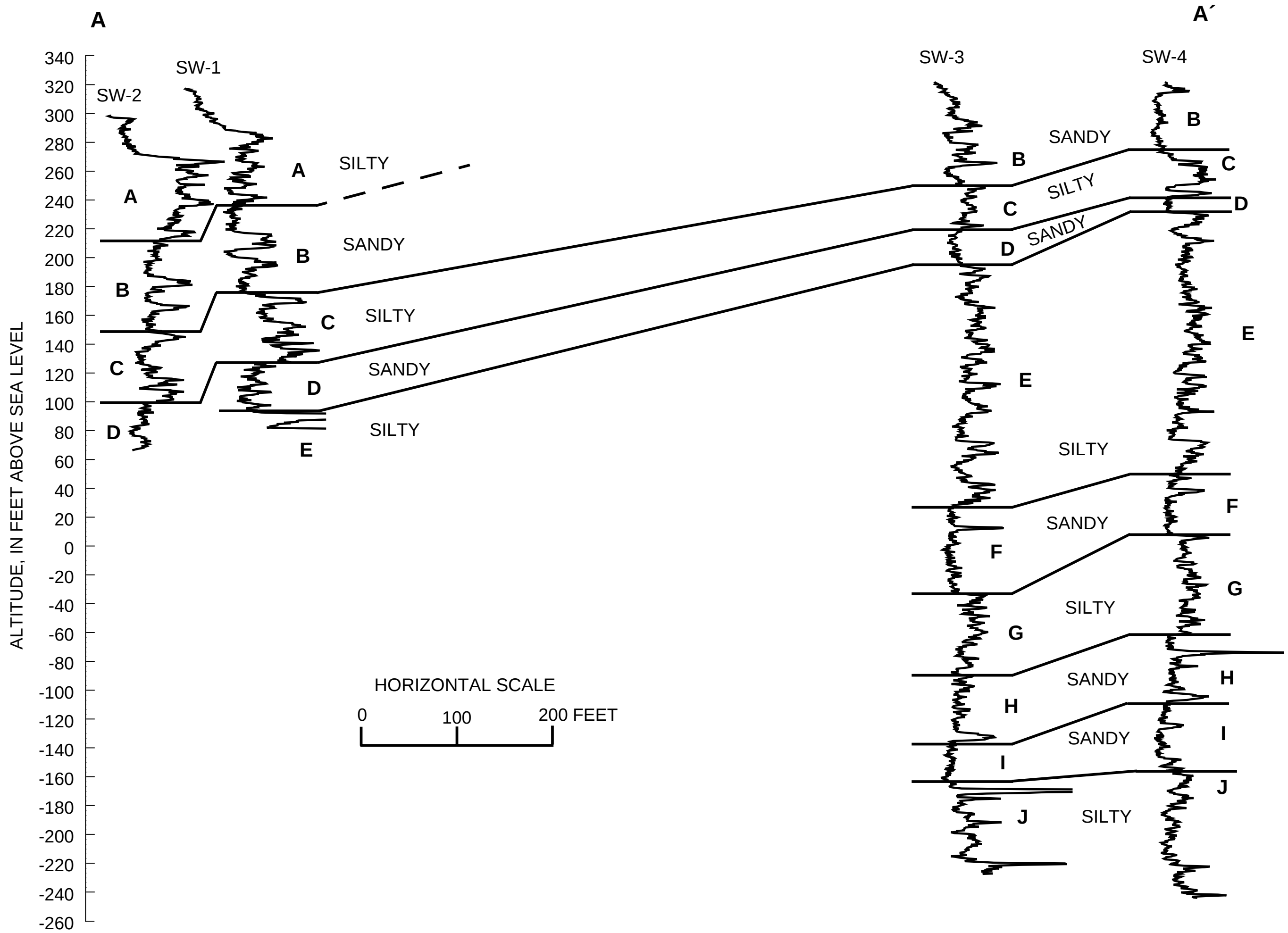


Figure 5. Correlation of natural-gamma logs from supply wells, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania. [The line of section is shown on figure 2.]

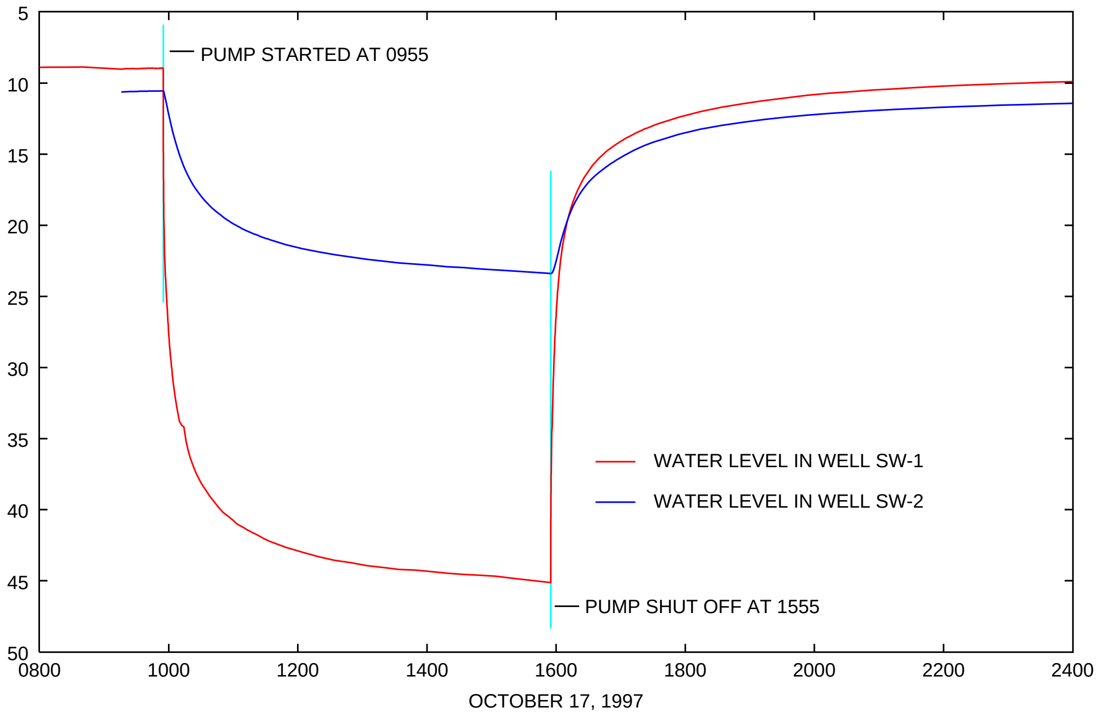


Figure 6. Hydrographs from aquifer test of well SW-1, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania. [The pumping rate was 53.3 gallons per minute.]

Table 3. *Intervals isolated and specific capacities for well SW-1, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania*

[--, insufficient data to calculate specific capacity]

Interval	Isolated depth interval[1] (feet below land surface)	Isolated fracture	Number of steps	Total water pumped (gallons)	Specific capacity (gallons per minute per foot)
1	216-247	Water-producing zone at 239 feet and water-receiving zone at 227 feet	3	498	0.12
2	202-222	Water-producing zone at 212 feet	1	17	--
3	164-194	Water-producing zone at 171 feet	3	1,590	2.3
4	144-164	Water-receiving zone at 158 feet	4	1,374	1.5
5	28-93	Water-receiving zone at 34-40 feet	1	238	--

[1] Center of packer to center of packer.

Aquifer-Isolation Test of Interval 1 (216 to 247 Feet below Land Surface)

For the aquifer-isolation test of interval 1, the center of the upper packer was set at 216 ft bls. Before packer inflation, the depth to water in the open borehole was 9.04 ft bls. Twenty-two minutes after packer inflation, the depth to water in the interval above the packer was 9.01 ft bls, an increase in water level of 0.03 ft, and the depth to water in the interval below the packer was 8.66 ft bls, an increase in water level of 0.38 ft.

The pumping rate for the first step (table 4) varied from a starting rate of 12.6 gal/min to a final rate of 2.4 gal/min; the average rate was 7.9 gal/min. The first step was 15 minutes long. Drawdown in the interval above the packer was 0.55 ft, and drawdown in the pumped interval below the packer was 35.05 ft. For the second step, the pumping rate was increased from 2.4 gal/min at the end of step 1 to 3.3 gal/min. The second step was 30 minutes long. At the end of the second step, the water level in the interval above the packer decreased an additional 0.36 ft, and the water level in the isolated interval decreased an additional 22.49 ft for a total drawdown of 57.30 ft. For the third step, the pumping rate was increased to 6.1 gal/min. The third step was 46 minutes long. At the end of the third step, the water level in the interval above the packer decreased an additional 0.58 ft; total drawdown was 1.49 ft. The water level in the isolated interval below the packer decreased an additional 26.28 ft; total drawdown was 83.58 ft. The specific capacity of interval 1 is 0.12 (gal/min)/ft.

The hydrographs for the intervals above and below the packer indicate a hydraulic connection outside the borehole between the intervals (fig. 7). Drawdown in well SW-2 caused by pumping the interval isolated from 216 to 247 ft bls in well SW-1 was 4.02 ft, indicating a hydraulic connection between the isolated interval and well SW-2.

Aquifer-Isolation Test of Interval 2 (202 to 222 Feet Below Land Surface)

An aquifer-isolation test of interval 2 was begun at 1515 on October 23, 1997. The center of the upper packer was set at 202 ft bls, and the center of the lower packer was set at 222 ft bls. Prior to the start of the test, the depth to water in the upper interval was 9.26 ft bls, depth to water in the isolated interval was 9.25 ft bls, and depth to water in the lower interval was 9.97 ft bls. Depth to water was the same in the upper and isolated intervals and was lower in the lower interval. This is consistent with

Table 4. *Schedule and pumping rates for the aquifer-isolation test of interval 1 (216 to 247 feet below land surface) in well SW-1, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania, October 23, 1997*

Time	Activity
1028	Begin upper packer inflation
1038	Packer inflated
1100	Start pump - step 1, rate decreasing from 12.6 to 2.4 gallons per minute; average rate = 7.9 gallons per minute
1115	Increase pumping rate - step 2, average rate = 3.3 gallons per minute
1145	Increase pumping rate - step 3, average rate = 6.1 gallons per minute
1231	Pump off
1311	Begin packer deflation

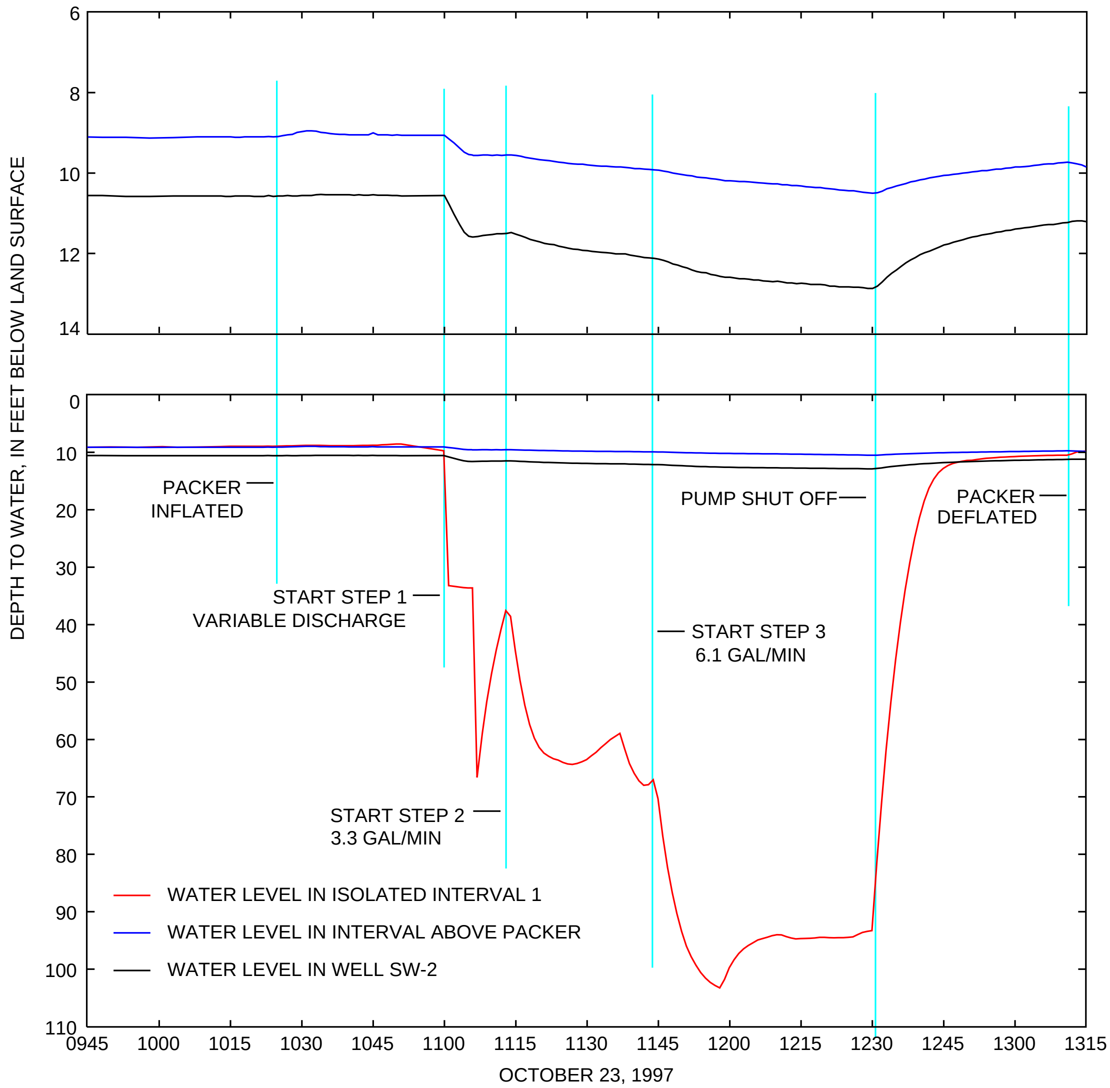


Figure 7. Hydrographs from aquifer-isolation test of interval 1 (216 to 247 feet below land surface) in well SW-1, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania.

the interpretation of the borehole geophysical logs and heatpulse-flowmeter measurements, which showed water moving downward in the borehole from fractures at 170-174 and 212 ft bls and exiting the borehole through a fracture at 227 ft bls.

Interval 2 was pumped for 7 minutes at a rate of 2.4 gal/min. After pumping for 4 minutes, the water level dropped below 106.4 ft bls (drawdown of 96.43 ft), which is where the transducer in the isolated zone was set. At the end of the test, drawdown in the upper interval was 0.08 ft, and drawdown in the lower interval was 0.04 ft. The water level in well SW-2 did not respond to pumping the interval isolated from 202 to 222 ft bls in well SW-1.

Aquifer-Isolation Test of Interval 3 (164 to 194 Feet Below Land Surface)

For the aquifer-isolation test of interval 3, the center of the upper packer was set at 164 ft bls, and the center of the lower packer was set at 194 ft bls. Prior to the start of the test, the depth to water in the upper interval was 7.86 ft bls, depth to water in the isolated interval was 7.70 ft bls, and depth to water in the lower interval was 8.55 ft bls. Depth to water was least in the isolated interval, indicating that this interval had the highest hydraulic head. This is consistent with the interpretation of the borehole geophysical logs and heatpulse-flowmeter measurements, which showed water moving into the borehole from a fracture at 170-174 ft bls and flowing both upward and downward.

The average pumping rate for the first step (table 5) was 9.8 gal/min. The first step was 32 minutes long. Drawdown in the upper interval was 3.72 ft, drawdown in the isolated interval was 3.74 ft, and drawdown in the lower interval was 1.86 ft. For the second step, the pumping rate was increased to 15.4 gal/min. The second step was 31 minutes long. At the end of the second step, the water level in the upper interval decreased an additional 2.03 ft, the water level in the isolated interval decreased an additional 1.98 ft for a total drawdown of 5.70 ft, and the water level in the lower interval decreased an additional 1.09 ft. For the third step, the pumping rate was increased to 16.4 gal/min, the maximum pump capacity. The third step was 44 minutes long. At the end of the third step, the water level in the upper interval decreased an additional 1.88 ft; total drawdown in the upper interval was 7.65 ft. The water level in the isolated interval decreased an additional 2.90 ft; total drawdown in the isolated interval was 8.60 ft. The water level in the lower interval decreased an additional 1.35 ft; total drawdown in the lower interval was 4.30 ft. The specific capacity of interval 3 is 2.3 (gal/min)/ft.

The hydrographs for the intervals above and below the packer indicate a strong hydraulic connection outside the borehole between the isolated interval and the intervals above and below the isolated interval (fig. 8). Drawdown in well SW-2 caused by pumping the interval isolated from 164 to 194 ft bls in well SW-1 was 7.55 ft, indicating a strong hydraulic connection between the isolated interval and well SW-2.

Aquifer-Isolation Test of Interval 4 (144-164 Feet Below Land Surface)

For the aquifer-isolation test of interval 4, the center of the upper packer was set at 144 ft bls, and the center of the lower packer was set at 164 ft bls. The water level in the lower zone had not stabilized and was still declining at the start of the test. At the start of the test, the depth to water in the upper and isolated intervals was 9.09 ft bls, and the depth to water in the lower interval was 9.85 ft bls.

The average pumping rate for the first step (table 6) was 5.1 gal/min. The first step was 7 minutes long. Drawdown in the upper interval was 1.04 ft, drawdown in the isolated interval was 1.68 ft, and drawdown in the lower interval was 0.39 ft. For the second step, the pumping rate was increased to 10 gal/min. The second step was 30 minutes long. At the end of the second step, the water level in the upper interval decreased an additional 2.26 ft, the water level in the isolated interval decreased an additional 4.24 ft for a total drawdown of 5.93 ft, and the water level in the lower interval decreased an additional 1.09 ft. For the third step, the pumping rate was increased to 15.5 gal/min. The third step was 33 minutes long. At the end of the third step, the water level in the upper interval decreased an additional 2.24 ft, the water level in the isolated interval decreased an additional 4.74 ft

Table 5. *Schedule and pumping rates for the aquifer-isolation test of interval 3 (164 to 194 feet below land surface) in well SW-1, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania, October 28, 1997*

Time	Activity
0948	Begin upper packer inflation
0950	Packers inflated
1050	Start pump - step 1, average rate = 9.8 gallons per minute
1122	Increase pumping rate - step 2, average rate = 15.4 gallons per minute
1153	Increase pumping rate - step 3, average rate = 16.4 gallons per minute
1237	Pump off

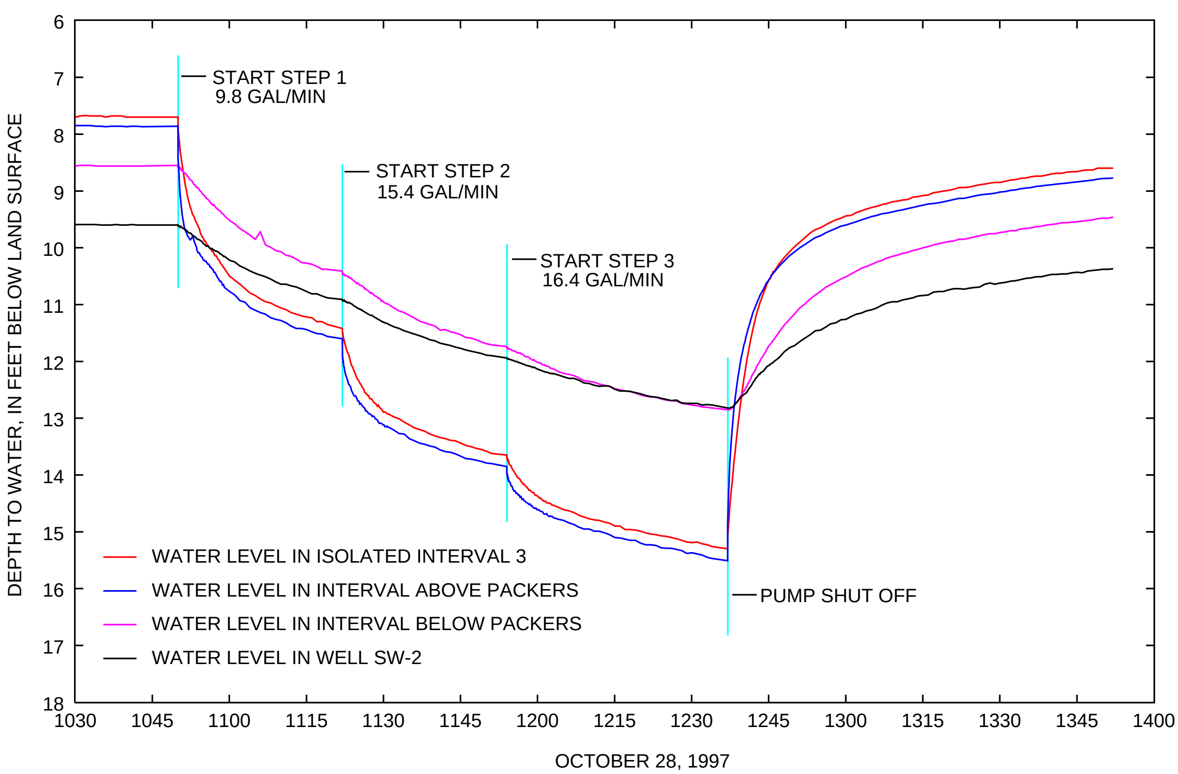


Figure 8. Hydrographs from aquifer-isolation test of interval 3 (164 to 194 feet below land surface) in well SW-1, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania.

Table 6. *Schedule and pumping rates for the aquifer-isolation test of interval 4 (144 to 164 feet below land surface) in well SW-1, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania, October 24, 1997*

Time	Activity
1027	Begin upper packer inflation
1045	Packers inflated
1115	Start pump - step 1, average rate = 5.1 gallons per minute
1122	Increase pumping rate - step 2, average rate = 10.0 gallons per minute
1152	Increase pumping rate - step 3, average rate = 15.5 gallons per minute
1225	Increase pumping rate - step 4, average rate = 16.5 gallons per minute
1258	Pump off
1400	Begin packer deflation

for a total drawdown of 10.67 ft, and the water level in the lower interval decreased an additional 0.54 ft. For the fourth step, the pumping rate was increased to 16.5 gal/min, the maximum pump capacity. The fourth step was 33 minutes long. At the end of the fourth step, the water level in the upper interval decreased an additional 1.03 ft; total drawdown in the upper interval was 6.57 ft. The water level in the isolated interval decreased an additional 1.95 ft; total drawdown in the isolated interval was 12.61 ft. The water level in the lower interval decreased an additional 0.34 ft; total drawdown in the lower interval was 2.35 ft. The specific capacity of interval 4 is 1.5 (gal/min)/ft. Step 1 of the test was not used to calculate the specific capacity because of its short duration.

The hydrographs for the intervals above and below the packer indicate a strong hydraulic connection outside of the borehole between the isolated interval and the upper interval and no hydraulic connection outside of the borehole between the isolated interval and the lower interval (fig. 9). Drawdown in well SW-2 caused by pumping the interval isolated from 144 to 164 ft bls in well SW-1 was 2.33 ft, indicating a strong hydraulic connection between the isolated interval and well SW-2.

Aquifer-Isolation Test of Interval 5 (28 to 93 Feet Below Land Surface)

For the aquifer-isolation test of interval 5, only the lower packer was inflated; the center of the lower packer was set at 93 ft bls. Prior to the start of the test, the depth to water in the interval above the packer was 11.80 ft bls, and the depth to water in the interval below the packer was 9.5 ft bls. Depth to water was higher in the interval below the packer than in the interval above it. This is consistent with the interpretation of the borehole geophysical logs and heatpulse-flowmeter measurements, which showed that water moving up the borehole exits the borehole through water-receiving fractures at 33-42 ft bls.

Interval 5 was pumped beginning at 1650 on October 24, 1997, for 22 minutes at a rate of 9.7 gal/min and for 9 minutes at a rate of 4.3 gal/min before the interval was pumped dry. The water level recovered slowly; during the first 6 hours of recovery, inflow to the well was approximately 0.4 gal/min. The water level in well SW-2 did not respond to pumping the interval isolated from 28 to 93 ft bls in well SW-1.

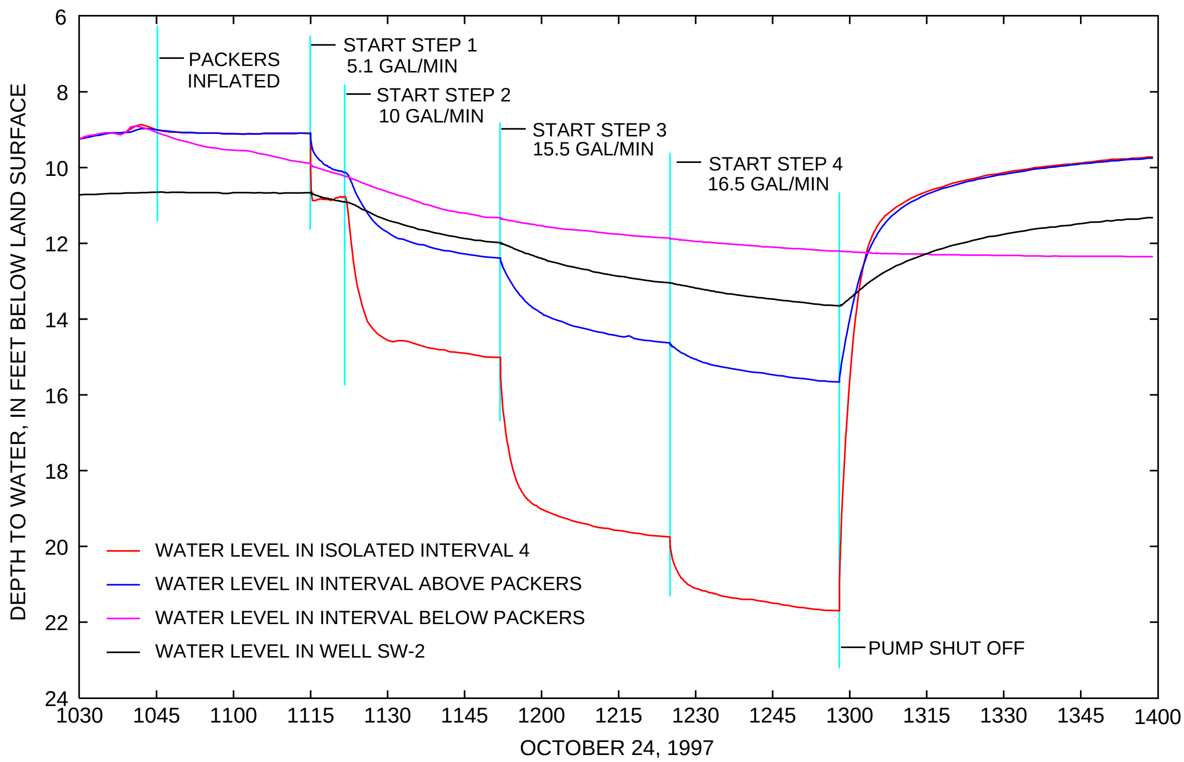


Figure 9. Hydrographs from aquifer-isolation test of interval 4 (144 to 164 feet below land surface) in well SW-1, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania.

SUPPLY WELL SW-2

USGS records dated October 8, 1946, indicated that well SW-2 (USGS well BK-374) was drilled to a depth of 250 ft. Drawdown in the well was 18 ft after pumping at a rate of 134 gal/min for 8 hours; the specific capacity was 7.4 (gal/min)/ft.

Interpretation of Borehole Geophysical Logs

A suite of borehole geophysical logs (fig. 10) was run in well SW-2 by the USGS. The caliper log shows that the well is 242 ft deep, 8 in. in diameter, and cased to 36 ft bls. The fluid-resistivity log shows changes in resistivity at 162 and 234 ft bls. The fluid-temperature log shows changes in temperature at 162 and 232 ft bls. A heatpulse flowmeter was used to measure vertical fluid movement in the well under nonpumping conditions. Heatpulse-flowmeter measurements made at 52, 114, 134, 150, 176, 194, and 219 ft bls showed upward flow at 1.2 gal/min at all depths. The suite of borehole geophysical logs, borehole television survey, and heatpulse-flowmeter measurements indicate that water enters the well through a near vertical fracture in sandy unit D at 230-238 ft bls, flows upward at a rate of 1.2 gal/min, and exits the borehole through a near vertical fracture in silty unit A at 39-44 ft bls (fig. 10). The fluid-resistivity log indicates that some water may enter the well through a fracture at 160-165 ft bls in silty unit C.

Aquifer Test

An aquifer test was conducted on October 29, 1997. Well SW-2 was pumped at a rate of 64.3 gal/min for 6 hours. On the basis of data from this aquifer test, the specific capacity of well SW-2 is 1.4 (gal/ min)/ft. Water levels in wells SW-1 and SW-2 were measured (fig. 11). Drawdown at the end of the test was 46.36 ft for well SW-2 and 14.95 ft for well SW-1, indicating that the wells are hydraulically connected.

Aquifer-Isolation Tests

On the basis of the borehole geophysical logs and heatpulse-flowmeter measurements, four intervals were selected for aquifer-isolation tests (table 7). For the test of the lowermost isolated interval (interval 1), only the upper packer was inflated (fig. 3A). For the test of the uppermost isolated interval (interval 4), only the lower packer was inflated (fig. 3C). For the test of intervals 2 and 3, both packers were inflated (fig. 3B). The quantity of water pumped and specific capacity calculated for each isolated interval are summarized in table 7.

Aquifer-Isolation Test of Interval 1 (212 to 242 Feet below Land Surface)

For the aquifer-isolation test of interval 1, the center of the upper packer was set at 212 ft bls. Only the upper packer was inflated. Before packer inflation, the depth to water in the open borehole was 9.61 ft bls. Fifty-five minutes after packer inflation, the depth to water in the interval above the packer was 11.77 ft bls, a decrease in water level of 2.16 ft, and the depth to water in the interval below the packer was 8.13 ft bls, an increase in water level of 1.48 ft. This is consistent with the interpretation of the borehole geophysical logs and upward borehole flow shown by the heatpulse-flowmeter measurements, which indicate that the isolated water-producing fracture at 230-238 ft bls has a higher head than the water-receiving fractures above it.

The average pumping rate for the first step (table 8) was 5.4 gal/min. The first step was 45 minutes long. Drawdown in the interval above the packer was 0.26 ft, and drawdown in the pumped interval below the packer was 3.94 ft. For the second step, the pumping rate was increased to 11.8 gal/min. The second step was 32 minutes long. At the end of the second step, the water level in the interval above the packer decreased an additional 0.32 ft, and the water level in the isolated interval decreased an additional 4.97 ft for a total drawdown of 8.91 ft. For the third step, the pumping rate was increased to 24.3 gal/min, the maximum pumping rate. The third step was 32 minutes long. At the end of the third step, the water level in the interval above the packer decreased an additional 0.71 ft; total drawdown was 1.29 ft. The water level in the isolated interval below the packer decreased an additional 11.18 ft; total drawdown was 20.09 ft. The specific capacity of interval 1 is 1.3 (gal/min)/ft.

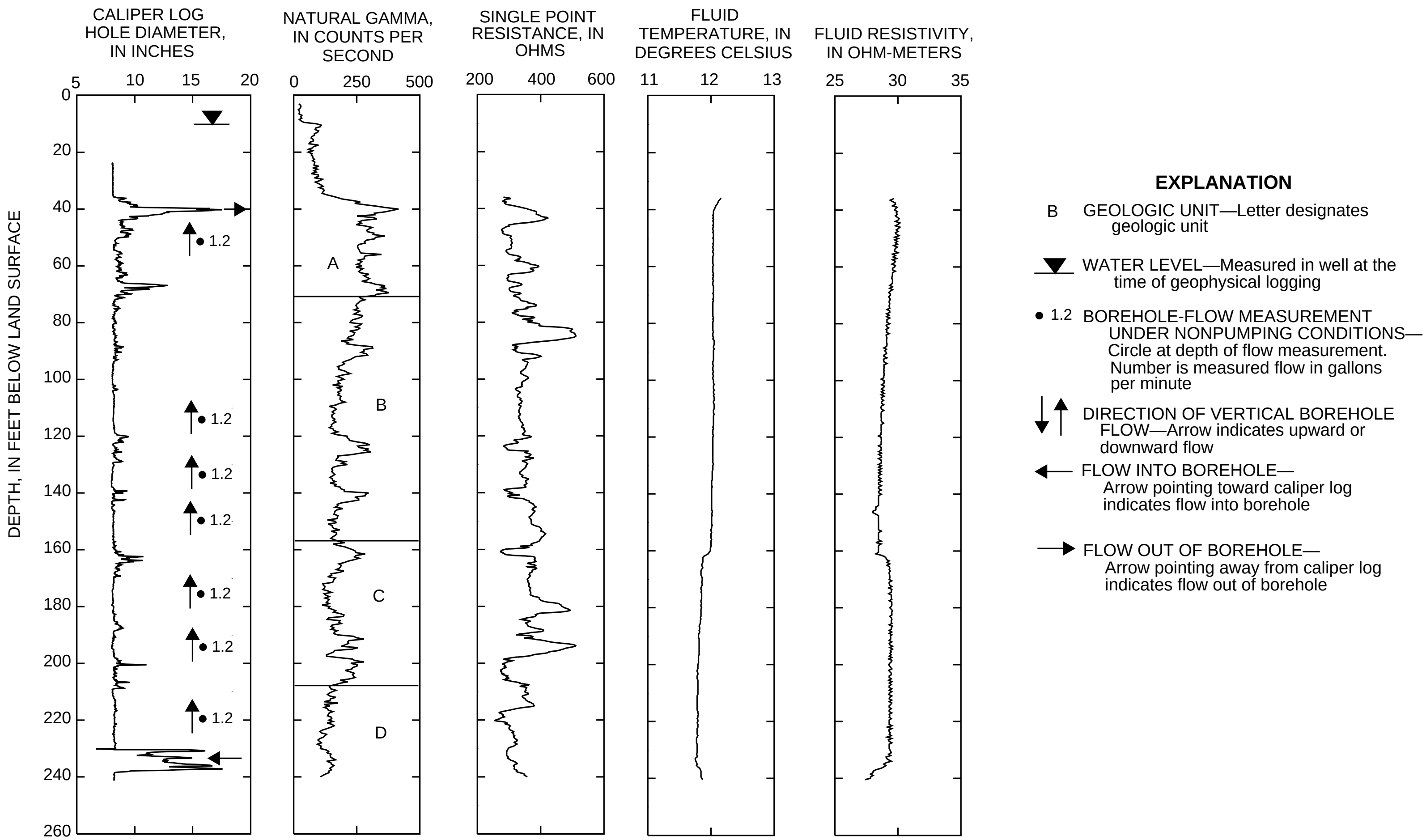


Figure 10. Borehole geophysical logs from well SW-2, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania.

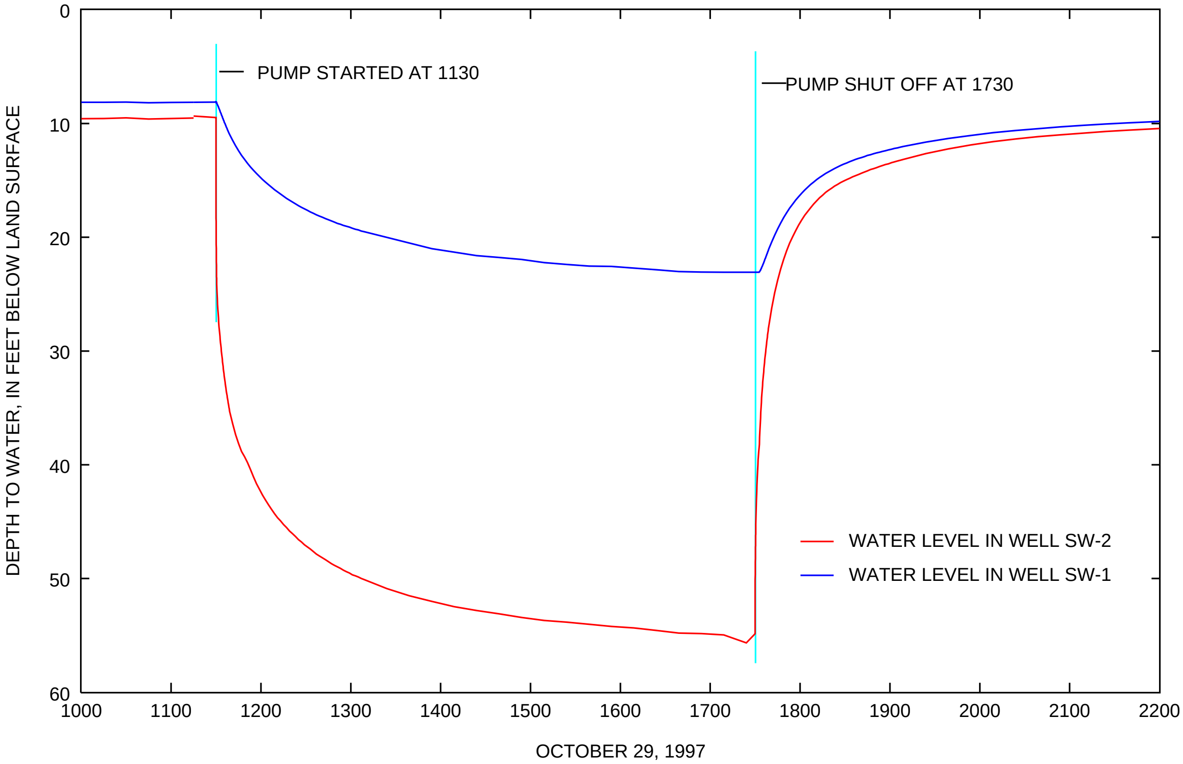


Figure 11. Hydrographs from aquifer test of well SW-2, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania. [The pumping rate was 64.3 gallons per minute.]

Table 7. *Intervals isolated and specific capacities for well SW-2, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania*
[--, insufficient data to calculate specific capacity]

Interval	Isolated depth interval[1] (feet below land surface)	Isolated fracture	Number of steps	Total water pumped (gallons)	Specific capacity (gallons per minute per foot)
1	212-242	Water-producing zone at 230-238 feet	3	1,421	1.3
2	192-212	Possible water-producing zone at 202 feet	1	19.8	--
3	154-174	Possible water-producing zone at 160-165 feet	3	977	.26
4	36-98	Water-receiving zone at 39-44 feet	3	1,299	.71

[1] Center of packer to center of packer.

Table 8. *Schedule and pumping rates for the aquifer-isolation test of interval 1 (212 to 242 feet below land surface) in well SW-2, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania, October 31, 1997*

Time	Activity
1020	Begin upper packer inflation
1102	Packer inflated
1200	Start pump - step 1, average rate = 5.4 gallons per minute
1245	Increase pumping rate - step 2, average rate = 11.8 gallons per minute
1317	Increase pumping rate - step 3, average rate = 24.3 gallons per minute
1349	Pump off
1447	Begin packer deflation

The hydrographs for the intervals above and below the packer indicate a hydraulic connection outside the borehole between the intervals (fig. 12). Drawdown in well SW-1 caused by pumping the interval isolated from 212 to 242 ft bls in well SW-2 was 1.24 ft, indicating a hydraulic connection between the isolated interval and well SW-1.

Aquifer-Isolation Test of Interval 2 (192 to 212 Feet Below Land Surface)

Interval 2 was chosen on the basis of a previous aquifer-isolation test conducted by the Earth Technology Corporation (1985a). The borehole geophysical logs did not indicate that this interval contained a water-producing or water-receiving zone. The Earth Technology Corporation isolated the interval from 188 to 208 ft bls and pumped 7 gal/min of water for approximately 2 hours (Earth Technology Corporation, 1985a). Their report does not indicate that water levels were monitored to determine a good packer seal.

For the aquifer-isolation test of interval 2, the center of the upper packer was set at 192 ft bls, and the center of the lower packer was set at 212 ft bls. The packers were left inflated for 3 days before the start of the test. Prior to the start of the test, the depth to water in the upper interval was 11.13 ft bls, depth to water in the isolated interval was 9.45 ft bls, and depth to water in the lower interval was 7.39 ft bls. Depth to water in the upper and isolated zones was lower than in the lower interval. This is consistent with the interpretation of the borehole geophysical logs and upward borehole flow shown by the heatpulse-flowmeter measurements, which indicate that the isolated water-producing fracture at 230-238 ft bls has a higher head than the water-receiving fractures above it.

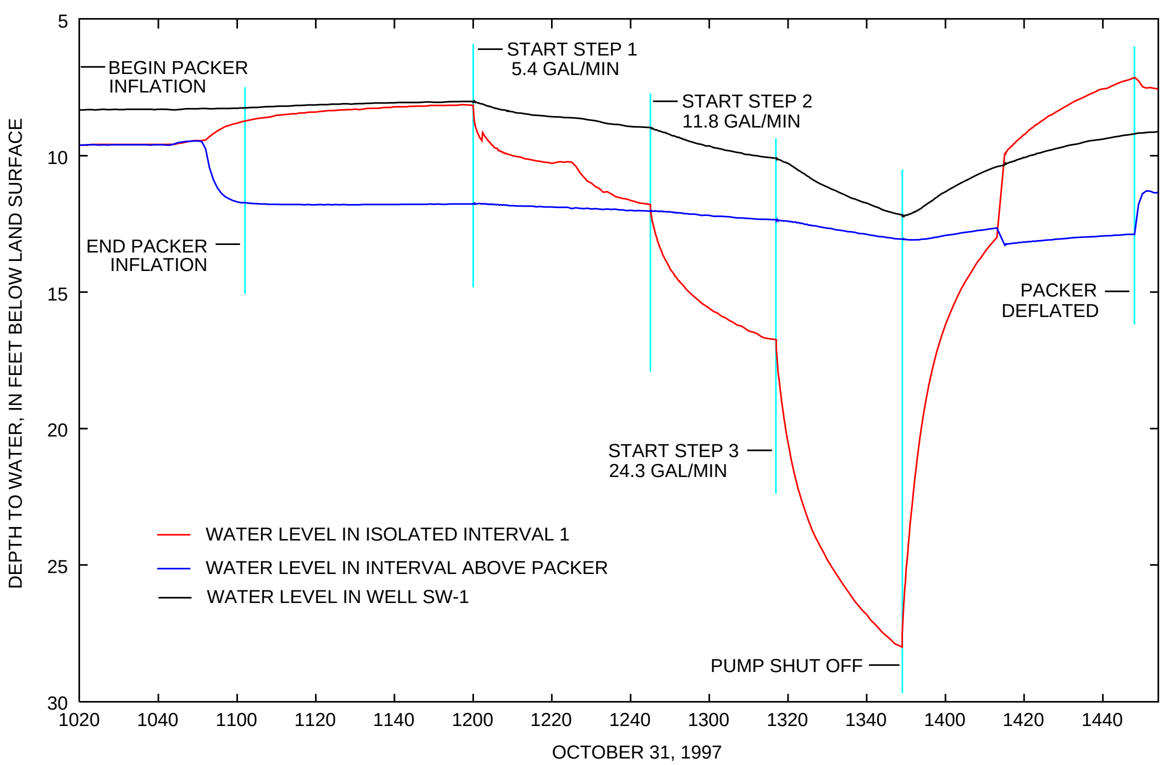


Figure 12. Hydrographs from aquifer-isolation test of interval 1 (212 to 242 feet below land surface) in well SW-2, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania.

Interval 2 was pumped for 4 minutes at a rate of 4.8 gal/min beginning at 0817 on November 3, 1997. The water level dropped below 108.91 ft bls (drawdown of 99.46 ft), which is where the transducer in the isolated zone was set. At the end of the test, drawdown in the upper interval was 0.01 ft, and drawdown in the lower interval was 0.04 ft. The water level in well SW-1 decreased by 0.19 ft in response to pumping the interval isolated from 192 to 212 ft bls in well SW-2, indicating a hydraulic connection.

Aquifer-Isolation Test of Interval 3 (154 to 174 Feet Below Land Surface)

For the aquifer-isolation test of interval 3, the center of the upper packer was set at 154 ft bls, and the center of the lower packer was set at 174 ft bls. Prior to packer inflation, depth to water was 8.98 ft bls. Twenty-seven minutes after packer inflation, depth to water in the upper interval was 13.46 ft bls, a decrease of 4.48 ft; depth to water in the isolated interval was 8.06 ft bls, an increase of 0.92 ft; and depth to water in the lower interval was 7.74 ft bls, an increase of 1.24 ft. This is consistent with the interpretation of the borehole geophysical logs and upward borehole flow shown by the heat-pulse-flowmeter measurements, which indicate that the isolated water-producing fracture at 230-238 ft bls has a higher head than the water-receiving fractures above it.

The average pumping rate for the first step (table 9) was 5.8 gal/min. The first step was 32 minutes long. Drawdown in the upper interval was 0.11 ft, drawdown in the isolated interval was 17.68 ft, and drawdown in the lower interval was 0.39 ft. For the second step, the pumping rate was increased to 10.9 gal/min. The second step was 31 minutes long. At the end of the second step, the water level in the upper interval decreased an additional 0.11 ft, the water level in the isolated interval decreased an additional 22.18 ft for a total drawdown of 39.86 ft, and the water level in the lower interval decreased an additional 0.71 ft. For the third step, the pumping rate was increased to 16.1 gal/min. The third step was 32 minutes long. At the end of the third step, the water level in the upper interval decreased an additional 0.22 ft; total drawdown in the upper interval was 0.44 ft. The water level in the isolated interval decreased an additional 45.97 ft; total drawdown in the isolated interval was 85.83 ft. The water level in the lower interval decreased an additional 1.69 ft; total drawdown in the lower interval was 2.79 ft. The specific capacity of interval 3 is 0.26 (gal/min)/ft.

Table 9. *Schedule and pumping rates for the aquifer-isolation test of interval 3 (154 to 174 feet below land surface) in well SW-2, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania, November 3, 1997*

Time	Activity
1050	Begin packer inflation
1113	Packers inflated
1140	Start pump - step 1, average rate = 5.8 gallons per minute
1211	Increase pumping rate - step 2, average rate = 10.9 gallons per minute
1243	Increase pumping rate - step 3, average rate = 16.1 gallons per minute
1315	Pump off
1349	Begin packer deflation

The hydrographs for the intervals above and below the packer indicate little connection between the isolated interval and the upper interval and a weak hydraulic connection outside of the borehole between the lower interval and the isolated interval (fig. 13). Drawdown in well SW-1 caused by pumping the interval isolated from 154 to 174 ft bls in well SW-2 was 2.53 ft, indicating a hydraulic connection between the isolated interval and well SW-1. Drawdowns in the lower interval and well SW-1 were similar.

Aquifer-Isolation Test of Interval 4 (36-98 Feet Below Land Surface)

For the aquifer-isolation test of interval 4, only the lower packer was inflated; the center of the lower packer was set at 98 ft bls. Prior to packer inflation, depth to water in well SW-2 was 9.04 ft bls. Forty-one minutes after packer inflation, depth to water in the upper interval was 13.98 ft bls, a decrease of 4.85 ft, and depth to water in the lower interval was 7.88 ft bls, an increase of 1.16 ft. This is consistent with the interpretation of the borehole geophysical logs and upward borehole flow shown by the heat-pulse-flowmeter measurements, which indicate that

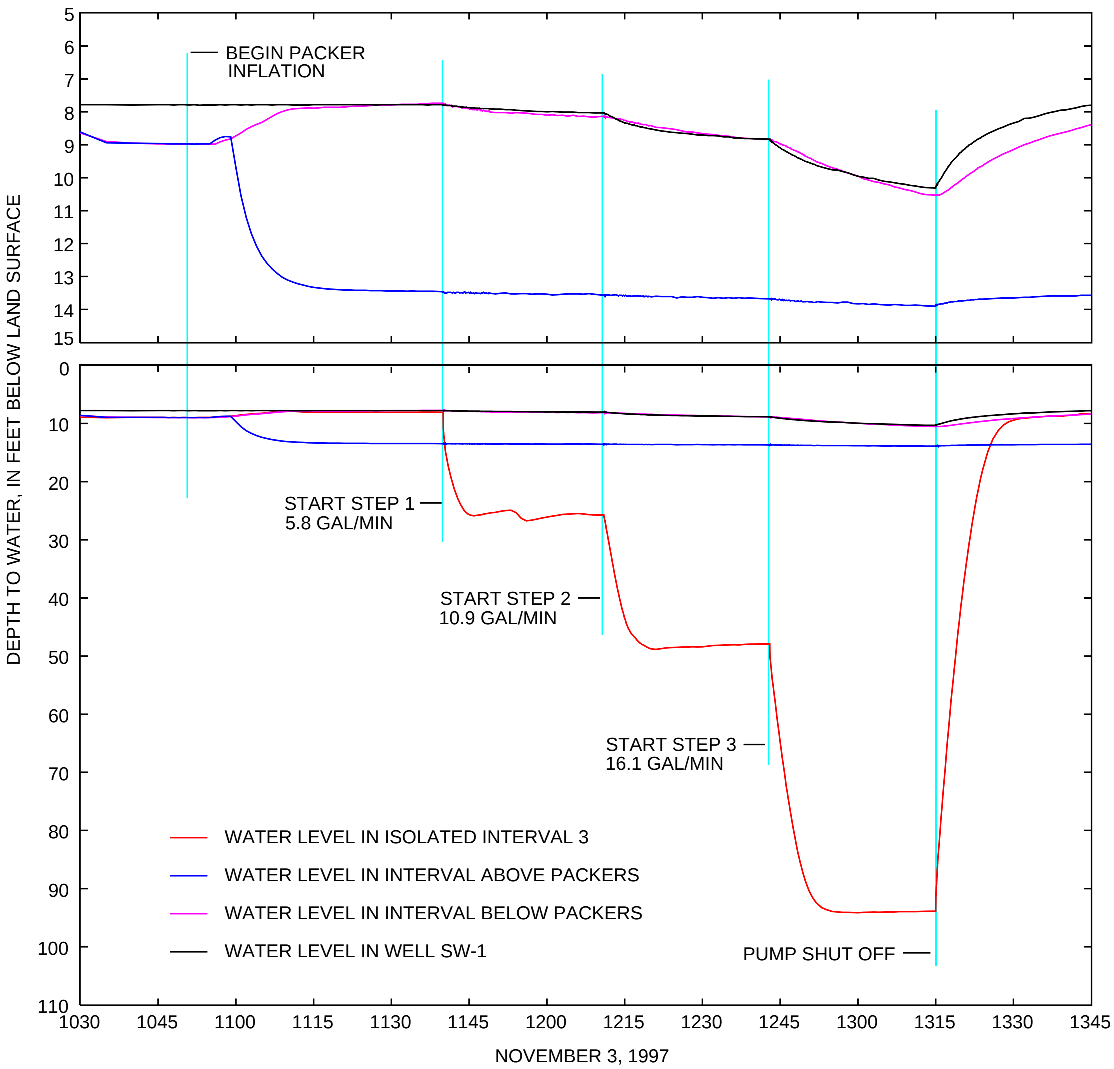


Figure 13. Hydrographs from aquifer-isolation test of interval 3 (154 to 174 feet below land surface) in well SW-2, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania.

the isolated water-producing fracture at 230-238 ft bls has a higher head than the water-receiving fractures above it. The water level in the lower interval was still rising at the start of the test.

The average pumping rate for the first step (table 10) was 5 gal/min. The first step was 30 minutes long. Drawdown in the upper interval was 5.06 ft, and the water level in the lower interval increased 0.1 ft. For the second step, the pumping rate was increased to 11.2 gal/min. The second step was 33 minutes long. At the end of the second step, the water level in the upper interval decreased an additional 8.04 ft for a total drawdown of 13.98 ft, and the water level in the lower interval decreased 0.04 ft. For the third step, the pumping rate was increased to 23.6 gal/min, the maximum pump capacity. The third step was 33 minutes long. At the end of the third step, the water level in the upper interval decreased an additional 39.2 ft; total drawdown in the upper interval was 52.3 ft. The water level in the lower interval decreased an additional 0.01 ft. The specific capacity of interval 4 is 0.71 (gal/ min)/ft. After cessation of pumping, well SW-2 recovered at a rate of 12 gal/min.

Table 10. *Schedule and pumping rates for the aquifer-isolation test of interval 4 (36 to 98 feet below land surface) in well SW-2, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania, November 3, 1997*

Time	Activity
1538	Begin lower packer inflation
1546	Packer inflated
1627	Start pump - step 1, average rate = 5.0 gallons per minute
1657	Increase pumping rate - step 2, average rate = 11.2 gallons per minute
1730	Increase pumping rate - step 3, average rate = 23.6 gallons per minute
1803	Pump off
--	Packer left inflated overnight

The hydrographs for the intervals above and below the packer indicate little hydraulic connection between the upper and lower intervals (fig. 14). Well SW-1 was flowing throughout the test, and, therefore, the hydrograph for well SW-1 is not shown on figure 14. Well SW-1 is in a pit equipped with a sump pump, and the top of casing of well SW-1 is 7.7 ft bls.

SUPPLY WELL SW-3

USGS records dated October 8, 1946, indicated that well SW-3 (USGS well BK-376) was drilled to a depth of 600 ft. Drawdown in the well was 101 ft after pumping at a rate of 152.5 gal/min for 8 hours; the specific capacity was 1.5 (gal/min)/ft.

Interpretation of Borehole Geophysical Logs

A suite of borehole geophysical logs (fig. 15) was run in well SW-3 by the USGS. The caliper log shows that the well is 560 ft deep, 8 in. in diameter, and cased to 30 ft bls. The fluid-resistivity log shows changes in resistivity at 61, 90, and 190 ft bls and indicates the well is filled with sediment below 549 ft bls. The fluid-temperature log shows changes in temperature at 90, 428, and about 552 ft bls. A heatpulse flowmeter was used to measure vertical fluid movement in the well under nonpumping conditions (table 11). The heatpulse-flowmeter measurements showed downward flow at 101, 120, 155, 205, 250, 354, 470, and 486 ft bls and no flow at 510 ft bls. The rate of flow was near the upper limit of the tool, and the rate of downward flow is probably about 1.2 gal/min at all depths where it was measured. The suite of borehole geophysical logs, borehole television survey, and heatpulse-flowmeter measurements indicate that water enters the well through a near vertical fracture (dip of 57° N. 29° E. and strike of N. 61° W.) in sandy unit B at 60 ft bls and a horizontal fracture (dip of 28° east-west and strike of north-south) in silty unit C at 89 ft bls and flows downward at a rate of approximately 1.2 gal/min. Water exits the borehole through a vertical fracture (N. 48° E. and strike N. 42° W.) in silty unit J at 491-496 bls (fig. 15) and probably at greater depth. A possible water-producing or water-receiving zone may be present at 428 ft bls.

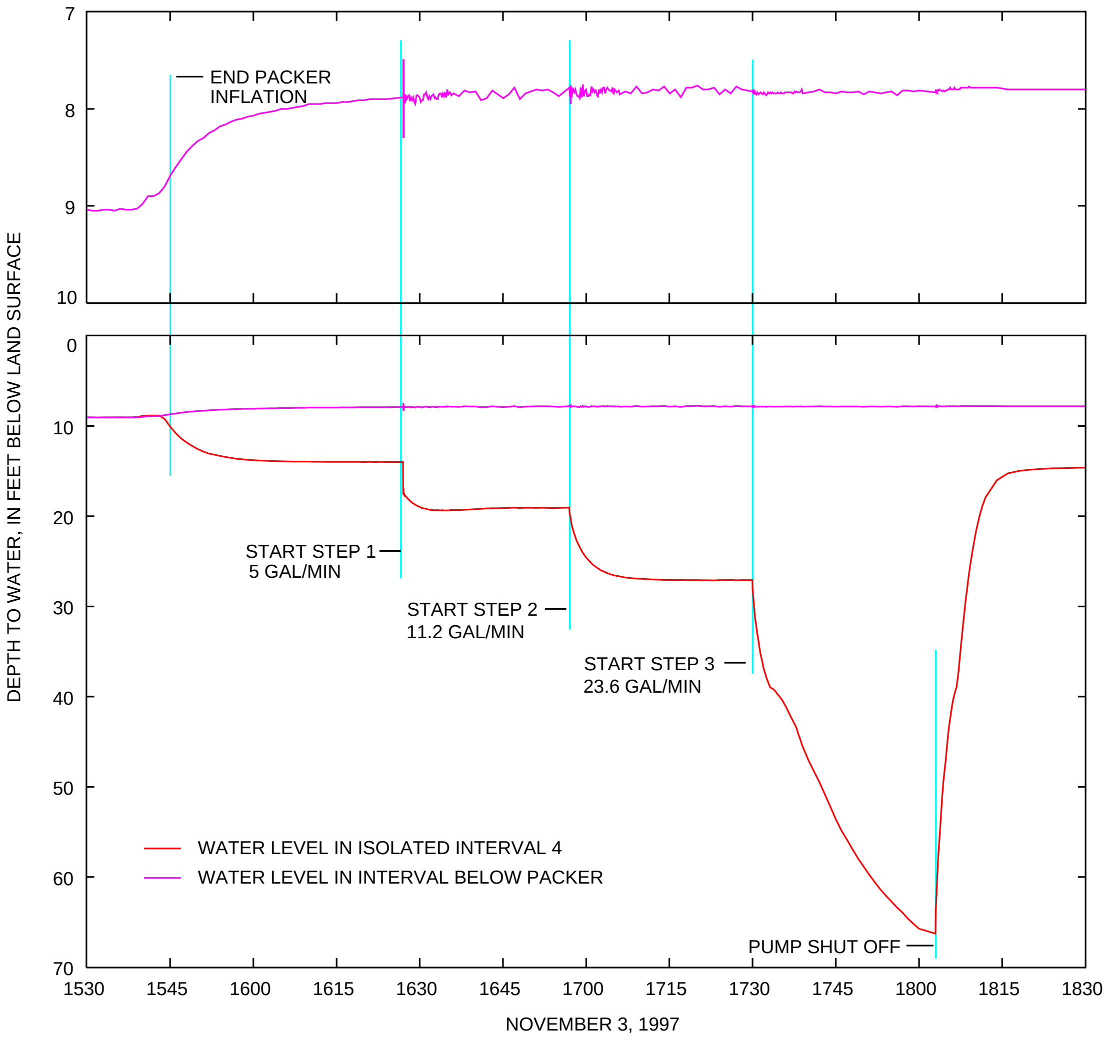


Figure 14. Hydrographs from aquifer-isolation test of interval 4 (36 to 98 feet below land surface) in well SW-2, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania.

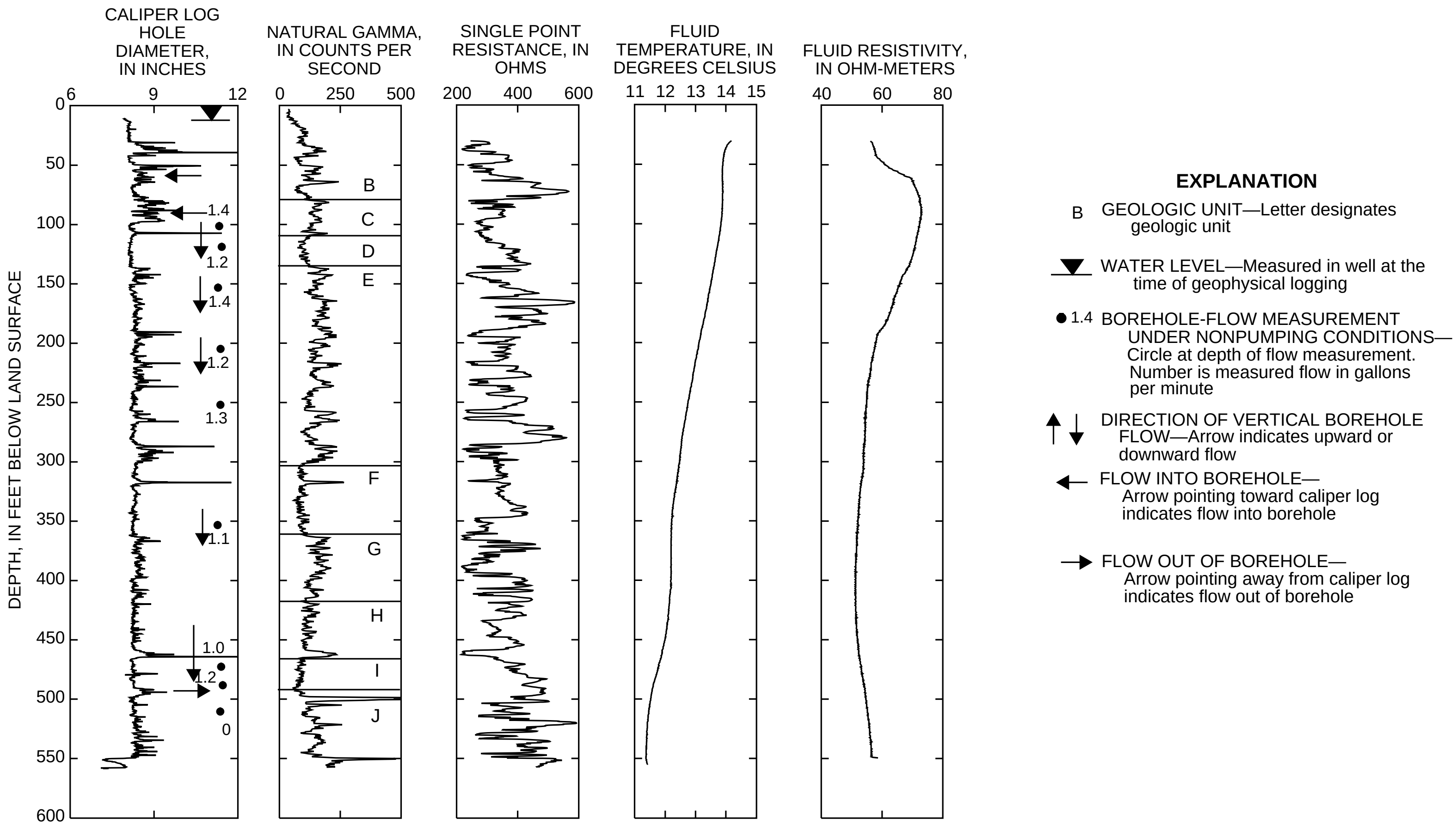


Figure 15. Borehole geophysical logs from well SW-3, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania.

Table 11. *Summary of heatpulse-flowmeter measurements made in well SW-3, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania*

Depth (feet below land surface)	Flow rate (gallons per minute)	Flow direction
101	1.4	Down
120	1.2	Down
155	1.4	Down
205	1.2	Down
250	1.3	Down
354	1.1	Down
470	1.0	Down
486	1.2	Down
510	0	--

Acoustic televiewer and borehole deviation logs were run in well SW-3. The borehole deviation log (fig. 16) shows that the bottom of well SW-3 is 11.8 ft S. 19° E. of the top of the well. Orientations were identified for 19 bedding-plane features, 23 near-horizontal fractures, and 17 near-vertical to vertical fractures on the acoustic televiewer log. The median orientation for bedding-plane features is a dip of 18° N. 85° E. and a strike of N. 6° W., for near-horizontal fractures a dip of 27° N. 73° W. and a strike of N. 17° E., and for near-vertical to vertical fractures a dip of 85° N. 32° E. and a strike of N. 58° W.

Aquifer Test

An aquifer test was conducted by the USGS on November 12, 1997. Well SW-3 was initially pumped at a rate of 74.3 gal/min; however, after 2 minutes the drawdown was greater than 107.27 ft bls, the depth at which the transducer was set. The test was

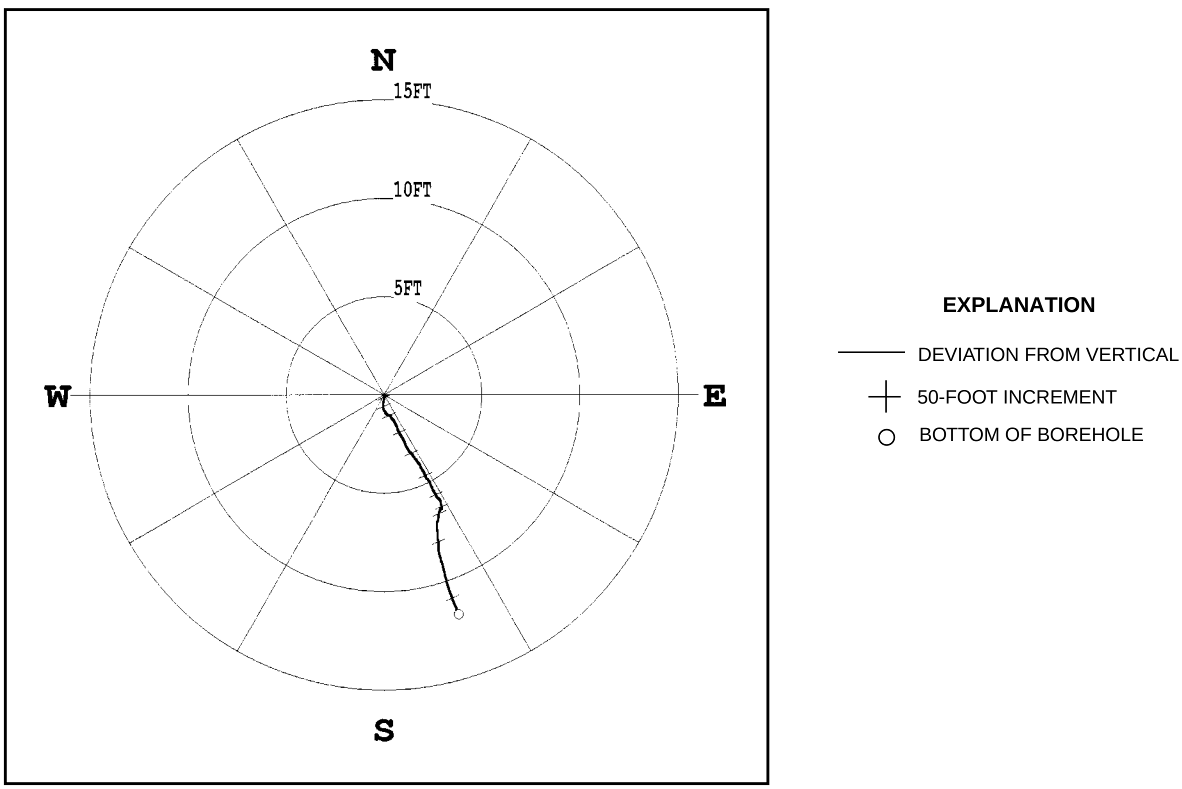


Figure 16. Deviation log of well SW-3, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania.

stopped after 7 minutes, and the water level was allowed to recover. A second test was conducted later in the day at an average rate of 15.3 gal/min for 164 minutes. After 45 minutes of pumping, the water level began to recover because of development of the well, and after 118 minutes of pumping, the discharge was increased slightly.

On the basis of data from the second test, the specific capacity of well SW-3 is 0.21 (gal/min)/ft. Water levels in wells SW-3 and SW-4, which are approximately 393 ft apart, were measured (fig. 17). Drawdown at the end of the test was 73.79 ft for well SW-3 and 0.34 ft for well SW-4, which indicates a weak hydraulic connection between the wells.

Aquifer-Isolation Tests

On the basis of the borehole geophysical logs and heatpulse-flowmeter measurements, three intervals were selected for aquifer-isolation tests (table 12). For the test of intervals 1 and 2, both packers were inflated (fig. 3B). For the test of the uppermost isolated interval (interval 3), only the lower packer was inflated (fig. 3C). The quantity of water pumped and specific capacity calculated for each isolated interval are summarized in table 12.

Aquifer-Isolation Test of Interval 1 (488 to 508 Feet below Land Surface)

For the aquifer-isolation test of interval 1, the center of the upper packer was set at 488 ft bls, and the center of the lower packer was set at 508 ft bls. Before packer inflation, the depth to water in the open borehole was 11.05 ft bls. Forty-eight minutes after packer inflation, the depth to water in the interval above the upper packer had stabilized at 10.81 ft bls, an increase in water level of 0.24 ft. When the packers were inflated, the isolated interval became pressurized causing the water level to rise; the water level subsequently dropped. The water level in the isolated interval was at 9.68 ft bls and was declining at the rate of approximately 0.1 ft/min at the start of the test. Depth to water in the lower interval was 59.24 ft bls, a decrease of 48.19 ft; the water level was still dropping at the start of the test (fig. 18).

Interval 1 was pumped for 11 minutes at an average rate of 4.5 gal/min beginning at 1353 on December 2, 1997. After 11 minutes, the water level was at 116.31 ft bls (drawdown of 106.63 ft), at which time the test was stopped just before the water level reached the transducer. At the end of the test, drawdown in the upper interval was 7.43 ft, indicating that the isolated interval in the well is hydraulically connected outside of the borehole to the upper interval. The water level in the lower zone continued to decline during and after the test; the water level stabilized at 61.26 ft bls before packer deflation, a decline of 50.21 ft. The water level in well SW-4 did not respond to pumping the interval isolated from 488 to 508 ft bls in well SW-3.

Aquifer-Isolation Test of Interval 2 (419 to 439 Feet Below Land Surface)

For the aquifer-isolation test of interval 2, the center of the upper packer was set at 419 ft bls, and the center of the lower packer was set at 439 ft bls. Before packer inflation, the depth to water in the open borehole was 11.03 ft bls. Eighty-five minutes after packer inflation, the depth to water in the interval above the packer had stabilized at 10.93 ft bls, an increase in water level of 0.1 ft. When the packers were inflated, the isolated interval became pressurized causing the water level to rise; the water level subsequently dropped. The water level in the isolated interval was at 6.63 ft bls and was declining at the rate of approximately 0.05 ft/min at the start of the test. Depth to water in the lower interval was 59.99 ft bls, a decrease of 48.96 ft; the water level was still dropping at the start of the test (fig. 19). This is consistent with the interpretation of the borehole geophysical logs and downward borehole flow shown by the heatpulse-flowmeter measurements, which indicate that the water-producing fractures at 60 and 89 ft bls have a higher head than the water-receiving fractures below them.

Interval 2 was pumped for 2.7 minutes at a rate of 4.3 gal/min beginning at 1128 on December 3, 1997. After pumping for 2 minutes, the water level dropped below 125.2 ft bls (drawdown of 119.31 ft), the depth at which the transducer in the isolated zone was set. The water level in the lower zone continued to decline during and after the test; the water level stabilized at 60.95 ft bls before packer deflation, a decline of 49.92 ft. Water levels in the upper zone and in well SW-4 did not respond to pumping the interval isolated from 419 to 439 ft bls in well SW-3.

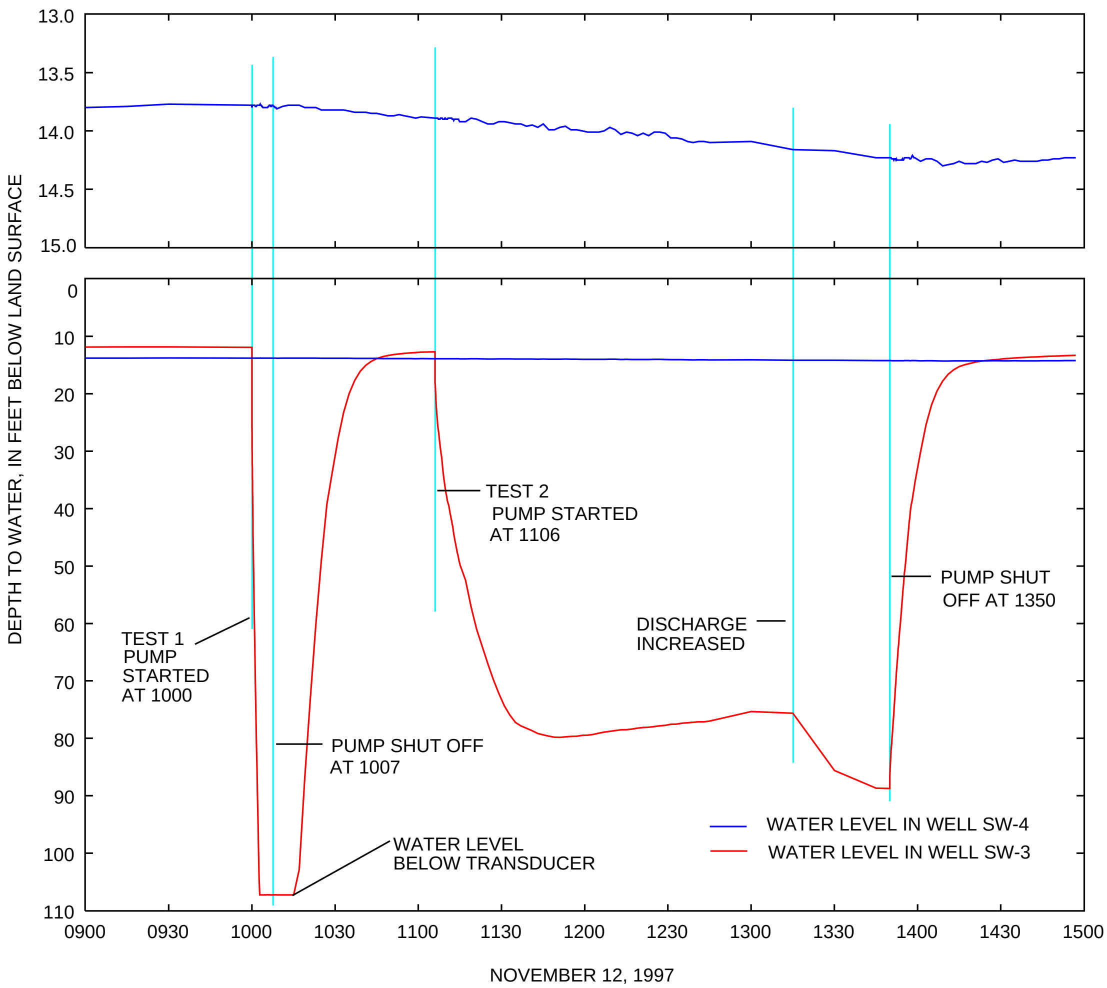


Figure 17. Hydrographs from aquifer test of well SW-3, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania. [The average pumping rate was 15.3 gallons per minute.]

Table 12. *Intervals isolated and specific capacity for well SW-3, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania*
[--, insufficient data to calculate specific capacity]

Interval	Isolated depth interval[1] (feet below land surace)	Isolated fracture	Number of steps	Total water pumped (gallons)	Specific capacity (gallons per minute per foot)
1	488-508	Water-receiving zone at 491-498 ft	1	11.5	--
2	419-439	Possible water-receiving zone at 428 ft	1	49	--
3	30-101	Water-producing zone at 58-62 ft	4	1,410	0.38

[1] Center of packer to center of packer.

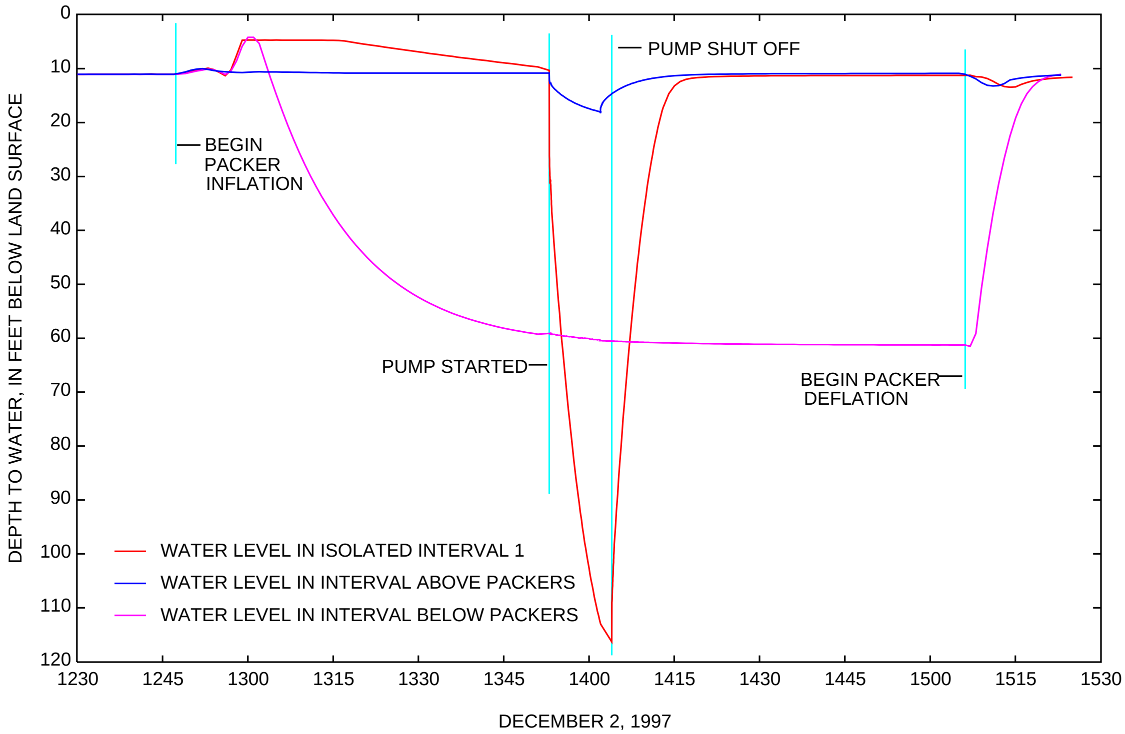


Figure 18. Hydrographs from aquifer-isolation test of interval 1 (488 to 508 feet below land surface) in well SW-3, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania.

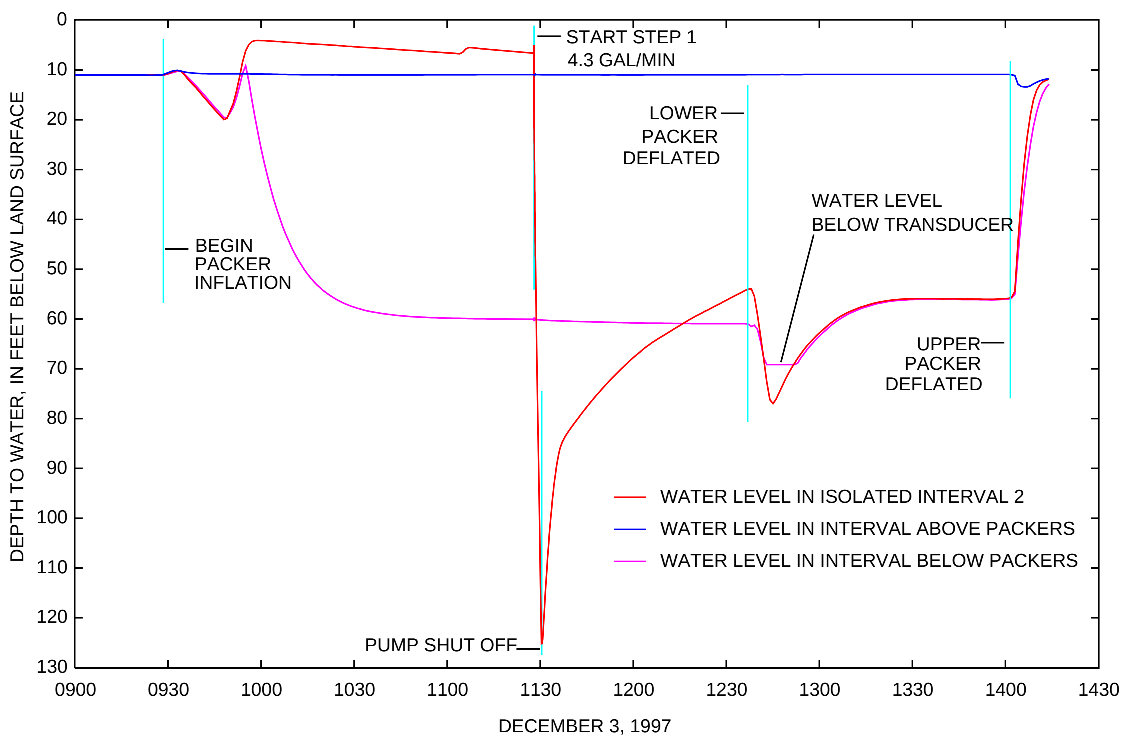


Figure 19. Hydrographs from aquifer-isolation test of interval 2 (419 to 439 feet below land surface) in well SW-3, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania.

Aquifer-Isolation Test of Interval 3 (30 to 101 Feet Below Land Surface)

For the aquifer-isolation test of interval 3, only the lower packer was inflated; the center of the lower packer was set at 101 ft bls. Before packer inflation, the depth to water in the open borehole was 11.72 ft bls. The packer was left inflated overnight. Twenty-three hours after packer inflation, the depth to water in the interval above the packer was 11.20 ft bls, an increase in water level of 0.52 ft. Depth to water in the lower interval was 16.11 ft bls, a decrease of 4.39 ft (fig. 20). This is consistent with the interpretation of the borehole geophysical logs and downward borehole flow shown by the heat-pulse-flowmeter measurements, which indicate that the water-producing fractures at 60 and 89 ft bls have a higher head than the water-receiving fractures below them.

The average pumping rate for the first step (table 13) was 4.4 gal/min. The first step was 34 minutes long. Drawdown in the upper interval was 8.72 ft, and drawdown in the lower interval was 0.06 ft. For the second step, the pumping rate was increased to 8.6 gal/min. The second step was 38 minutes long. At the end of the second step, the water level in the upper interval decreased an additional 13.08 ft for a total drawdown of 21.8 ft, and the water level in the lower interval decreased an additional 0.01 ft. For the third step, the pumping rate was increased to 11.3 gal/min. The third step was 35 minutes long. At the end of the third step, the water level in the upper interval decreased an additional 10.75 ft for a total drawdown of 32.55 ft, and the water level in the lower interval decreased an additional 0.02 ft. For the fourth step, the pumping rate was increased to 13.8 gal/min. The fourth step

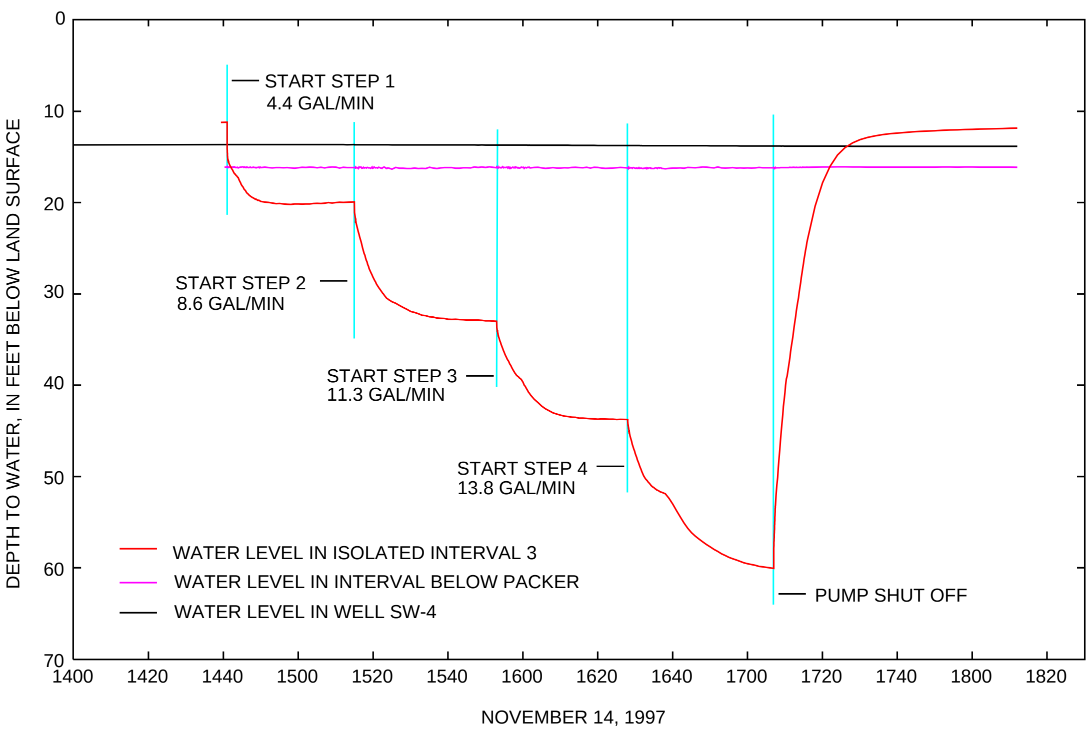


Figure 20. Hydrographs from aquifer-isolation test of interval 3 (30 to 101 feet below land surface) in well SW-3, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania.

was 33 minutes long. At the end of the fourth step, the water level in the upper interval decreased an additional 16.31 ft; total drawdown in the upper interval was 48.86 ft. The water level in the lower interval did not change; total drawdown in the lower interval was 0.09 ft. The specific capacity of interval 3 is 0.38 (gal/ min)/ft.

The hydrographs for the intervals above and below the packer (fig. 20) indicate no hydraulic connection between the upper and lower intervals. Drawdown in well SW-4 caused by pumping the interval isolated from 30 to 101 ft bls in well SW-3 was 0.14 ft; however, the water level in well SW-4 continued to decline after cessation of pumping, indicating no hydraulic connection between the isolated interval and well SW-4. For the first 30 minutes after cessation of pumping, interval 3 recovered at the rate of 4.1 gal/min.

Table 13. *Schedule and pumping rates for the aquifer-isolation test of interval 3 (30 to 101 feet below land surface) in well SW-3, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania, November 14, 1997*

Time	Activity
	Packer inflated at 1532 on November 13
1441	Start pump - step 1, average rate = 4.4 gallons per minute
1515	Increase pumping rate - step 2, average rate = 8.6 gallons per minute
1553	Increase pumping rate - step 3, average rate = 11.3 gallons per minute
1628	Increase pumping rate - step 4, average rate = 13.8 gallons per minute
1701	Pump off
	Packer deflated at 1026 on November 15

SUPPLY WELL SW-4

USGS records dated October 8, 1946, indicated that well SW-4 (USGS well BK-375) was drilled to a depth of 600 ft. Drawdown in the well was 94 ft after pumping at a rate of 164 gal/min for 8 hours; the specific capacity was 1.7 (gal/min)/ft.

Interpretation of Borehole Geophysical Logs

A suite of borehole geophysical logs (fig. 21) and a borehole television survey were run in well SW-4 by the USGS. The caliper log shows that the well is 573 ft deep, 8 in. in diameter, and cased to 52 ft bls. The fluid-resistivity log shows changes in resistivity at about 114, 156, 212, 332, and 546 ft bls. The fluid-temperature log shows a change in temperature at about 141 ft bls. A heatpulse flowmeter was used to measure vertical fluid movement in the well under nonpumping conditions (table 14). The heatpulse-flowmeter measurements showed upward flow at 70, 90, and 140 ft bls; downward flow at 180, 204, 230, 286, 310, 350, 400, 446, 472, and 530 ft bls; and no flow at 561 ft bls. The suite of borehole geophysical logs, borehole television survey, and heatpulse-flowmeter measurements indicate that water enters the well through fractures (dip of 20° N. 7° W. and strike of N. 83° E.) in silty unit E at 158-161 ft bls and flows both upward and downward. Water flows upward at a rate of 0.28 gal/min and exits the borehole through a near-vertical fracture (dip of 66° north-south and strike of east-west) in unit E at 108-110 ft bls (0.08 gal/min) and a vertical fracture (N. 10° E. and strike of N. 80° W.) in sandy unit B at 52-62 ft bls (0.2 gal/min). Water flows downward from the fractures at 158-161 ft bls at a rate of 0.4 gal/min. Additional water (about 0.7 gal/min) enters the well through a near-horizontal fracture (dip of 16° N. 45° W. and strike of N. 45° E.) at 213 ft bls and moves downward. Water exits the borehole through a near-vertical fractures (dip of 79° N. 40° E. and strike of N. 50° W.) in silty unit G at 330-336 ft bls and a near-vertical fracture (dip of 85° N. 32° E. and strike of N. 58° W.) in silty unit J at 542-556 ft bls (fig. 21).

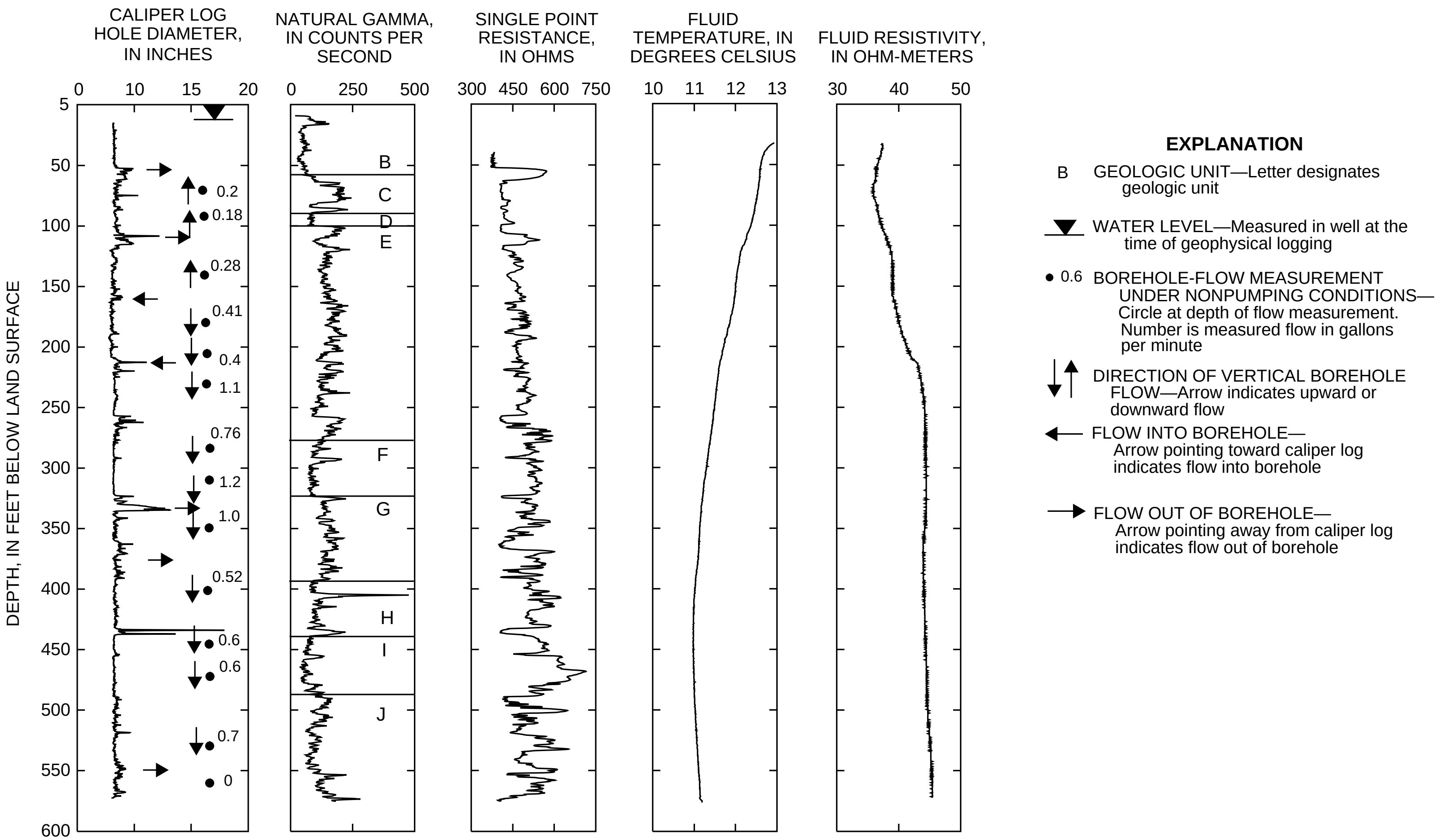


Figure 21. Borehole geophysical logs from well SW-4, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania.

Table 14. ***Summary of heatpulse-flowmeter measurements made in well SW-4, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania***

Depth (feet below land surface)	Flow rate (gallons per minute)	Flow direction
70	0.2	Up
90	.18	Up
140	.28	Up
180	.41	Down
204	.4	Down
230	1.1	Down
286	.76	Down
310	1.2	Down
350	1.0	Down
400	.52	Down
446	.6	Down
472	.6	Down
530	.7	Down
561	0	--

Acoustic televiewer and borehole deviation logs were run in well SW-4. The borehole deviation log (fig. 22) shows that the bottom of well SW-4 is 1.8 ft N. 78° W. of the top of the well. Orientations were identified for 33 bedding-plane features, 14 near-horizontal fractures, and 16 near-vertical to vertical fractures on the acoustic televiewer log. The median orientation for bedding-plane features is a dip of 16° N. 56° E. and a strike of N. 34° W., for near-horizontal fractures a dip of 20° east-west and a strike of north-south, and for near-vertical to vertical fractures a dip of 74° N. 7° E. and a strike of N. 83° W.

Aquifer Test

A stepped aquifer test was conducted by the USGS on November 20, 1997. Well SW-4 was pumped at rates up to 58.4 gal/min for 366 minutes (table 15). On the basis of data from the test, the specific capacity of well SW-4 is 0.56 (gal/min)/ft. The average pumping rate was 48.5 gal/min. Water levels in wells SW-3 and SW-4 were measured (fig. 23). Drawdown at the end of the test was 90.56 ft for well SW-4 and 2.31 ft for well SW-3, which indicates that the wells are hydraulically connected.

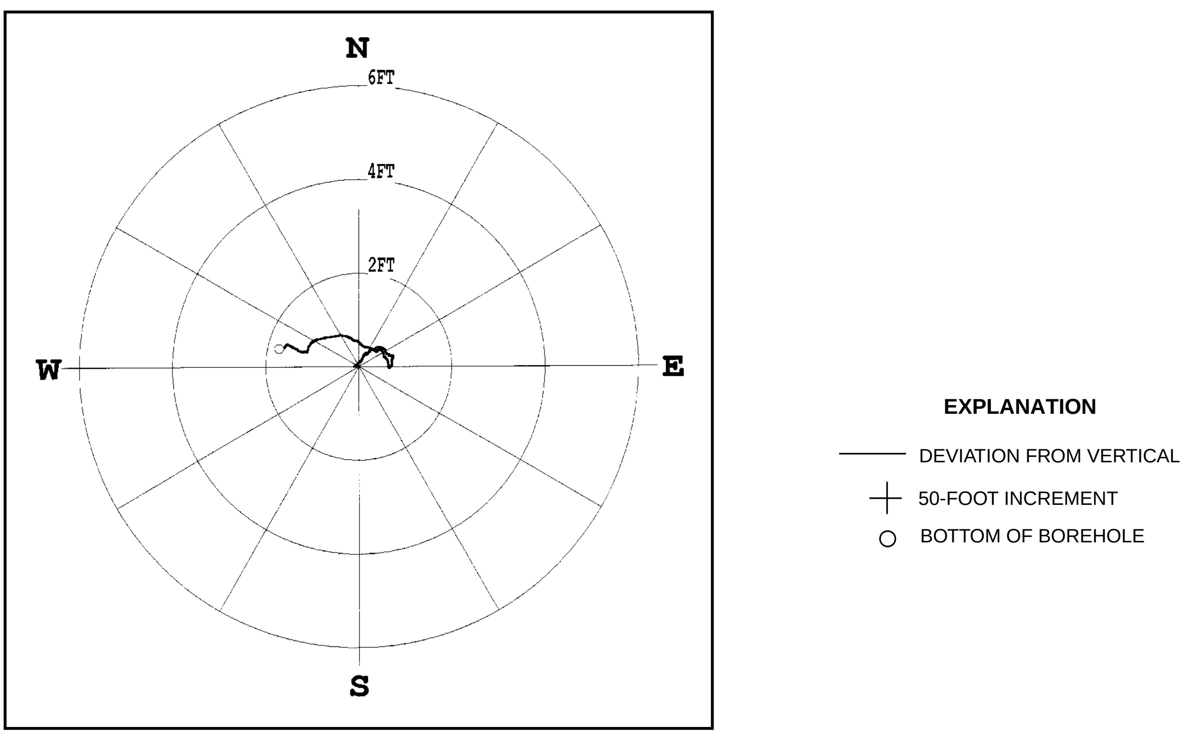


Figure 22. Deviation log of well SW-4, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania.

__Table 15.__ Schedule and pumping rates for the aquifer test of well SW-4, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania, November 20, 1997

Time	Activity
1220	Start pump - step 1, average rate = 23.1 gallons per minute
1321	Increase pumping rate - step 2, average rate = 41.2 gallons per minute
1437	Increase pumping rate - step 3, average rate = 56.2 gallons per minute
1557	Increase pumping rate - step 4, average rate = 58.4 gallons per minute
1826	Pump off

Aquifer-Isolation Tests

On the basis of the borehole geophysical logs and heatpulse-flowmeter measurements, five intervals were selected for aquifer-isolation tests (table 16). For the test of the lowermost isolated interval (interval 1), only the upper packer was inflated (fig. 3A). For the test of the uppermost isolated interval (interval 5), only the lower packer was inflated (fig. 3C). For the test of the intervals 2, 3, and 4, both packers were inflated (fig. 3B). The quantity of water pumped and specific capacity calculated for each isolated interval are summarized in table 16.

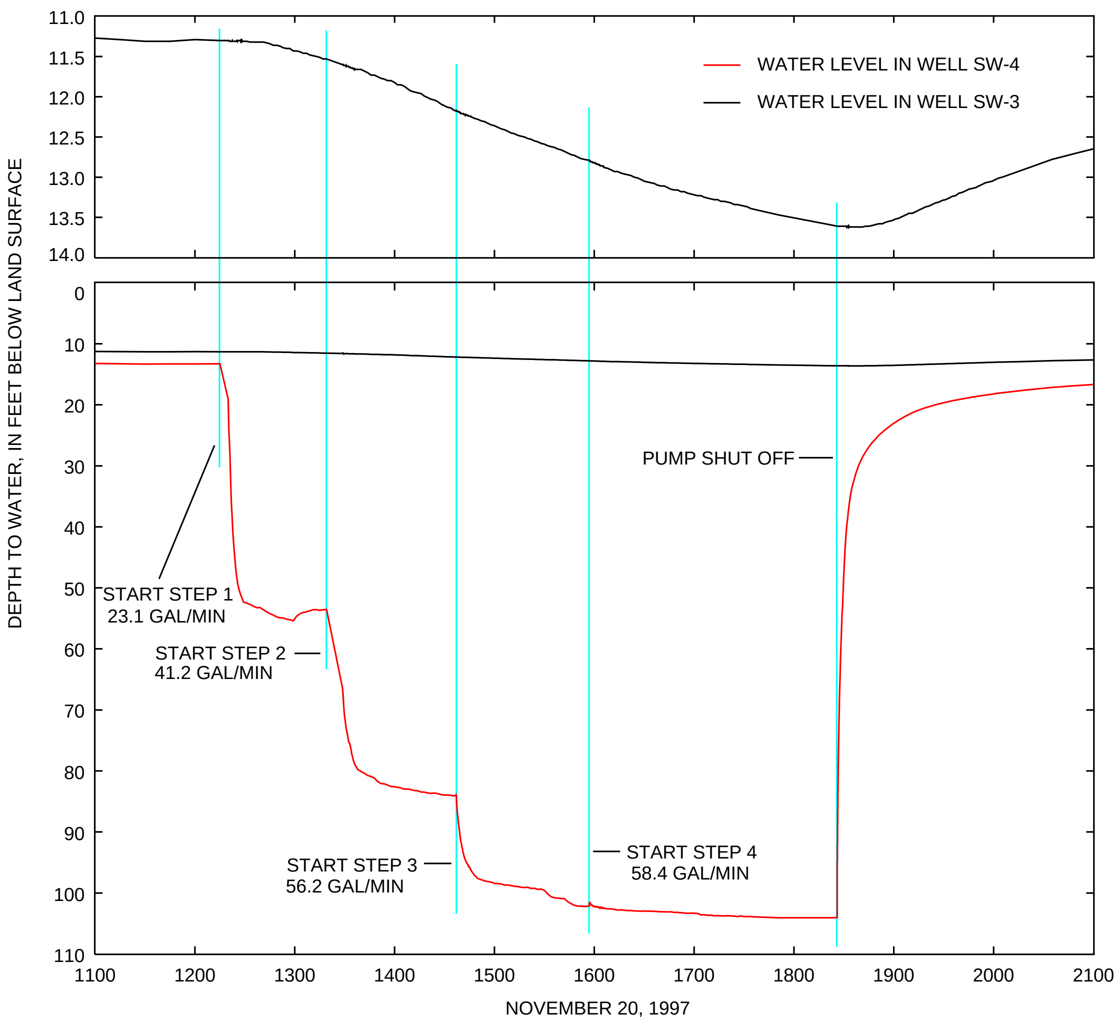


Figure 23. Hydrographs from aquifer test of well SW-4, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania.

Table 16. *Intervals isolated and specific capacities for well SW-4, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania*
[--, insufficient data to calculate specific capacity]

Interval	Isolated depth interval[1] (feet below land surface)	Isolated fracture	Number of steps	Total water pumped (gallons)	Specific capacity (gallons per minute per foot)
1	409-577	Water-receiving zones at 542-556 feet	1	18	--
2	320-345	Water-receiving zone at 330-336 feet	1	12.5	--
3	204-229	Water-producing zone at 213 feet	4	2,111	0.40
4	142-167	Water-producing zone at 158-161 feet	1	688	.09
5	32-146	Water-receiving zones at 52-62 and 108-110 feet	4	1,957	.59

[1] Center of packer to center of packer.

Aquifer-Isolation Test of Interval 1 (409-577 Feet Below Land Surface)

For the aquifer-isolation test of interval 1, the center of the upper packer was set at 409 ft bls. Only the upper packer was inflated. Before packer inflation, the depth to water in the open borehole was 13.31 ft bls. Seventy-one minutes after packer inflation, the depth to water in the interval above the packer was 12.86 ft bls, an increase in water level of 0.45 ft. The depth to water in the interval below the packer was 36.78 ft bls, a decrease in water level of 23.47 ft; the water level in the isolated interval was at 36.78 ft bls and was declining at the rate of approximately 0.08 ft/min at the start of the test. This is consistent with the interpretation of the borehole geophysical logs and downward borehole flow shown by the heatpulse-flowmeter measurements, which indicate that the isolated water-receiving fractures below 409 ft bls have a lower head than the water-producing fractures above them.

Interval 1 was pumped for 4 minutes at a rate of 4.8 gal/min beginning at 1156 on November 26, 1997. Drawdown in the isolated interval was 106.42 ft, and no drawdown was measured in the interval above the packer. The hydrographs for the intervals above and below the packer and for well SW-3 indicate no hydraulic connection between the intervals (fig. 24). No drawdown was measured in well SW-3 from pumping the interval isolated from 409 to 577 ft bls in well SW-4.

Aquifer-Isolation Test of Interval 2 (320 to 345 Feet Below Land Surface)

For the aquifer-isolation test of interval 2, the center of the upper packer was set at 320 ft bls, and the center of the lower packer was set at 345 ft bls. Prior to packer inflation, depth to water in the open borehole was 12.68 ft bls. Eighty-three minutes after packer inflation, the depth to water in the upper interval was 12.46 ft bls, depth to water in the isolated interval was 37.62 ft bls, and depth to water in the lower interval was 37.66 ft bls. Depth to water was nearly the same in the isolated and lower intervals. This is consistent with the interpretation of the borehole geophysical logs and heatpulse-flowmeter measurements, which showed water moving downward in the borehole from fractures at 151-161 and 213 ft bls and exiting the borehole through fractures at 330-336 and 542-556 ft bls.

Interval 2 was pumped for 3 minutes at a rate of 4.2 gal/min beginning at 1356 on November 25, 1997. After pumping for 1 minute, the water level in the lower zone dropped below 77.56 ft bls (drawdown greater than 39.9 ft), which is where the transducer was set. No drawdown was measured in the upper zone. The maximum drawdown in the isolated zone was 77.34 ft (water level at 114.96 ft bls). The water level in well SW-3 did not respond to pumping the interval isolated from 320 to 345 ft bls in well SW-4 (fig. 25).

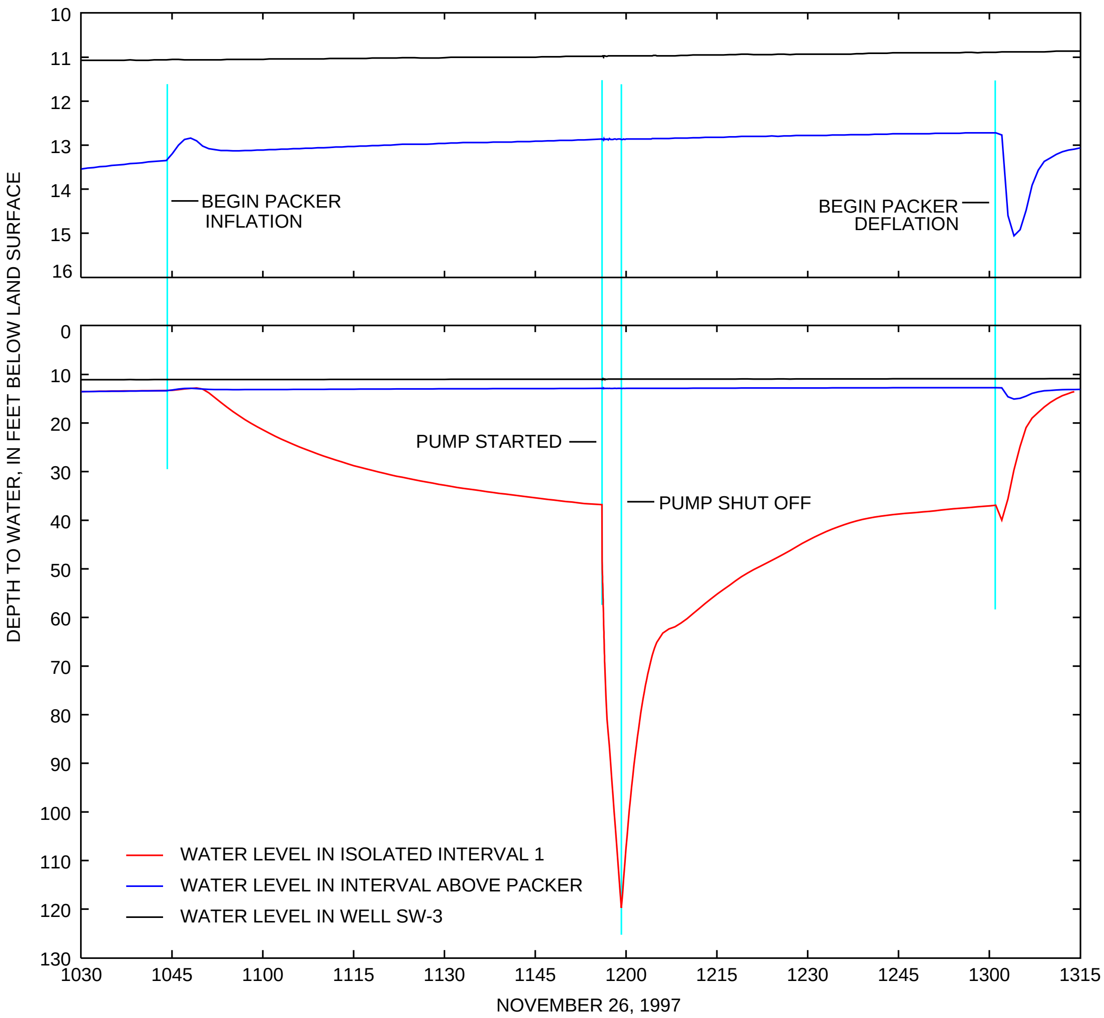


Figure 24. Hydrographs from aquifer-isolation test of interval 1 (409 to 577 feet below land surface) in well SW-4, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania.

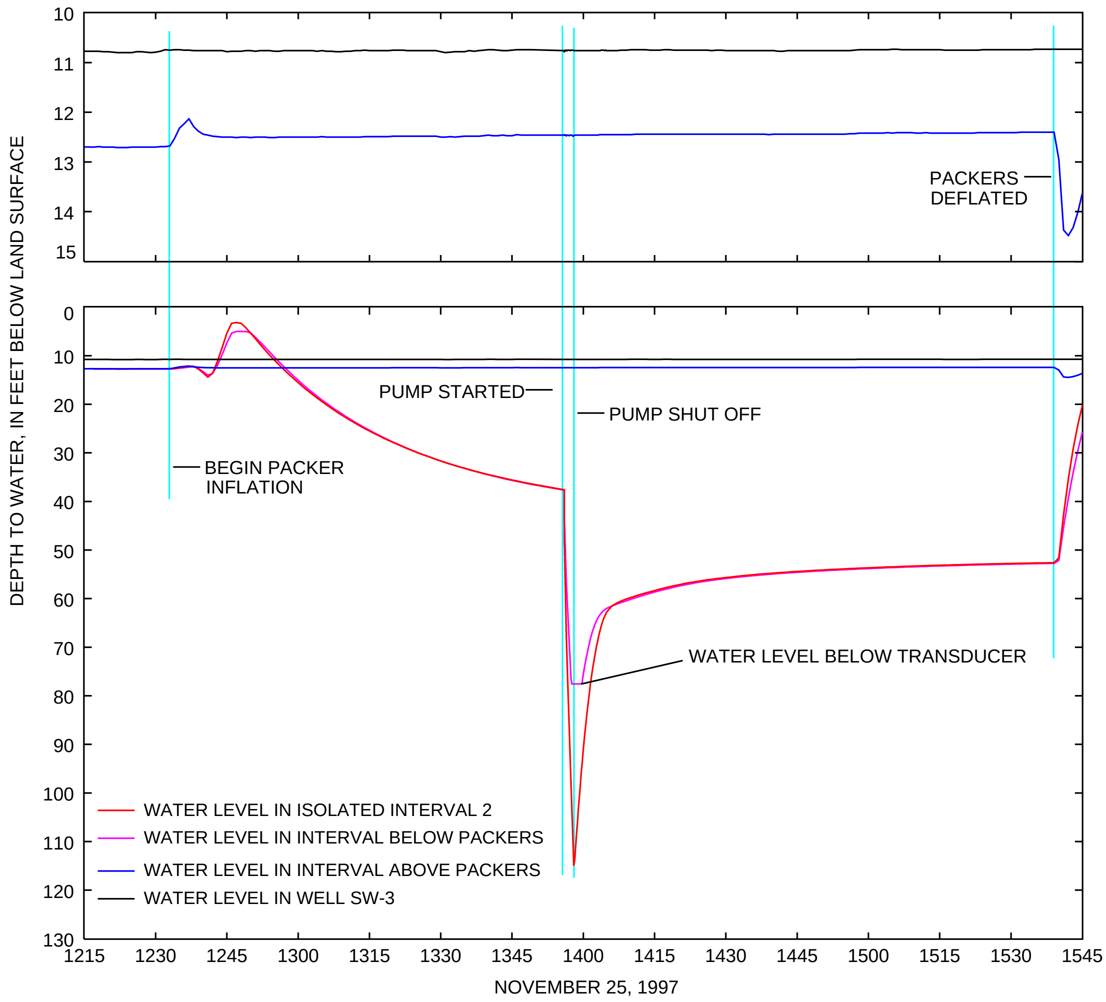


Figure 25. Hydrographs from aquifer-isolation test of interval 2 (320 to 345 feet below land surface) in well SW-4, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania.

Aquifer-Isolation Test of Interval 3 (204 to 229 Feet Below Land Surface)

For the aquifer-isolation test of interval 3, the center of the upper packer was set at 204 ft bls, and the center of the lower packer was set at 229 ft bls. Prior to packer inflation, depth to water in the open borehole was 12.56 ft bls. Fifty-three minutes after packer inflation, the depth to water in the upper interval was 12.46 ft bls, and depth to water in the isolated interval was 12.27 ft bls. The depth to water in the lower interval was 36.69 ft bls and had not stabilized at the start of the test. Depth to water was least in the isolated interval, indicating that this interval has the highest hydraulic head. This is consistent with the interpretation of the borehole geophysical logs and heatpulse-flowmeter measurements, which indicated water moving into the borehole from a fracture at 213 ft bls and flowing downward.

The average pumping rate for the first step (table 17) was 5.8 gal/min. The first step was 40 minutes long. No drawdown was measured in the upper interval. Drawdown in the isolated interval was 12.55 ft, and drawdown in the lower interval was 1.23 ft. For the second step, the pumping rate was increased to 11.4 gal/min. The second step was 35 minutes long. At the end of the second step, no drawdown was measured in the upper interval. The water level in the isolated interval decreased an additional 15.73 ft for a total drawdown of 28.28 ft, and the water level in the lower interval decreased an additional 0.67 ft. For the third step, the pumping rate was increased to 15.2 gal/min. The third step was 32 minutes long. At the end of the third step, the water level in the upper interval decreased 0.02 ft, the water level in the isolated interval decreased an additional 12.33 ft for a total drawdown 40.61 ft, and the water level in the lower interval decreased an additional 0.47 ft. For the fourth step, the pumping rate was increased to 23.1 gal/min, the maximum pump capacity. The fourth step was 43 minutes long. At the end of the fourth step, the water level in the upper interval decreased an additional 0.07 ft; total drawdown in the upper interval was 0.09 ft. The water level in the isolated interval decreased an additional 31.57 ft; total drawdown in the isolated interval was 72.18 ft. The water level in the lower interval decreased an additional 0.63 ft; total drawdown in the lower interval was 3 ft. Some of the water-level decline in the lower interval was because the water level had not stabilized before the start of the test. After cessation of pumping, the water level in the lower zone increased by only 0.42 ft in 70 minutes. The specific capacity of interval 3 is 0.40 (gal/min)/ft.

Table 17. *Schedule and pumping rates for the aquifer-isolation test of interval 3 (164 to 194 feet below land surface) in well SW-4, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania, November 24, 1997*

Time	Activity
1222	Begin packer inflation
1237	Packers inflated
1315	Start pump - step 1, average rate = 5.8 gallons per minute
1355	Increase pumping rate - step 2, average rate = 11.4 gallons per minute
1430	Increase pumping rate - step 3, average rate = 15.2 gallons per minute
1502	Increase pumping rate - step 4, average rate = 23.1 gallons per minute
1545	Pump off
1659	Begin packer deflation

The hydrograph for well SW-4 indicates a hydraulic connection outside the borehole between the isolated interval and the interval below the isolated interval and little hydraulic connection between the isolated interval and the interval above the isolated interval (fig. 26). The decline of 0.04 ft in water level in well SW-3 probably was not caused by pumping well SW-4. The water level in well SW-3 continued to decline after the cessation of pumping.

Aquifer-Isolation Test of Interval 4 (142-167 Feet Below Land Surface)

For the aquifer-isolation test of interval 4, the center of the upper packer was set at 142 ft bls, and the center of the lower packer was set at 167 ft bls. Prior to packer inflation, depth to water in the open borehole was 12.53 ft bls. Forty-six minutes after packer inflation, the depth to water in the upper interval was 12.69 ft bls, a decrease of 0.16 ft; depth to water in the isolated interval was 10.42 ft bls, an increase of 2.11 ft; and depth to water in the lower interval was 12.72 ft bls, a decrease of 0.19 ft. The isolated interval has the highest head of any interval

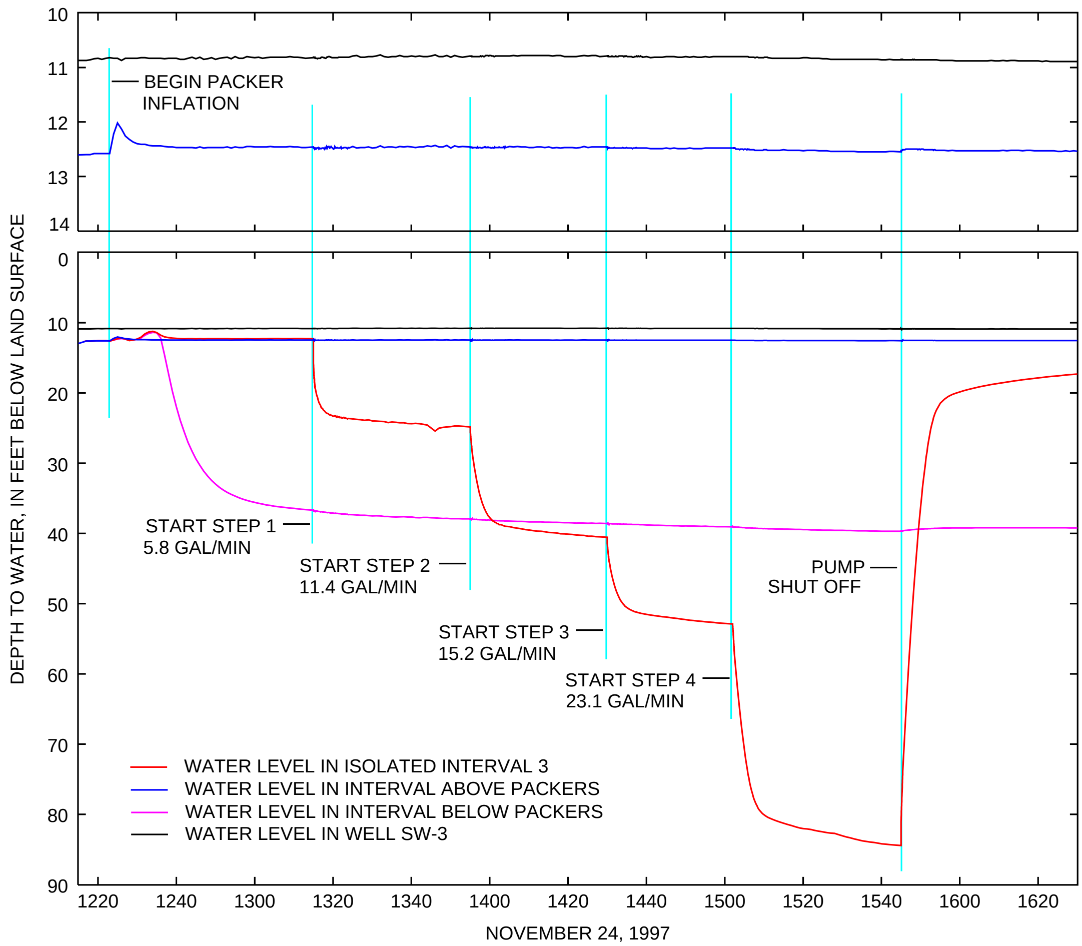


Figure 26. Hydrographs from aquifer-isolation test of interval 3 (204 to 229 feet below land surface) in well SW-4, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania.

isolated in the borehole. This is consistent with the interpretation of the borehole geophysical logs and heatpulse-flowmeter measurements, which showed water entering the borehole from a fracture at 158-161 ft bls and moving upward and downward. The isolated interval was pumped for 100 minutes at 6.9 gal/min beginning at 1218 on November 23, 1997. Drawdown in the upper interval was 1.11 ft, drawdown in the isolated interval was 81.15 ft, and no drawdown was measured in the lower interval. The specific capacity of interval 4 is 0.09 (gal/min)/ft.

The hydrograph for well SW-4 indicates a hydraulic connection outside the borehole between the isolated interval and the upper interval and no hydraulic connection between the isolated interval and the lower interval (fig. 27). The 0.02-ft decline in water level measured in well SW-3 was not caused by pumping the interval isolated from 144 to 164 ft bls in well SW-4.

Aquifer-Isolation Test of Interval 5 (32 to 146 Feet Below Land Surface)

For the aquifer-isolation test of interval 5, only the lower packer was inflated; the center of the lower packer was set at 146 ft bls. Prior to packer inflation, depth to water in the open borehole was 12.79 ft bls. Twenty-two minutes after packer inflation, the depth to water in the interval above the packer (isolated interval) was 12.92 ft bls, a decrease of 0.13 ft, and depth to water in the interval below the packer was 12.51 ft bls, an increase of 0.28 ft. This is consistent with the interpretation of the borehole geophysical logs and heatpulse-flowmeter measurements, which showed that water moving up the borehole exits through water-receiving fractures at 108-110 and 52-62 ft bls.

The average pumping rate for the first step (table 18) was 4.9 gal/min. The first step was 38 minutes long. Drawdown in the interval above the packer was 6.64 ft, and drawdown in the interval below the packer was 0.01 ft. For the second step, the pumping rate was increased to 10.2 gal/min. The second step was 35 minutes long. At the end of the second step, the water level in the interval above the packer decreased an additional 9.22 ft for a total drawdown of 15.86 ft, and the water level in the interval below the packer decreased an additional 0.07 ft. For the third step, the pumping rate was increased to 17.1 gal/min. The third step was 32 minutes long. At the end of the third step, the water level in the interval above the packer decreased 13.8 ft for a total drawdown 29.66 ft, and the water level in the interval below the packer decreased an additional 0.05 ft. For the fourth step, the pumping rate was increased to 23.4 gal/min, the maximum pump capacity. The fourth step was 37 minutes long. At the end of the fourth step, the water level in the interval above the packer decreased an additional 15.83 ft; total drawdown in the isolated interval was 54.49 ft. The water level in the interval below the packer decreased an additional 0.05 ft; total drawdown in the lower interval was 0.18 ft. The specific capacity of interval 5 is 0.59 (gal/min)/ft.

The hydrograph for well SW-4 indicates little hydraulic connection between the isolated interval and the interval below the isolated interval (fig. 28). Drawdown in well SW-3 was 0.47 ft, which indicates that the wells are hydraulically connected. The water level in well SW-3 continued to decline until 33 minutes after the cessation of pumping. For the first 30 minutes after cessation of pumping, interval 5 recovered at the rate of 3.6 gal/min.

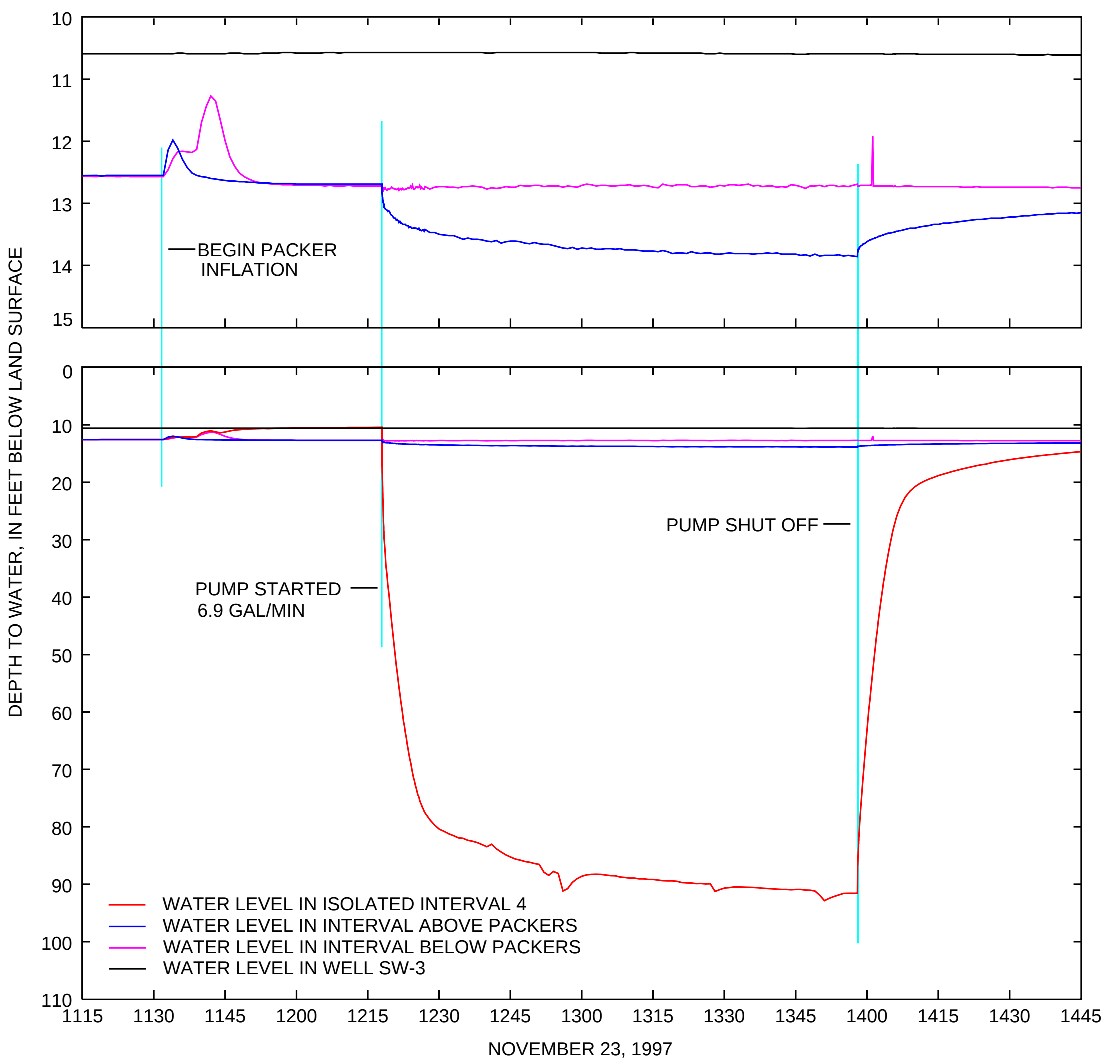


Figure 27. Hydrographs from aquifer-isolation test of interval 4 (142 to 167 feet below land surface) in well SW-4, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania.

Table 18. *Schedule and pumping rates for the aquifer-isolation test of interval 5 32 to 146 feet below land surface) in well SW-4, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania, November 22, 1997*

Time	Activity
1334	Begin packer inflation
1341	Packers inflated
1356	Start pump - step 1, average rate = 4.9 gallons per minute
1434	Increase pumping rate - step 2, average rate = 10.2 gallons per minute
1509	Increase pumping rate - step 3, average rate = 17.1 gallons per minute
1541	Increase pumping rate - step 4, average rate = 23.4 gallons per minute
1618	Pump off
1719	Begin packer deflation

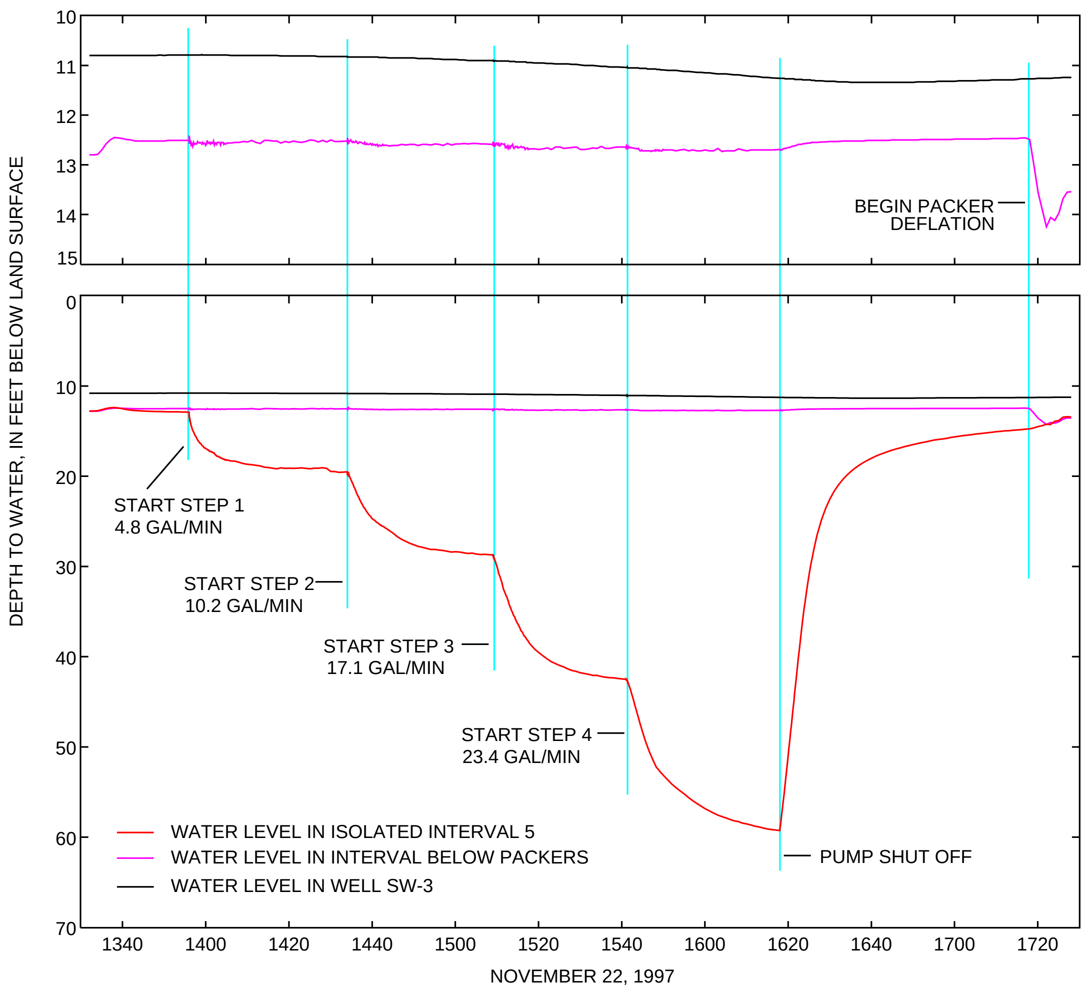


Figure 28. Hydrographs from aquifer-isolation test of interval 5 (32 to 146 feet below land surface) in well SW-4, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania.

SUMMARY AND CONCLUSIONS

Caliper, natural-gamma, single-point-resistance, fluid-resistivity, and fluid-temperature logs and borehole television surveys were run in the four supply wells in Area D at the former U.S. Naval Air Warfare Center (NAWC) in Warminster, Pa. Acoustic borehole televiewer and borehole deviation logs were run in wells SW-3 and SW-4. The direction and rate of borehole-fluid movement were measured with a high-resolution heatpulse flowmeter. The logs were used to locate water-bearing fractures, determine probable zones of vertical borehole-fluid movement, and determine the depth to set straddle packers. Interpretation of borehole geophysical logs and measurements of vertical borehole-fluid movement provide information on which fractures are interconnected by an open borehole. These open boreholes may provide a conduit for the movement of contaminants among interconnected fractures.

An aquifer test was conducted in each well to determine the effect of pumping the open borehole on water levels in nearby wells and to obtain a water sample for chemical analysis. Aquifer-test data were used to calculate a specific capacity for each well. Aquifer-isolation tests, commonly known as packer tests, were conducted in each well to determine depth-discrete specific capacities, to obtain depth-discrete water samples, and to determine the effect of pumping an individual fracture or fracture zone on water levels in nearby wells. Water-level data collected during aquifer-isolation tests were consistent with and confirmed interpretations of borehole geophysical logs and heatpulse-flowmeter measurements.

The borehole geophysical logs and heatpulse-flowmeter measurements showed both upward and downward flow in well SW-1 under nonpumping conditions. Borehole flow was upward in the upper part of the borehole (above 150 ft bls) and both upward and downward in the lower part of the borehole (below 150 ft bls). The major water-producing fractures are at 159-164 and 170-174 ft bls. Specific capacities of the fractures when isolated by a straddle packer system were 2.3 and 1.5 (gal/min)/ft, respectively. The specific capacity for the short-term aquifer-isolation test of the major water-producing fracture at 159-164 ft bls (2.3 [gal/min]/ft) was higher than the specific capacity for the longer-term aquifer test (1.5 [gal/min]/ft) of well SW-1 because of the lower pumping rate and shorter duration of the aquifer-isolation test. A minor water-producing fracture (specific capacity of 0.12 [gal/min]/ft) is at 239 ft bls. Pumping from the isolated fractures produces drawdown in well SW-2.

Well SW-2 is only 90 ft from well SW-1 and drilled to approximately the same depth, yet the pattern of borehole flow is different. Borehole flow was upward over nearly the entire length of the open borehole under nonpumping conditions. The borehole geophysical logs and heatpulse-flowmeter measurements showed that water enters well SW-2 through a water-producing fracture at 230-238 ft bls, flows upward at a rate 1.2 gal/min, and exits the borehole through a fracture 39-44 ft bls. The fractures at 230-238 and 39-44 ft bls are the major water-bearing zones in the well. Specific capacities of these fractures when isolated by a straddle packer system were 1.3 and 0.71 (gal/min)/ft, respectively. A minor water-producing fracture (specific capacity of 0.26 [gal/min]/ft) is at 160-165 ft bls. Pumping from the isolated fractures produces drawdown in well SW-1.

The borehole geophysical logs and heatpulse-flowmeter measurements showed downward flow in well SW-3 under nonpumping conditions. Water enters the well through fractures at 60 and 89 ft bls and flows downward at a rate of approximately 1.2 gal/min to a fracture at 491-496 bls and possibly fractures at greater depth, where it exits the well. Downward flow is caused by a large difference in head (greater than 49 ft) between water-bearing fractures in the upper and lower part of the borehole. The major water-producing fractures are at 60 and 89 ft bls. The specific capacity of this interval when isolated by a straddle packer system was 0.38 (gal/min)/ft, which is approximately the same magnitude as the specific capacity of the well calculated from the aquifer test (0.21 [gal/min]/ft). Well SW-3 is capable of producing about 15 gal/min, which is substantially less than the yield when drilled.

The borehole geophysical logs and heatpulse-flowmeter measurements showed upward and downward flow in well SW-4 under nonpumping conditions. Borehole flow was upward in the upper part of the borehole (above 160 ft bls) and downward in the lower part of the borehole (below 160 ft bls). Downward flow is caused by a large difference in head (about 25 ft) between water-bearing fractures in the upper and lower part of the borehole. The major water-producing fractures are at 52-62, 108-110, and 204-229 ft bls; a minor water-producing zone is at 158-161 ft bls. The water-producing fracture at 158-161 ft bls has the highest head of any isolated zone, and, under nonpumping conditions, water produced by this fracture flows upward and downward in the borehole. Specific capacities of the fractures when isolated by a straddle packer system were 0.55 (gal/ min)/ft for the water-receiving fracture at 204-229 ft bls, 0.37 (gal/min)/ft for the water-receiving fractures at 52-62 and 108-110 ft bls, and 0.09 (gal/ min)/ft for the water-producing fracture at 158-161 ft bls.

Approximately half of the fractures identified as water-producing or water-receiving zones by borehole geophysical methods produced water at a rate of more than 6 gal/min when isolated and pumped. The other fractures identified as water-producing or water-receiving zones by borehole geophysical methods probably produce less than 2 gal/min when pumped. All hydrologically active fractures below 250 ft bls were identified as water-receiving zones.

Vertical distribution of specific capacity between land surface and 250 ft bls is not related to depth. The four highest specific capacities, in descending order, were at depths of 164-194, 144-164, 212-242, and 36-98 ft bls.

REFERENCES CITED

Brown and Root Environmental, 1996a, Feasibility study report for groundwater in areas A, B, and D Naval Air Warfare Center (NAWC), Warminster, Pennsylvania: Wayne, Pa. [variously paged].

_____1996b, Focused feasibility study report for interim groundwater action in area D operable unit 4 (OU4) Naval Air Warfare Center (NAWC), Warminster, Pennsylvania: Wayne, Pa. [variously paged].

_____1998, Draft area D supply well and water level study report Naval Air Warfare Center (NAWC), Warminster, Pennsylvania: King of Prussia, Pa. [variously paged].

Earth Technology Corporation, 1985a, Final study submission well profile studies: (wells number 1 and 2) at the Naval Air Development Center, Warminster, Pennsylvania: Somerset, N.J. [variously paged].

_____1985b, Well profile studies: (wells number 4 and 5) at the Naval Air Development Center, Warminster, Pennsylvania: Somerset, N.J. [variously paged].

_____1988, Final study submission supplemental report well profile studies (well SW#3) at the Naval Air Development Center, Warminster, Pennsylvania: Somerset, N.J. [variously paged].

Keys, W.S., 1990, Borehole geophysics applied to ground-water investigations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 2, chap. E-2, 149 p.

Rima, D.R., Meisler, Harold, and Longwill, Stanley, 1962, Geology and hydrology of the Stockton Formation in southeastern Pennsylvania: Pennsylvania Geologic Survey, 4th ser., Water Resources Report 14, 111 p.

Sloto, R.A., 1997, Results of borehole geophysical logging and aquifer-isolation tests conducted in the John Wagner and Sons, Inc. former production well, Ivyland, Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 97-4095, 18 p.

Sloto, R.A., Macchiaroli, Paola, and Towle, M.T., 1996, Geohydrology of the Stockton Formation and cross-contamination through open boreholes, Hatboro Borough and Warminster Township, Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 96-4047, 49 p.