Geohydrology of the Stockton Formation and Cross-Contamination Through Open Boreholes, Hatboro Borough and Warminster Township, Pennsylvania

By RONALD A. SLOTO, PAOLA MACCHIAROLI, and MICHAEL T. TOWLE

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
foot per minute (ft/min)	0.3048	meter per minute
	Area	
square mile (mi^2)	2.590	square kilometer
	Volume	
gallon (gal)	3.785	liter
	Flow	
gallon per minute (gal/min)	0.06308	liter per second
gallon per year (gal/yr)	3.785	liter per year

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

Abbreviated water-quality units used in report:

micrograms per liter (µg/L)
milligrams per liter (mg/L)

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Abstract

The study area consists of a 9-square-mile area underlain by sedimentary rocks of the middle arkose member of the Stockton Formation of Upper Triassic age. In the Hatboro area, the Stockton Formation strikes approximately N. 65° E. and dips approximately 9° NW. The rocks are chiefly arkosic sandstone and siltstone. Rocks of the Stockton Formation form a complex, heterogeneous, multiaquifer system consisting of a series of gently dipping lithologic units with different hydraulic properties. Most ground water in the unweathered zone moves through a network of interconnecting secondary openings—fractures, bedding planes, and joints. Ground water is unconfined in the shallower part of the aquifer and semiconfined or confined in the deeper part of the aquifer. Nearly all deep wells in the Stockton Formation are open to several water-bearing zones and are multiaquifer wells. Each water-bearing zone usually has a different hydraulic head. 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.

Determination of the potential for borehole flow was based on caliper, natural-gamma, single-point-resistance, fluid-resistivity, and (or) fluid-temperature logs that were run in 162 boreholes 31 to 655 feet deep. The direction and rate of borehole-fluid movement were determined in 83 boreholes by the brine-tracing method and in 10 boreholes by use of a heat-pulse flowmeter. Borehole flow was measurable in 65 of the 93 boreholes (70 percent). Fluid movement at rates up to 17 gallons per minute was measured. Downward flow was measured in 36 boreholes, and upward flow was measured in 23 boreholes, not including those boreholes in which two directions of flow were measured. Both upward and downward vertical flow was measured in six boreholes; these boreholes are 396 to 470 feet deep and were among the deepest boreholes logged. Fluid movement was upward in the upper part of the borehole and downward in the lower part of the borehole in two boreholes. Fluid movement was downward in the upper part of the borehole and upward in the lower part of the borehole in three boreholes.

Ground-water contamination by volatile organic compounds (VOC's) is widespread in the study area. Detectable concentrations of VOC's were present in water samples from all 24 wells sampled in Hatboro Borough and in water samples from 10 of 14 wells (71 percent) sampled in Warminster Township. Samples of borehole flow from nine boreholes in the industrial area of Hatboro were collected for laboratory analysis to estimate the quantity of VOC's in borehole flow. Downward flow was measured in all of these boreholes. Concentrations of TCE, TCA, and 1,1-DCE as great as 5,800, 1,400, and 260 micrograms per liter, respectively, show that some water moving downward in the aquifer through these open boreholes is highly contaminated and that open boreholes may contribute

substantially to ground-water contamination. An estimated 14.7 gallons per year of VOC's were moving downward through the nine open boreholes sampled from the contaminated, upper part of the aquifer to the lower part, which is tapped by public supply wells.

Borehole geophysical logs were used as a guide to design and construct monitor-well networks at three National Priorities List sites in the area. An open borehole was drilled, and a suite of geophysical logs was run. Interpretation of geophysical logs enabled the identification of water-bearing zones that produce and receive water; these are zones that should not be connected. From the logs, discrete intervals to be monitored were selected. In the Stockton Formation, the same water-bearing zone may not be intersected in adjacent boreholes, especially if it is a vertical fracture with a different magnetic orientation than that of the adjacent boreholes. In most areas of the Stockton Formation, depth of water-bearing zones in an area cannot be determined from one borehole. Each borehole should be logged and evaluated separately.

INTRODUCTION

Many public supply and industrial wells in the United States are completed as open boreholes that obtain water from several formations or from several water-bearing zones in a single formation. The advantage of this construction practice is that a much greater yield can be obtained than if a well is open to a single formation or water-bearing zone. Unfortunately, these boreholes, which connect several aquifers or water-bearing zones, commonly short-circuit the ground-water-flow system and act as conduits for the transport of contaminants.

Hatboro Borough and Warminster Township are underlain by a bedrock-aquifer system in the Triassic age Stockton Formation. The residents of Hatboro Borough and Warminster Township depend on ground water withdrawn from the Stockton Formation for their drinking-water supply. The Stockton Formation is one of the most important aquifers in southeastern Pennsylvania and provides the water supply for more than one million residents.

Purpose and Scope

This report presents the results of a study done by the U.S. Geological Survey (USGS) in cooperation with the U.S. Environmental Protection Agency (USEPA) to identify and assess cross-contamination by multiaquifer boreholes in the Stockton Formation. The study used a combination of borehole geophysical methods, measurement of vertical borehole flow, and sampling and analysis of borehole fluid to assess aquifer cross-contamination in the Stockton Formation in Hatboro Borough and Warminster Township in southeastern Pennsylvania.

The purpose of this report is to (1) describe the hydrogeology of the Stockton Formation, (2) quantify the amount and quality of borehole flow in multiaquifer wells, (3) estimate the quantity of volatile organic compounds (VOC's) in borehole flow, and (4) describe how borehole geophysical methods can be used properly to design and construct monitor wells that correct and (or) prevent cross-contamination problems.

The results of this study have wide application to other multiaquifer systems in southeastern Pennsylvania and the Nation. Similar cross-connections between water-bearing zones by wells in other aquifers in the Newark Basin were noted by Sloto and Schreffler (1994).

In this report, the term "borehole" is used to describe open-hole construction drilled holes used for the collection of geologic, hydrologic, and geophysical data. The term "well" is used to describe drilled holes completed as monitor wells, public supply wells, or industrial supply wells.

Location and Description of Study Area

The study area is a 9-mi^2 area in Hatboro Borough in Montgomery County and Warminster Township in Bucks County, Pa. (fig. 1), underlain by the Stockton Formation. The study area is centered mainly around an older industrial area typical of many other communities in southeastern Pennsylvania. Much of the industry dates from the World War II or post-World War II eras. In most of these areas, industrial and public supply wells drilled into the Stockton Formation are constructed as open holes with short casings and are open to multiple water-bearing zones. Many of these wells are now abandoned.

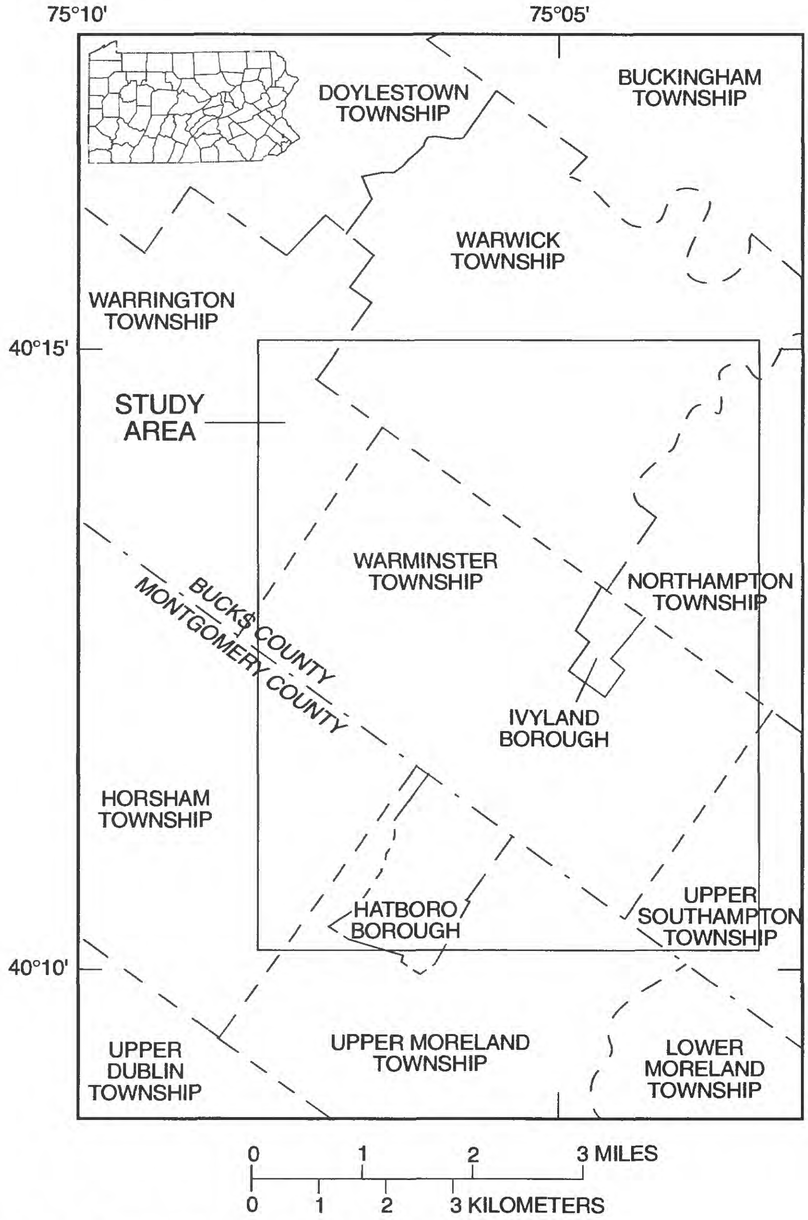


Figure 1. Location of study area.

Ground-water contamination by organic compounds in the Hatboro area has been a problem for many years. A letter dated July 3, 1914, in the files of the Pennsylvania Department of Environmental Protection summarizes the cause of complaints about the water being supplied by the Hatboro Water Company, which operated the borough's water system before it was taken over by Hatboro Borough. One problem noted in the letter was that the drilled supply well was being contaminated by lubricating oil.

The study area includes three sites designated as National Priorities List (NPL) sites, also known as superfund sites, by the USEPA (fig. 2): the Raymark Site, the Fischer and Porter Company Site, and the U.S. Naval Air Warfare Center (NAWC) (U.S. Environmental Protection Agency, 1992).

The Raymark NPL Site in Hatboro has been the location of a metal-fabrication shop since 1948. Solvent containing trichloroethylene (TCE) was used to clean and degrease metal parts. Over several decades of operations, TCE was introduced

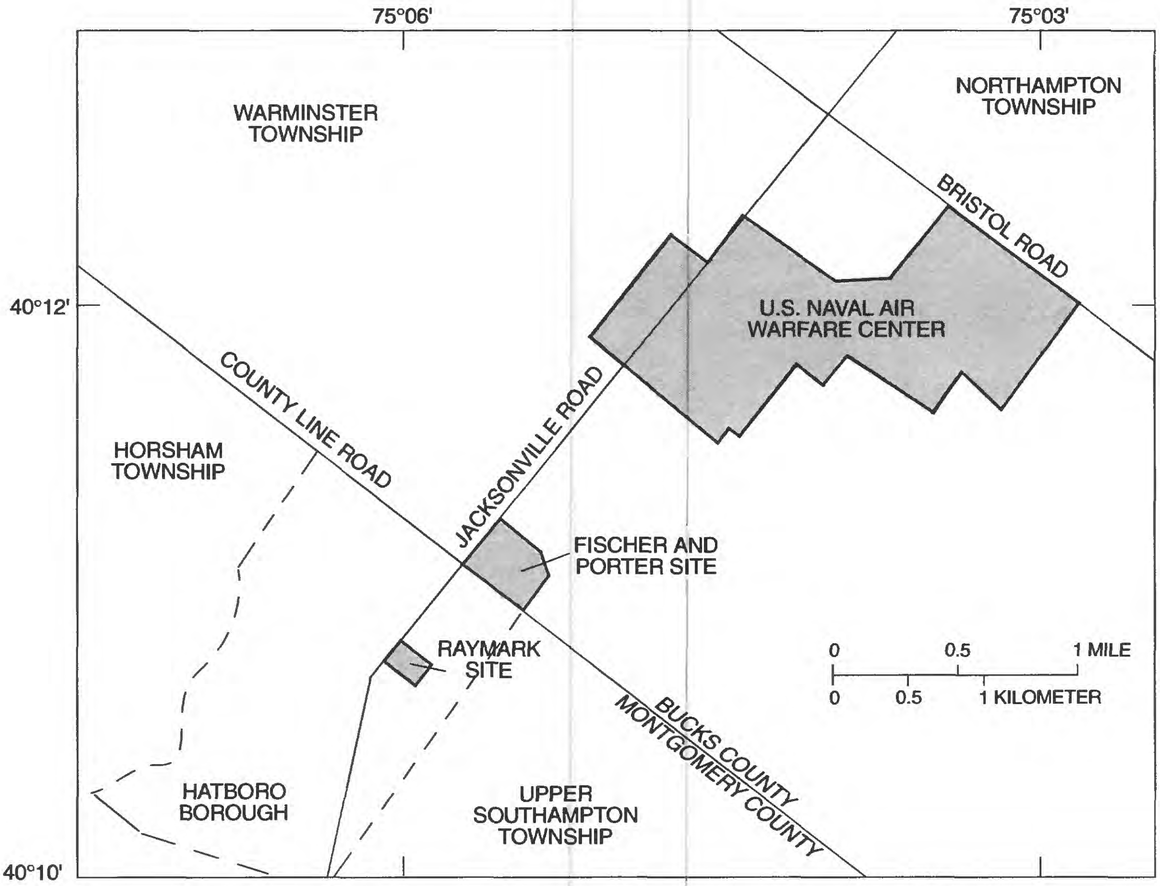


Figure 2. Location of National Priorities List (superfund) sites in Hatboro Borough and Warminster Township, Pennsylvania.

into the environment at the location of a solvent storage tank, a metal degreaser, and four disposal lagoons.

The Fischer and Porter Company NPL Site is a manufacturing facility that produces water-flow and process-control equipment. Solvent containing TCE was used in the manufacturing process and has entered the ground-water system. In 1979, VOC's were detected in nearby public supply wells. VOC's also were detected in Fischer and Porter's onsite supply wells.

The NAWC, formerly the Johnsville Naval Air Development Center, is a U.S. Navy facility commissioned in 1944. Before that, the site was used for manufacturing aircraft. NAWC is used for research, development, testing, and evaluation of naval air-craft systems. NAWC also conducts studies in anti-submarine warfare systems and software development. Wastes were generated at NAWC during aircraft maintenance and repair operations, firefighter training, machine and plating shop operations, spray painting, and research and testing activities. The wastes included solvents, paints, oils, and sludges (Haliburton NUS Environmental Corporation, 1992).

Acknowledgments

The authors thank the Fischer and Porter Company, Hatboro Authority, HIP Industries, the U.S. Navy, and Warminster Township Municipal Authority for access to their wells for borehole geophysical logging and sampling. Special thanks are due to Robert Todd, Jeff Orient, Kevin Kilmartin, Don Whalen, Lonnie Monaco, Carson Freeman, William Gross, and Michael Hunter for their help.

Borehole Geophysical Logs

Borehole geophysical logs used for this study are from (1) boreholes logged for this study, (2) boreholes previously logged by the USGS, and (3) boreholes logged as part of other studies by the USGS for the USEPA at the Raymark and Fischer and Porter Company Sites and for the USEPA and U.S. Navy at the NAWC. Besides boreholes logged during this study, geophysical logs run by the USGS between 1956 and 1990 in the study area were available for 14 boreholes.

Caliper, natural-gamma, single-point-resistance, fluid-resistivity, and (or) fluid-temperature logs were run in 162 boreholes 31 to 655 ft deep to interpret lithostratigraphy, identify water-bearing fractures, and determine possible zones of vertical borehole-fluid movement. A complete suite of geophysical logs from borehole BK–2512 is shown on figure 3.

Caliper Logs

Caliper logs provide a continuous record of average borehole diameter, which is related to fractures, lithology, and drilling technique. The caliper tool is calibrated at land surface after each log is run. Caliper logs were used to help correlate lithostratigraphy, identify fractures and possible water-bearing openings, and qualitatively correct other geophysical logs for changes in borehole diameter. Correlation of caliper logs with single-point-resistance, fluid-resistance, and fluid-temperature logs was used to identify fractures and water-producing and water-receiving zones.

The caliper log (fig. 3) and borehole television survey from borehole BK–2512 show many minor fractures and several major fractures. Major horizontal fractures are at 96, 101, 148, 217, and 255.5 ft below land surface (bls). Major vertical fractures are at 99–101, 105.5–109, 128–130, 137–142, 144–146, 242–250, and 259–261 ft bls. The large vertical fracture at 242–250 ft bls is the dominant feature in the borehole (fig. 4).

Natural-Gamma Logs

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 and siltstone units and to correlate lithostratigraphy between boreholes.

Single-Point-Resistance Logs

Single-point-resistance logs record the electrical resistance between the borehole and an electrical ground at land surface. Overall, 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 were used to correlate lithostratigraphy and sometimes helped to identify the location of water-bearing zones because a fluid-filled fracture is less resistive than solid rock.

Fluid-Resistivity Logs

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 in resistivity, and intervals of borehole flow were identified by a low resistivity gradient between water-producing and water-receiving zones. The fluid-resistivity log from borehole BK–2512 (fig. 3) shows a change in slope at 98, 213, and 252 ft bls. These changes in slope coincide with fractures shown on the caliper log at 217 and 242–250 ft bls.

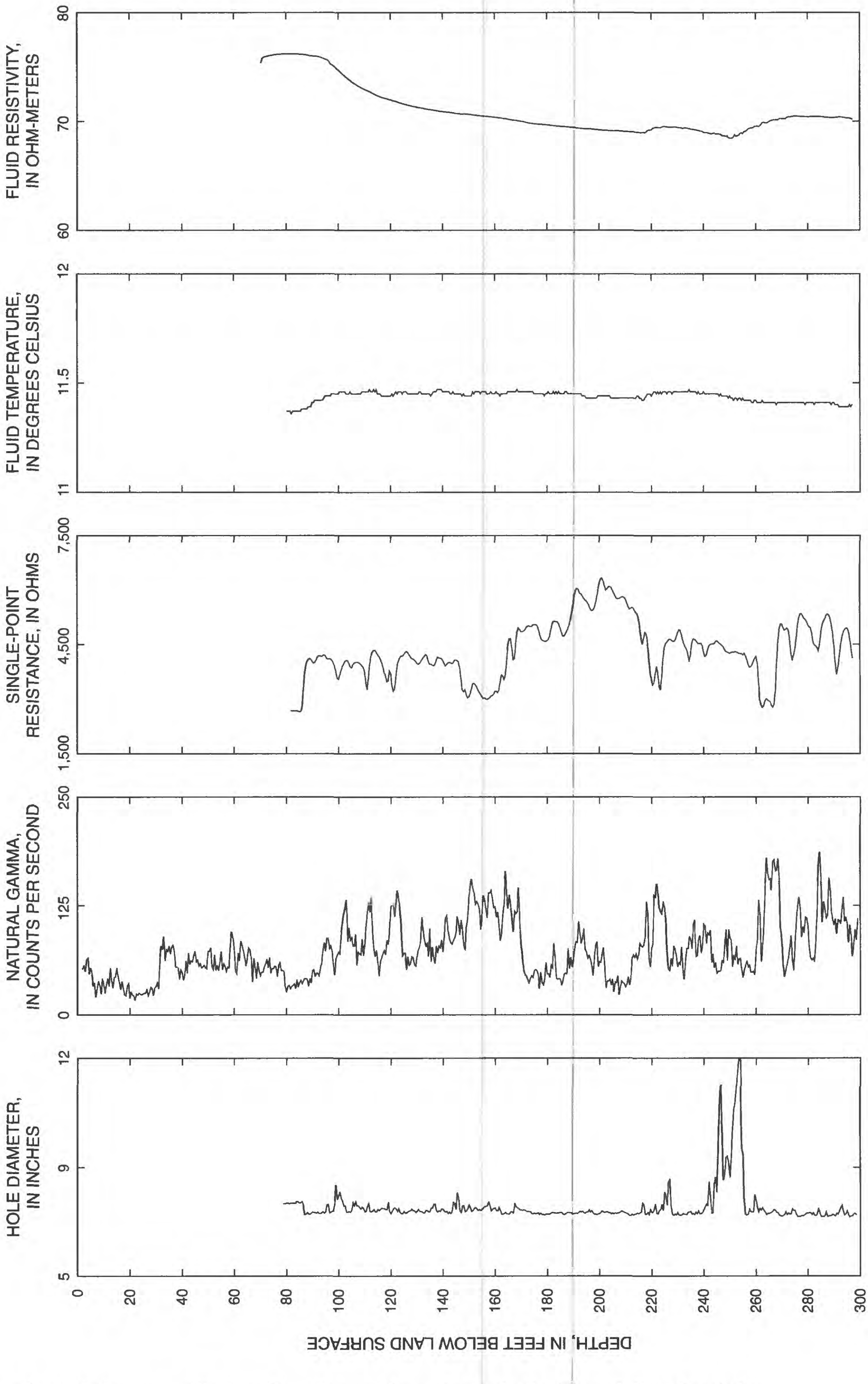


Figure 3. Caliper, natural-gamma, single-point-resistance, fluid-temperature, and fluid-resistivity logs from borehole BK–2512, Warminster Township, Pennsylvania.

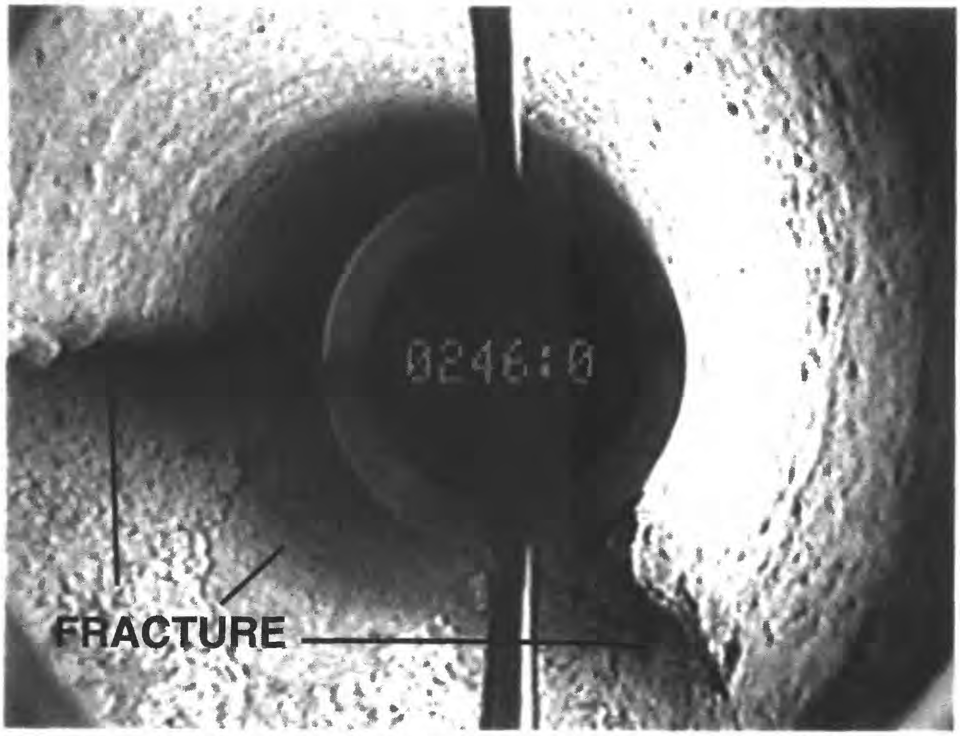


Figure 4. Photograph from borehole television survey of borehole BK–2512, Warminster Township, Pennsylvania, showing fracture at 246 feet below land surface.

Fluid-Temperature Logs

Fluid-temperature logs provide a continuous record of the temperature of the fluid in the borehole. 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. In the study area, fluid-temperature logs from boreholes with no borehole flow generally show a decrease in fluid temperature with depth caused by surface heating in the upper part of the borehole and an increase in fluid temperature with depth as a function of the geothermal gradient in the lower part of the borehole. The fluid-temperature log from borehole BK–2512 (fig. 3) shows a change in slope at 98 and 252 ft bls and very little gradient between 98 and 252 ft bls, which indicates borehole flow.

Measurement of Vertical Borehole Flow

Upon completion of geophysical logging, the suite of logs was evaluated in the field to choose zones of potential borehole flow. The direction and rate of borehole-fluid movement were determined in 83 wells by injecting a slug of high-conductance fluid at a specific depth in a borehole and monitoring the movement of the slug with the fluid-resistivity tool. This is the brine-tracing method described by Patten and Bennett (1962). The lower limit of flow measurement is about 0.5 gal/min in a 6-in.-diameter borehole. Borehole flow was calculated by

$$Q = 7.481\ V\ \pi\ r^2,$$

where

Q is borehole flow, in gallons per minute;
V is the rate of vertical borehole fluid movement, in feet per minute; and
r is the radius of the borehole, in feet.

The rate and direction of borehole-fluid movement was determined in 10 boreholes by use of a heat-pulse flowmeter. A heat-pulse flowmeter operates by slightly heating a small sheet of water between two sensitive thermistors, one below and one above the heating grid. A measurement of direction and flow rate is computed when a peak temperature is recorded by a thermistor. The range of measurable flow is 0.01 to 1.0 gal/min in a 2- to 10-in. borehole.

Slugs of high-conductance fluid were injected in borehole BK–2512 at 120, 190, 230, and 270 ft bls. Downward flow at the rate of 1.4 gal/min was measured at 120 and 190 ft bls. No borehole flow was measurable at 230 or 270 ft bls. The movement of the slug of high-conductance fluid injected at 120 ft bls is shown in figure 5. The slug moved downward at 0.52 ft/min, which is equal to a flow rate of 1.4 gal/min in an 8-in.-diameter borehole.

The suite of geophysical logs for borehole BK–2512 (fig. 3) shows that water enters the borehole through a horizontal fracture at 96 ft bls and moves downward at the rate of 1.4 gal/min (fig. 6). The borehole television survey shows a disruption of downward particle movement at this fracture. Most of the water is lost to a water-receiving fracture at 217 ft bls; the borehole television survey shows a disruption of downward particle movement at this fracture. The rest of the water is lost to the water-receiving fracture at 242–250 ft bls, which probably receives less than 0.5 gal/min of water.

Borehole Television Surveys

Borehole television surveys were conducted in selected boreholes by lowering a waterproof video camera with a wide-angle lens down the borehole and recording the images on videotape. Borehole television surveys were used to aid interpretation of geophysical logs.

GEOHYDROLOGY OF THE STOCKTON FORMATION

The study area is in the Triassic Lowland Section of the Piedmont Physiographic Province and is underlain by sedimentary rocks of the Stockton Formation of Upper Triassic age. The Stockton Formation is the basal unit of the Newark Supergroup rocks in the Triassic and Jurassic Newark Basin. This basin contains 16,000 to 20,000 ft of nonmarine sedimentary rocks. The Newark Basin is approximately 140 mi long and 32 mi wide and is the largest

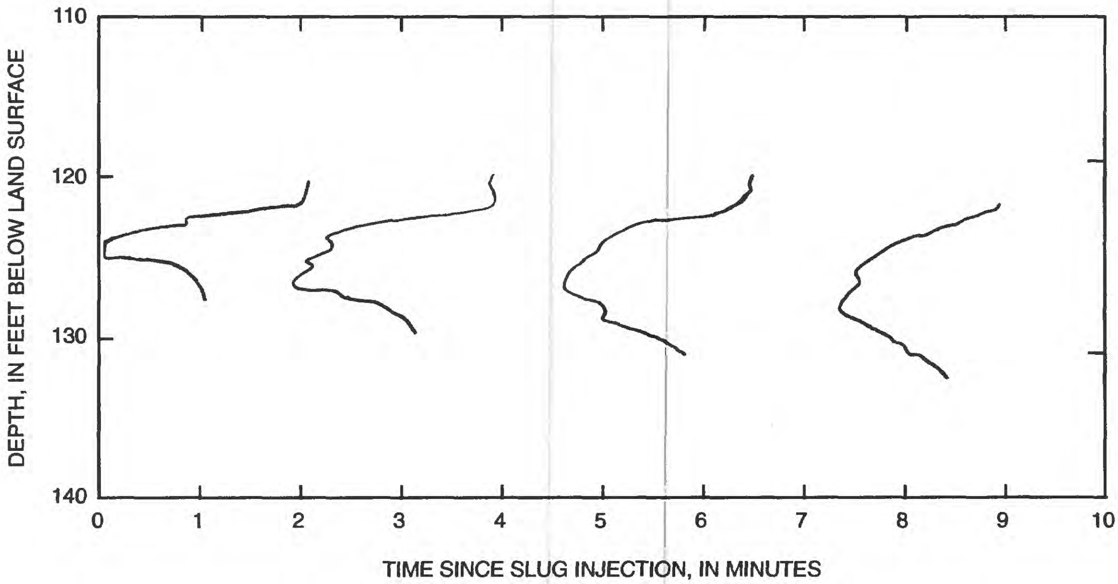


Figure 5. Movement of a high-conductance fluid slug injected 120 feet below land surface in borehole BK–2512, Warminster Township, Pennsylvania.

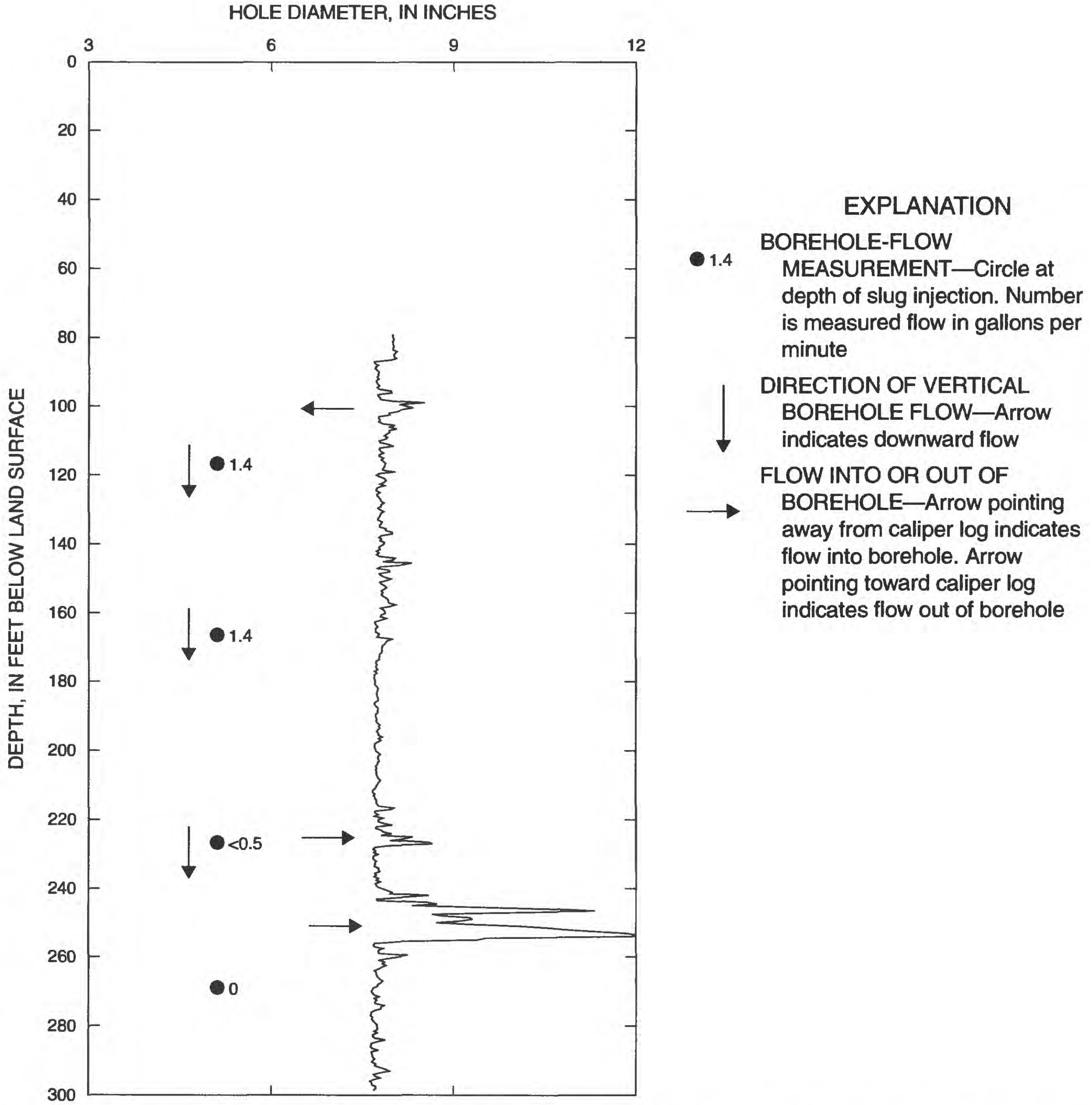


Figure 6. Borehole-flow measurements made in borehole BK–2512, Warminster Township, Pennsylvania.

of the 13 major exposed Triassic-Jurassic rift basins stretching from Nova Scotia to South Carolina. Sedimentation was the result of infilling of a rift basin formed during the initial stages of continental breakup (Turner-Peterson and Smoot, 1985, p. 10). Sedimentation in the Newark Basin began with an influx of arkosic detritus from uplifted crystalline rocks to the south not far from the present-day southern basin margin (Glaeser, 1966, p. 26). One characteristic of the Stockton is the thickbedded to locally massive arkosic sandstones. Sediments were deposited on folded and deeply eroded Precambrian and Paleozoic rocks. The basin filled with thousands of feet of sediments over a period of about 45 million years.

Geology

The Stockton Formation was subdivided into three units called the lower arkose, middle arkose, and upper shale members by Rima and others (1962). Rocks that underlie the study area belong to the middle arkose member; some deep boreholes may penetrate the lower arkose member. The Stockton Formation is 6,000 ft thick near the Bucks-Montgomery County boundary; the middle arkose member accounts for 70 percent of its thickness. In the Hatboro area, the Stockton Formation strikes approximately N. 65° E. and dips approximately 9° NW. (Sloto and others, 1992). The rocks are chiefly arkosic sandstone and siltstone. Quartz and feldspar are the dominant minerals.

The Stockton Formation includes alluvial fans, fluvial and lacustrine sandstones, and fluvial and near-shore lacustrine siltstones (Turner-Peterson and Smoot, 1985). Near its southern margin, the Stockton Formation contains laterally coalescing alluvial fans deposited by well-established streams. Thick, poorly defined, upward fining cycles possibly were deposited by large, perennial, meandering rivers.

Correlation of Lithostratigraphic Units Identified in Rock Cores to Geophysical Logs

Two continuous rock cores were collected at the Raymark Site (MG–1223 and MG–1283), and three continuous rock cores were collected at the Fischer and Porter Site (BK–2516, BK–2517, and BK–2518). The cores provide a continuous record of site geology and reference points to correlate geophysical logs to lithology. Borehole MG–1223 was cored from the land surface to 200 ft bls; borehole MG–1283 was cored from 190 to 300 ft bls. The two boreholes are 5.8 ft apart. Rock cores from coreholes BK–2516, BK–2517, and BK–2518 extend 262 ft, 277 ft, and 274.5 ft bls, respectively. Eight lithologies were identified from the cores and are listed as follows:

1. Siltstone, reddish-brown or dark purple-gray, can be micaceous.
2. Sandstone, pinkish-gray, silty, fine-grained.
3. Sandstone, dark-gray, very fine-grained.
4. Sandstone, gray, fine-grained.
5. Sandstone, gray, poorly sorted, fine- to medium-grained.
6. Sandstone, gray, medium-grained.
7. Sandstone, light-gray, medium- to coarse-grained.
8. Conglomerate, light-gray or brown.

Each lithology contains a variable percentage of silt, organic material (lignite), disseminated iron oxides in pore spaces, stylolites, and fractures. Organic material is accompanied by a localized abundance of sulfide minerals. Most fractures are either filled or partly lined with calcite or kaolinite (in the siltstone units). Some fractures are coated with a light green, soapy textured mineral identified by X-ray diffraction analysis as muscovite.

The rock cores show some gradational lithologic units consistent with the fluvial-deltaic depositional environment of the Stockton Formation. A few transitional layers are characterized as a combination of two lithologic units. Transitional layers appear banded or as a random mixture of material from units above and below. Some portions of the rock cores show bedding structures that dip up to 30° from the horizontal of the core orientation. Stylolites also appear with similar dip angles.

The shale units in the middle arkose member described by Rima and others (1962) were not present in the rock cores and are assumed to have a geophysical response similar to the siltstone units. If a borehole penetrates a shale unit, it would be interpreted as a siltstone unit.

Rock cores were compared with the caliper, natural-gamma, and single-point-resistance logs from each corehole. Variations in natural-gamma and single-point-resistance responses correspond to textural variations. Thin interbeds in each general unit also account for some variation in log response. Overall, siltstone units were identified by an elevated natural-gamma response and a weak single-point-resistance response. Zones of increased borehole diameter (highly fractured zones) shown by the caliper logs correlate with fissile siltstone units; discrete increases in borehole diameter suggest discrete fractures.

Silty, fine-grained sandstone units were identified by an elevated natural-gamma response and commonly parallel variations in natural-gamma and single-point-resistance responses. Very fine- and fine-grained sandstone units were identified by a weak natural-gamma and an elevated single-point-resistance response. Fine-grained sandstone produced the weakest natural-gamma response of all the lithologic units. Stylolites, which cause a sharp spike on the natural-gamma log because they contain gamma-emitting minerals, were observed in the sandstone units of the cores. Because sharp gamma spikes are seen within interpreted sandstone units in logs from other boreholes, stylolites are assumed to be indicators of sandstone.

Poorly sorted, fine- to medium-grained sandstone and medium-grained sandstone units were identified by a weak natural-gamma response and a moderate single-point-resistance response that was less than that of the fine-grained sandstone units. Medium- to coarse-grained sandstone and conglomerate were identified by a weak natural-gamma response and an elevated single-point-resistance response that were weaker than the responses of the fine-grained sandstone units but stronger than the responses of the medium-grained sandstone units.

Correlation of Lithostratigraphy Using Geophysical Logs

Caliper, natural-gamma, and single-point-resistance logs were used for lithostratigraphic correlation. Lithostratigraphic interpretations and correlations were based on the relative response of the geophysical logs for each borehole and on the comparison of the geophysical logs from each borehole with the geophysical and lithologic logs from coreholes. Driller or geologist logs, where available, helped lithologic interpretations.

Because lithologic units of the Stockton Formation grade, interfinger, and coalesce, none of the units could be used as location indicators (marker beds) within the lithostratigraphic sequence. Therefore, the lithology was first interpreted and subsequently a best fit was made to construct lithostratigraphic models. The accuracy of the correlations deteriorates near the land surface because of the absence of single-point-resistance measurements and dampened natural-gamma response caused by casing and dissolution of gamma-producing elements. Correlations among most of the boreholes are consistent with strike and dip. Correlation of geophysical logs was less certain when the distance between boreholes exceeded 400 ft along strike and 300 ft along dip.

The interpreted lithology of each borehole was extended along strike (N. 65° E.) or dip (9° NW.) to the next nearest borehole location to correlate lithostratigraphy. The lithologic units commonly correlated above or below the expected projection line. This is most likely the manifestation of the lens-like structures characteristic of coalescing alluvial fans. Most units have been interpreted to be continuous, dipping to the northwest with only localized shifts in dip because of thinning of units.

Most geophysical logs are affected by borehole diameter (Keys, 1990, p. 28). The diameter of logged boreholes ranged from 2-in.-diameter coreholes to a 14-in.-diameter abandoned public supply well (MG–212). Because relative log response was used to interpret and correlate lithostratigraphy, the effect of borehole diameter on log response was considered inconsequential.

To evaluate the effect of borehole diameter on geophysical logs, borehole BK–1845 was logged twice, once as a 6-in.-diameter borehole and again after it was reamed to a 10-in.-diameter borehole. Major fractures are more distinct on the caliper log of the 6-in.-diameter borehole (fig. 7) than on the caliper log of the 10-in.-diameter borehole, probably because of the reaming. The natural-gamma logs (fig. 7) show higher gamma counts for the 10-in.-diameter borehole than for the 6-in.-diameter borehole, but the pattern of log response is nearly identical. The natural-gamma logs are identical in the lower part of the borehole below 320 ft bls. Single-point-resistance logs show a higher resistance for the 6-in.-diameter borehole than for the 10-in.-diameter borehole, but the pattern of log response is the same (fig. 7); the decrease in resistance is caused by the increase in borehole diameter.

Natural-gamma logs run in boreholes constructed as monitor wells can be used for stratigraphic correlation, even though the gamma response is dampened. For example, borehole BK–2584 (fig. 8) was logged as a 6-in.-diameter open borehole with 19 ft of 6-in.-diameter steel casing shortly after the completion of drilling. The borehole subsequently was constructed as a monitor well with a PVC screen surrounded by a coarse sand filter pack from 254 to 271 ft bls. From the land surface to 254 ft bls, a 2-in.-diameter PVC inner casing was installed, and the annulus between the inner casing and the formation was sealed with a mixture of cement grout and bentonite. Although the response of the natural-gamma log is dampened in the monitor well, the pattern of log response is the same as that of the open borehole (fig. 8).

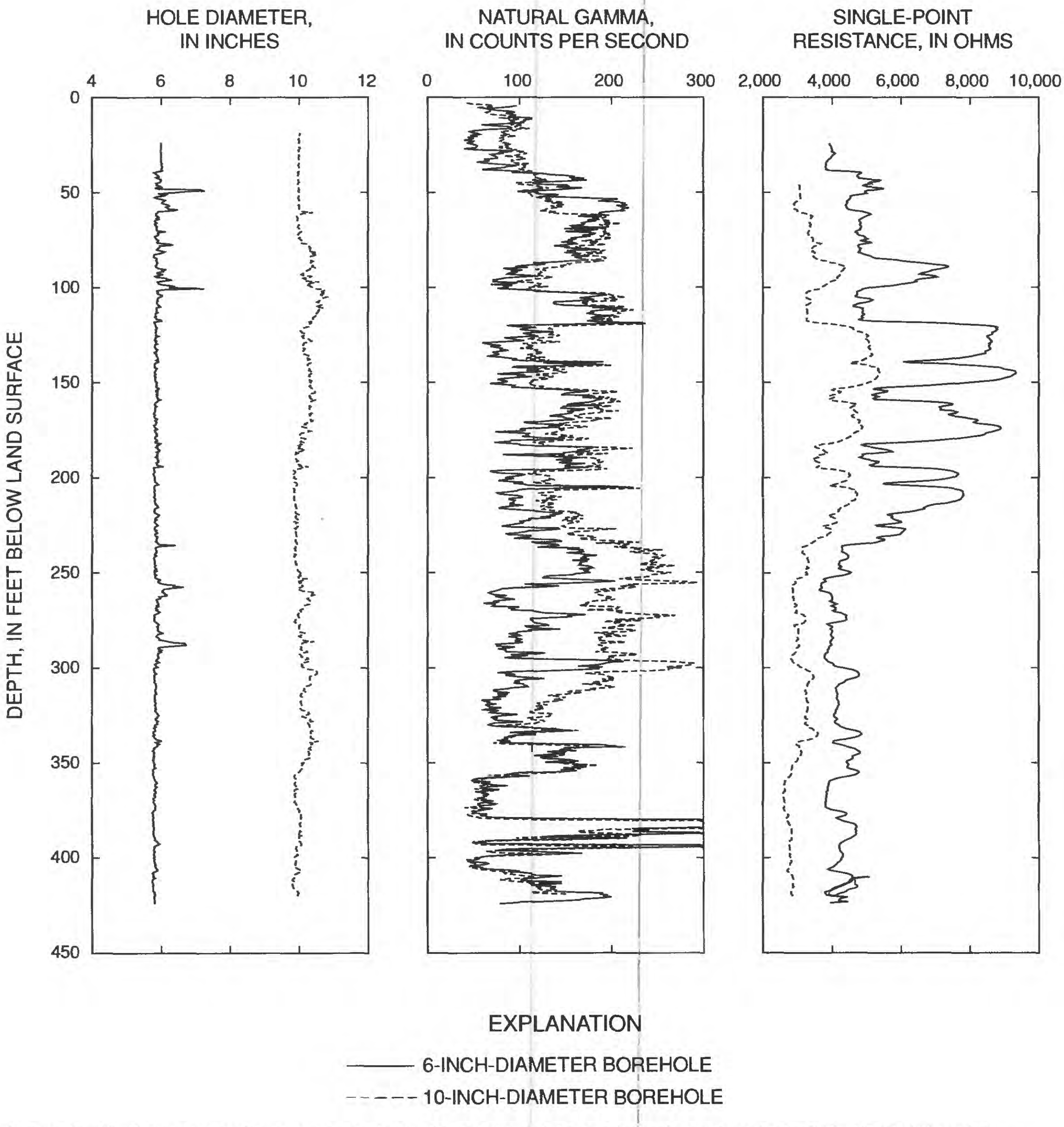


Figure 7. Caliper, natural-gamma, and single-point-resistance logs from borehole BK–1845, Warwick Township, Pennsylvania.

Two lithostratigraphic models were developed for the study area from borehole geophysical logs. A lithostratigraphic model developed for the Fischer and Porter Site was presented by Sloto and others (1996). A lithostratigraphic model for part of Hatboro near the Raymark Site is presented in this report. The interpreted lithostratigraphic correlation of geophysical logs projected to a line approximately along strike is shown on plate 1, and the interpreted lithostratigraphic correlation of geophysical logs projected to line approximately perpendicular to strike (dip direction) is shown on plate 2. The cross sections show the thinning and thickening of units across the area, which is consistent with the lens-like deposition characteristic of alluvial-fan environments. Cross sections also show the grading and pinching of beds, which is characteristic of the Stockton Formation.

Hydrology

In the Stockton Formation, ground water in the weathered zone moves through intergranular openings that have formed from weathering. In

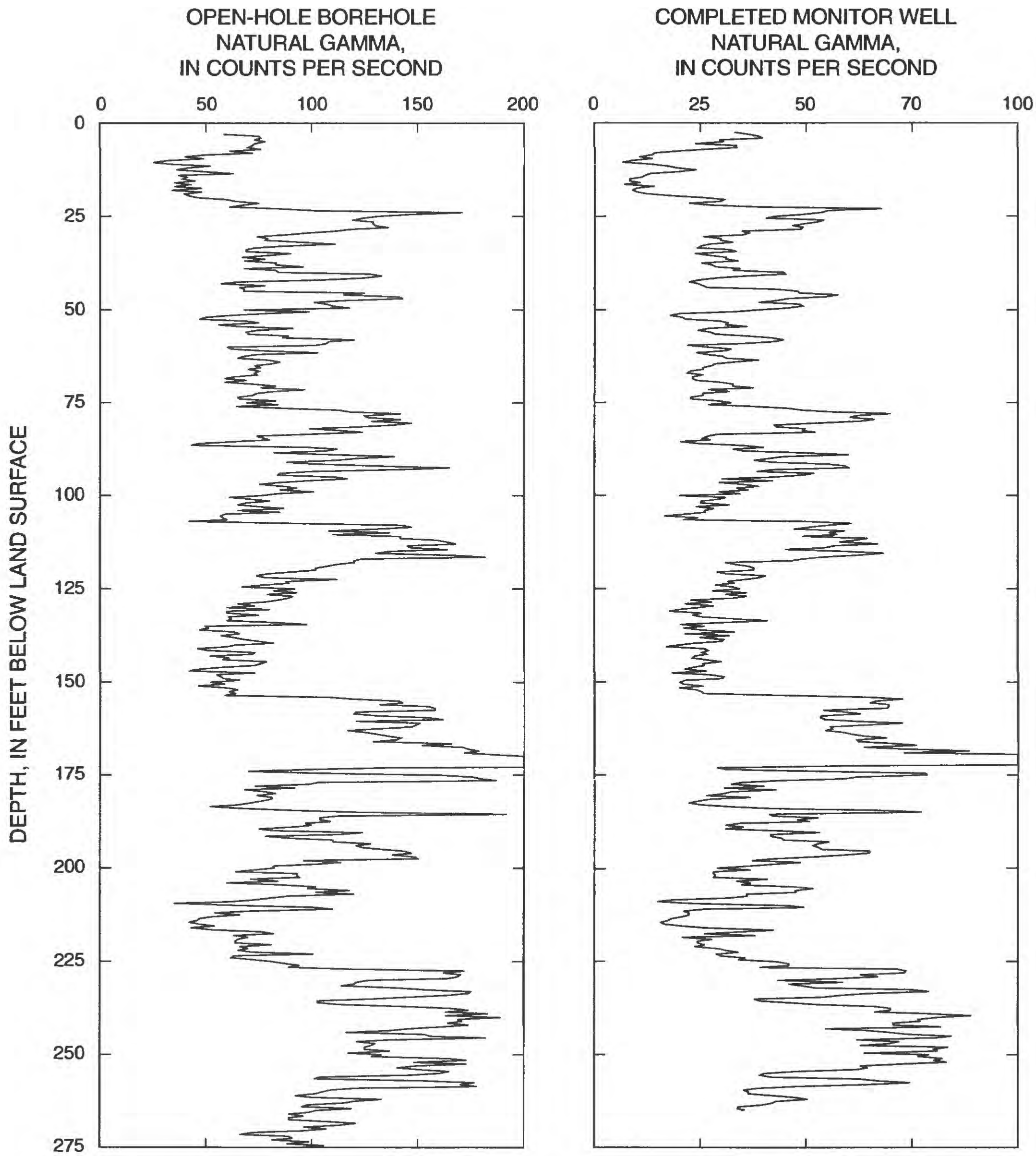


Figure 8. Natural-gamma logs from well BK–2584, Warminster Township, Pennsylvania, before and after construction as a monitor well.

some places, permeability of the weathered zone may be poor because of a high percentage of clay derived from weathering of siltstone. Most ground water in the unweathered zone moves through a network of interconnecting secondary openings—fractures, bedding plane partings, and joints. Horizontal fractures observed in borehole television surveys are aligned with bedding. Some horizontal fractures are within beds, such as the fracture at 78.2 ft bls in borehole BK–2530 (fig. 9), while others are at the contact between beds, such as the fracture at 141.9 ft bls in borehole BK–2536 (fig. 10), which is at the contact between sandstone (upper unit) and siltstone (lower unit). Steeply dipping or nearly vertical fractures within sandstone units generally produce water. A very large, steeply dipping fracture intersected by borehole BK–2597 at 168.5 ft bls is shown in figure 11. The borehole intersects this fracture between 162 and 172 ft bls. This fracture produced 10 gal/min while drilling and produces water that flows upward in the borehole at 6 gal/min under nonpumping conditions (fig. 12).

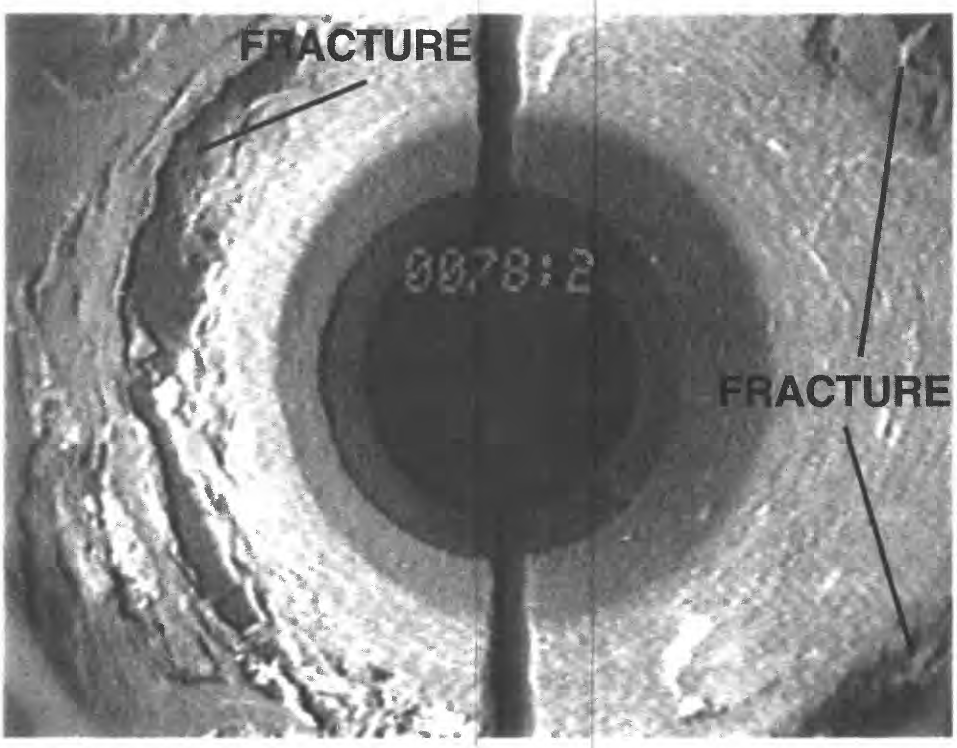


Figure 9. Photograph from borehole television survey of borehole BK–2530, Warminster Township, Pennsylvania, showing a horizontal fracture within a sandstone bed at 78.2 feet below land surface.

Beds within the Stockton Formation are hydraulically connected by vertical joints throughout that cross each other at various angles; therefore, ground water may move across beds, particularly in the direction of dip, rather than through individual beds. Some water-bearing openings may be slightly enlarged by circulating ground water that has weathered and eroded mineral constituents in fractures. Primary porosity that existed before lithification has been almost eliminated by compaction and cementation. Some water may move through intergranular openings in the rock where the cement has been removed and the permeability has increased, but this generally is restricted to only a few sandstone and conglomerate beds.

The rocks of the Stockton Formation form a complex, heterogeneous, multiaquifer system (Sloto and Davis, 1983). This aquifer system consists of a series of gently dipping lithologic units with different hydraulic properties. The ground-water system can be visualized as a series of dipping sedimentary beds with a high transmissivity separated by beds with a low transmissivity. The beds, a few inches to a few feet thick, act as a series of alternating aquifers and confining or semiconfining units that form a leaky, multiaquifer system. Each bed generally has different hydraulic properties, and permeability commonly differs from one bed to another. In general, the sandstone units are the principle water-bearing units, but some finer grained units may contain water-bearing zones. However, because of the softness and fine grain size of the siltstone units, water-bearing openings clog. In addition, the soft siltstone beds deform without breaking under stress and, as a result, have lower permeability than the harder sandstone beds, which develop fractures and joints under stress and are more permeable.

Ground water is unconfined in the shallower part of the aquifer system and semiconfined or confined in the deeper part of the aquifer system. Ground water is confined under pressure greater than atmospheric by overlying, less permeable lithologic units. Differences in the ratio of vertical to horizontal hydraulic conductivity and differences in vertical hydraulic conductivity within and among lithologic units create confining conditions.

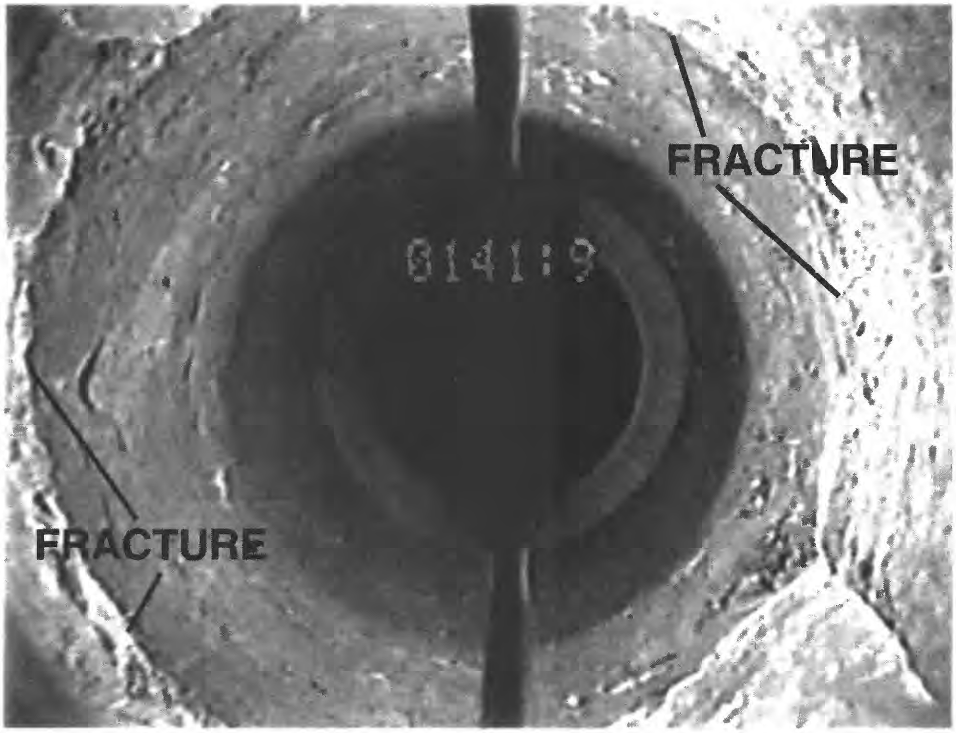


Figure 10. Photograph from borehole television survey of borehole BK–2536, Warminster Township, Pennsylvania, showing a horizontal fracture at the contact between a sandstone bed (upper bed) and a siltstone bed (lower bed) at 141.9 feet below land surface.

Figure 11. Photograph from borehole television survey of borehole BK–2597, Warminster Township, Pennsylvania, showing a nearly vertical fracture at 168.5 feet below land surface.

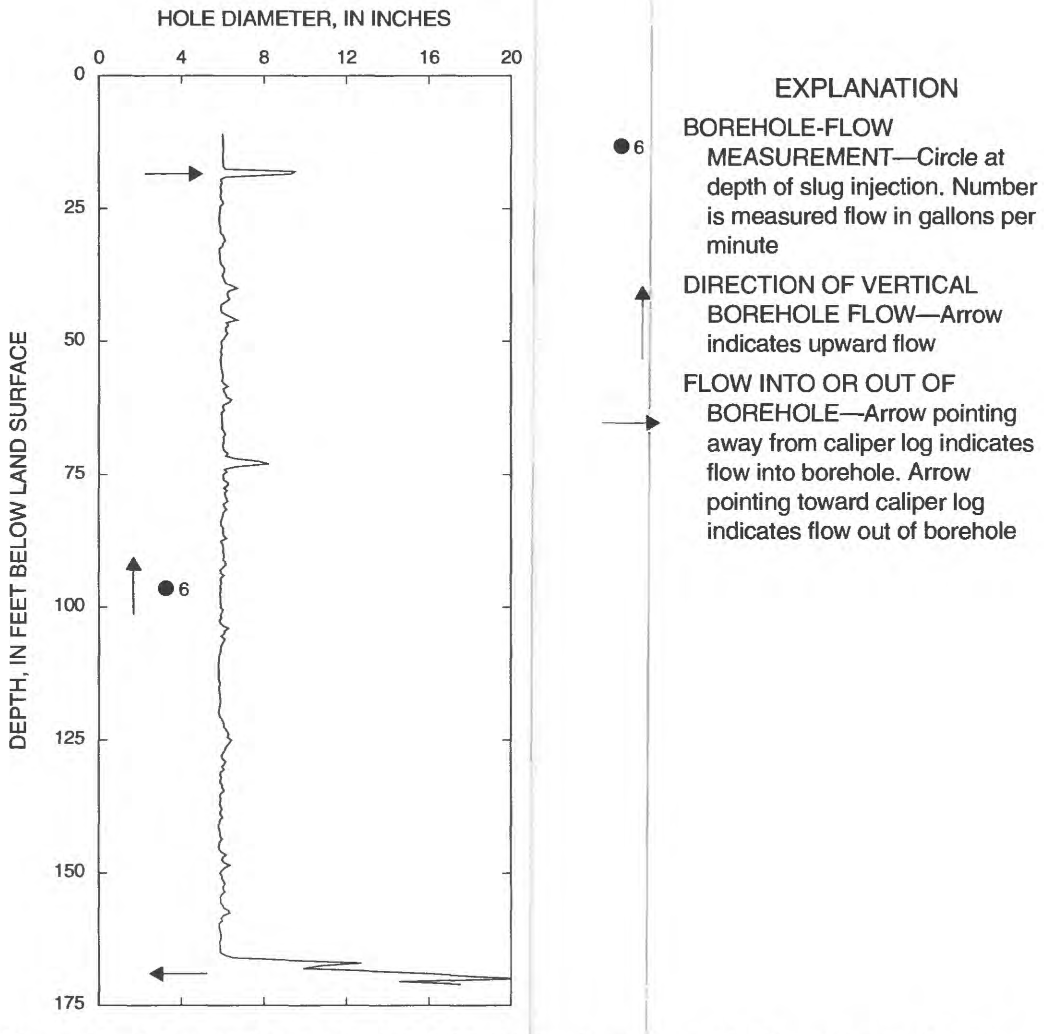


Figure 12. Caliper log from borehole BK–2597, Warminster Township, Pennsylvania, showing borehole-flow measurement.

Nearly all deep wells in the Stockton Formation are open to several water-bearing zones and are multi-aquifer wells. Each water-bearing zone usually has a different hydraulic head. The hydraulic head in a deep, open-hole well is the composite of the heads in the several water-bearing zones penetrated. 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.

Water-level measurements made at the MG–1222 monitor well cluster at the Raymark Site (fig. 2) on August 5, 1991, showed a water level 36.48 ft bls for the open interval 33–63 ft bls, a water level 49.91 ft bls for the open interval 118–138 ft bls, and a water level 55.85 ft bls for the open interval 185–195 ft bls (fig. 13). At the Raymark Site, water moves downward through the aquifer system in response to this downward head gradient, which is caused in part by the pumping of deep public supply wells.

The response of water levels in the MG–1222 monitor well cluster to the pumping of public supply well MG–944 (Hatboro-14), 3,800 ft away along strike, is shown in figure 14. The response of the water level in the deep monitor well (MG–1222), which is screened from 185 to 195 ft bls, is very pronounced; the pumping schedule of well MG–944 can be clearly seen in the hydrograph. Pumping of well MG–944 caused daily water-level changes up to 2.53 ft in well MG–1222. The response of the water level in the intermediate-depth monitor well, which is screened from 118 to 138 ft bls, to the pumping of well MG–944 can be seen, but the daily change in water level is less than 0.15 ft.

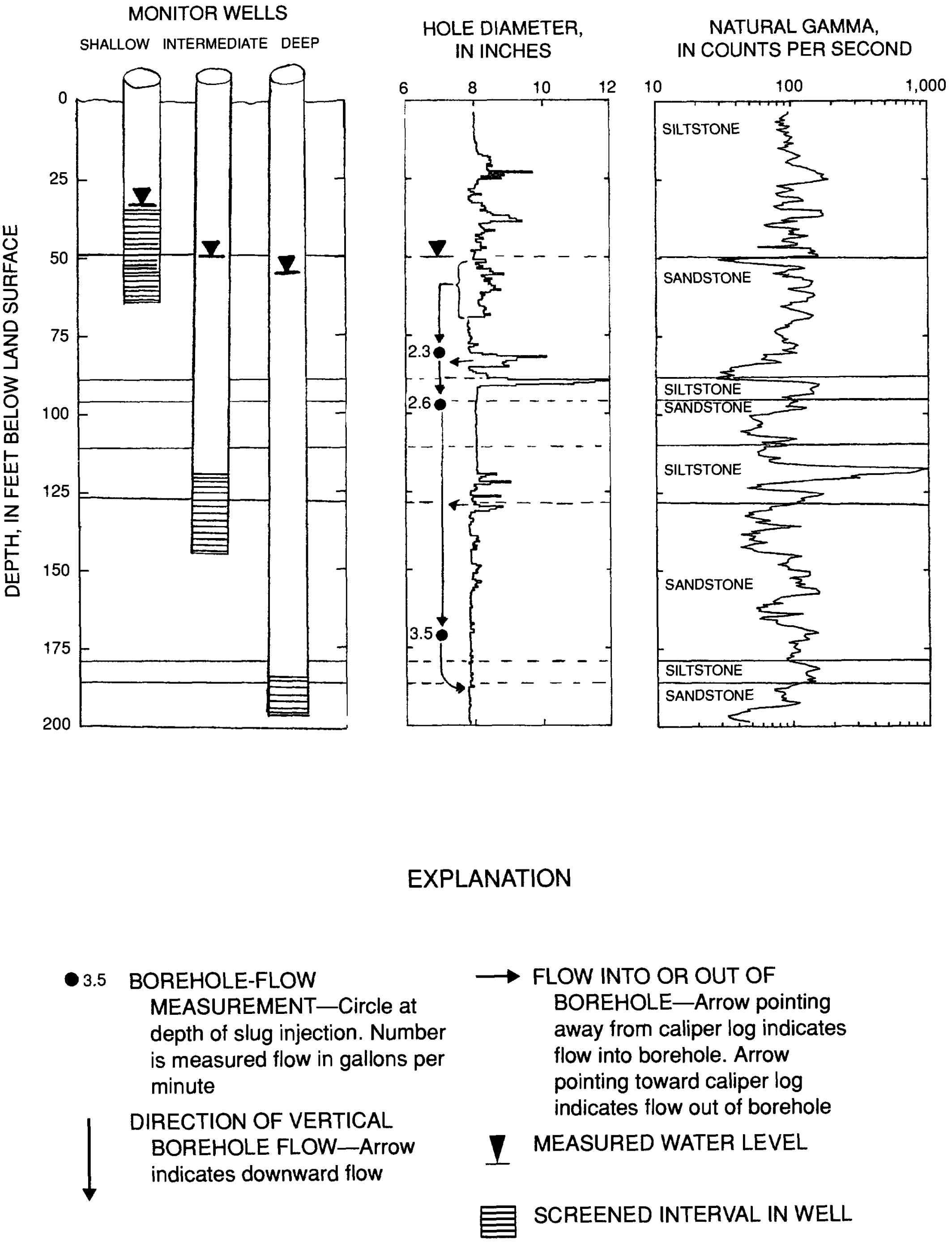


Figure 13. Caliper, natural-gamma, and generalized lithologic logs; screened intervals; borehole-flow measurements; and water levels for the MG–1222 monitor well cluster, Hatboro Borough, Pennsylvania.

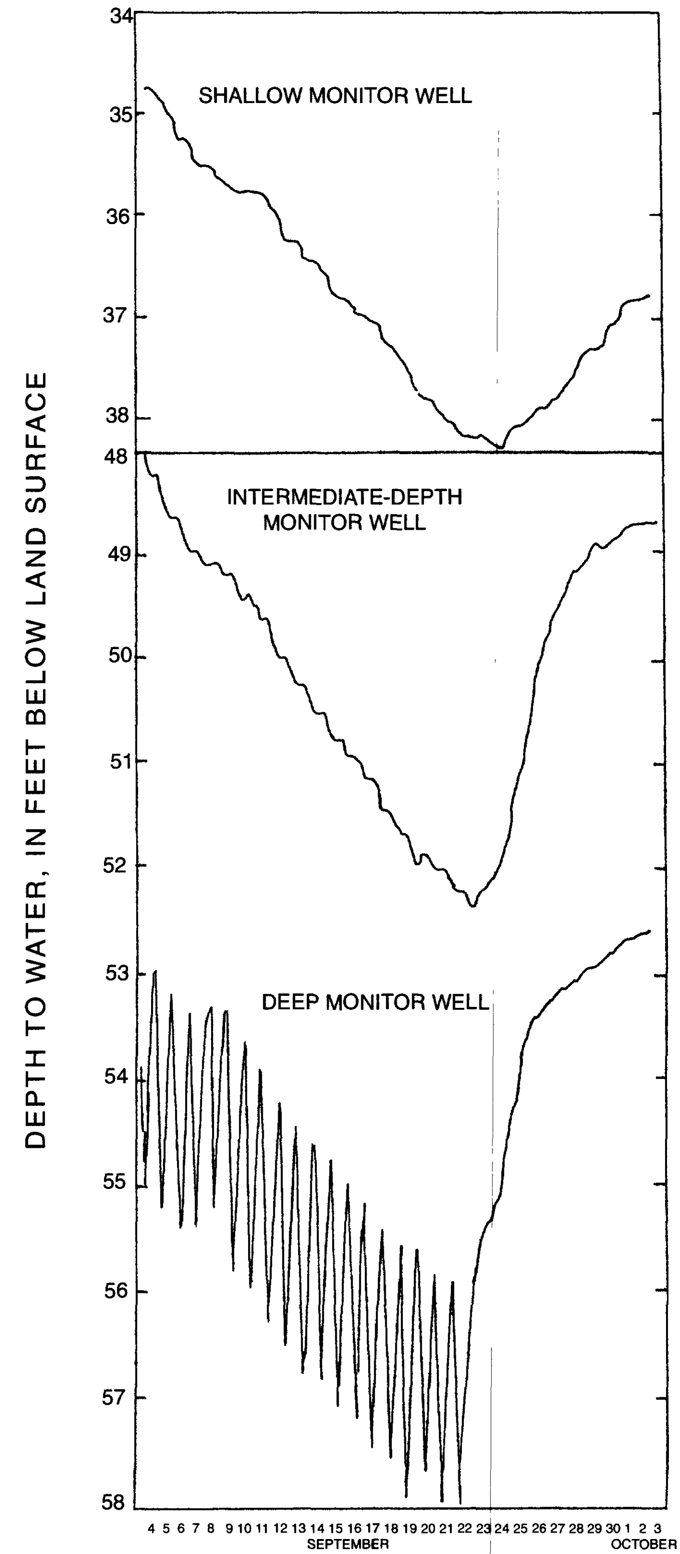


Figure 14. Hydrographs from the MG–1222 monitor well cluster, Hatboro Borough, Pennsylvania, September 4 to October 3, 1991.

The water level in the shallow monitor well, which is screened from 33 to 63 ft bls, does not show a daily water-level fluctuation caused by the pumping of well MG–944 but does show a rise in water level when well MG–944 stopped pumping. On September 23, pumping of well MG–944 ceased; the resultant recovery of water levels in each screened zone in the MG–1222 monitor well cluster also is shown on figure 14. Water levels recovered 5.47 ft in the deep zone, 3.67 ft in the intermediate-depth zone, and 1.47 ft in the shallow zone. A downward head gradient is still present.

Hydraulic Properties of the Rock Matrix

Hydraulic properties of the rock matrix were determined in the laboratory from two cores collected at the Raymark Site. Borehole MG–1223 was cored from the land surface to 200 ft bls, and borehole MG–1283 was cored from 190 to 300 ft bls.

The porosity of several lithologic units in the rock core from borehole MG–1223 was estimated from thin sections prepared from the core. Two slides were prepared from each of 10 core sections, one perpendicular to the core axis and one parallel to the core axis, to estimate porosity and other characteristics associated with or perpendicular to bedding planes. The thin sections were prepared with a blue epoxy resin for easy identification of pore spaces.

In the thin sections, all of the sandstone units are noticeably compacted, and the grains are partly crushed. Sutured grain boundaries are common, but all pore space is not eliminated. The siltstone units are extremely fine grained. Using an estimated percentage of pore space observed in two-dimensional space (horizontal and vertical directions), an approximate pore volume was calculated for each thin section (table 1).

Mean porosity is 3 percent for siltstone, 22.5 percent for silty, fine-grained sandstone, 9.6 percent for fine-grained sandstone, 8.6 percent for medium-grained sandstone, and 5.6 percent for coarse-grained sandstone (fig. 15). This is similar to laboratory porosity measurements made on rock samples from outcrops by Rima and others (1962, p. 29). Porosity is higher in the horizontal direction than in the vertical direction. Porosity generally increases with increasing grain size from siltstone to silty, fine-grained sandstone and then decreases with increasing grain size from silty, fine-grained sandstone to medium- to coarse-grained sandstone. Fine- and medium-grained sandstones are better sorted than the coarse-grained sandstones. Finer grained units exhibit a decrease in porosity as grain size decreases, most likely because of infilling of pore space by clay- and silt-sized particles. The medium-grained sandstone sample from 20 to 20.3 ft bls has additional porosity created by dissolution from weathering of the unit. Rima and others (1962, p. 30) found that porosity

Table 1. Porosity estimated from thin sections of rock cores from boreholes MG–1223 and MG–1283, Hatboro Borough, Pennsylvania

[<, less than]

Borehole identification number	Depth (feet below land surface)	Lithology	Porosity (percent)	
			Horizontal direction	Vertical direction
MG–1223	20–20.3	Sandstone, gray, medium-grained, weathered	20–25	10
MG–1223	23.7–24	Sandstone, gray, medium-grained	1	1
MG–1223	34.3–34.5	Siltstone, reddish purple	3	3
MG–1223	54.6–54.8	Sandstone, silty, fine-grained	25	20
MG–1223	88.5–88.9	Sandstone, gray, fine-grained	1–2	2
MG–1223	104.2–104.4	Sandstone, gray, fine-grained, weathered	25	10
MG–1223	127.4–127.8	Siltstone	5	1
MG–1223	159.8–160	Siltstone to fine-grained sandstone	1	<1
MG–1223	188.3–188.5	Sandstone, gray, medium- to coarse-grained	7–10	3–5
MG–1283	224.5–224.7	Sandstone, gray, medium- to coarse-grained	5–7	3–5

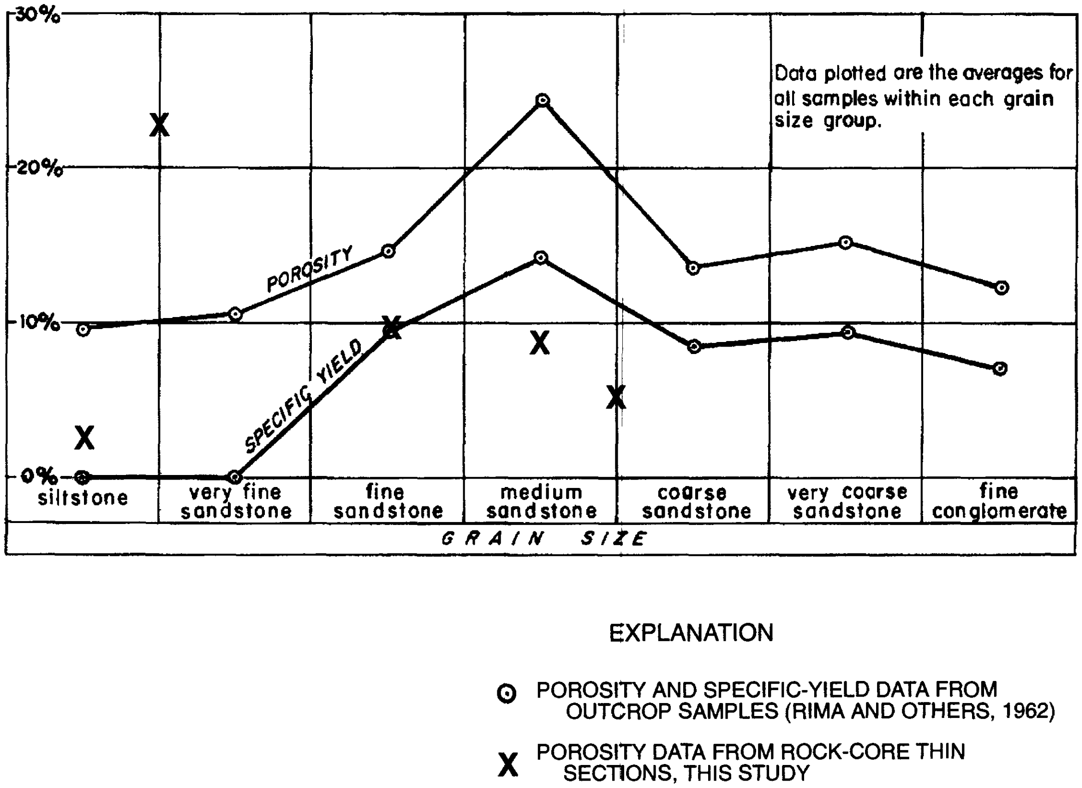


Figure 15. Porosity of the rock matrix determined from outcrop samples and rock-core thin sections. Modified from Rima and others (1962, p. 29).

was consistently greater than the specific yield for each lithologic unit, which means that the aquifer will not yield to gravity flow all of the water contained in the pore spaces.

Laboratory hydraulic conductivity measurements were made on three sections of the rock core from borehole MG–1223 and one section of the rock core from borehole MG–1283 (table 2). The tests followed the procedures developed by Olsen and others (1991). Hydraulic conductivity ranges more than seven orders of magnitude. The core samples, except one, were very smooth and were unsaturated. The core section, a sandstone unit from 224.5 to 224.7 ft bls that had the highest laboratory hydraulic conductivity, had a grainy feel and was saturated, showing some primary porosity. Deep monitor wells at the Raymark Site penetrate this sandstone unit. The combination of primary and secondary porosity of this unit enables the strong hydraulic connection with public supply well MG–944 shown on figure 14.

Table 2. Hydraulic conductivity determined in the laboratory from rock cores from boreholes MG–1223 and MG–1283, Hatboro Borough, Pennsylvania

Borehole identification number	Depth (feet below land surface)	Lithology	Hydraulic conductivity (feet per day)
MG–1223	86.1–86.3	Sandstone, gray, fine-grained	1.18×10^{-4}
MG–1223	130.0–130.2	Sandstone, red, silty, fine-grained	2.92×10^{-6}
MG–1223	161.0–161.2	Siltstone, red	5.14×10^{-7}
MG–1283	224.5–224.7	Sandstone, gray, medium- to coarse-grained	0.19

Borehole-Flow Measurements

Measurements of vertical fluid movement in boreholes under nonpumping conditions were made in 93 boreholes in the study area. Slugs of high-conductance fluid were injected in 83 boreholes at different depths to determine the direction and rate of borehole flow (brine-tracing method). As many as nine slugs were injected in a single borehole. Fluid movement at rates up to 17 gal/min was measured. No flow was measurable in 18 boreholes. The direction and rate of borehole flow were indeterminable for nine boreholes by use of the brine-tracing method. Difficulty in determining borehole flow is caused by horizontal flow through the formation, low velocities caused by large-diameter boreholes (up to 14 in. in diameter), rough-sided boreholes, and fast slug movement. A heat-pulse flowmeter was used to measure borehole flow in 10 boreholes.

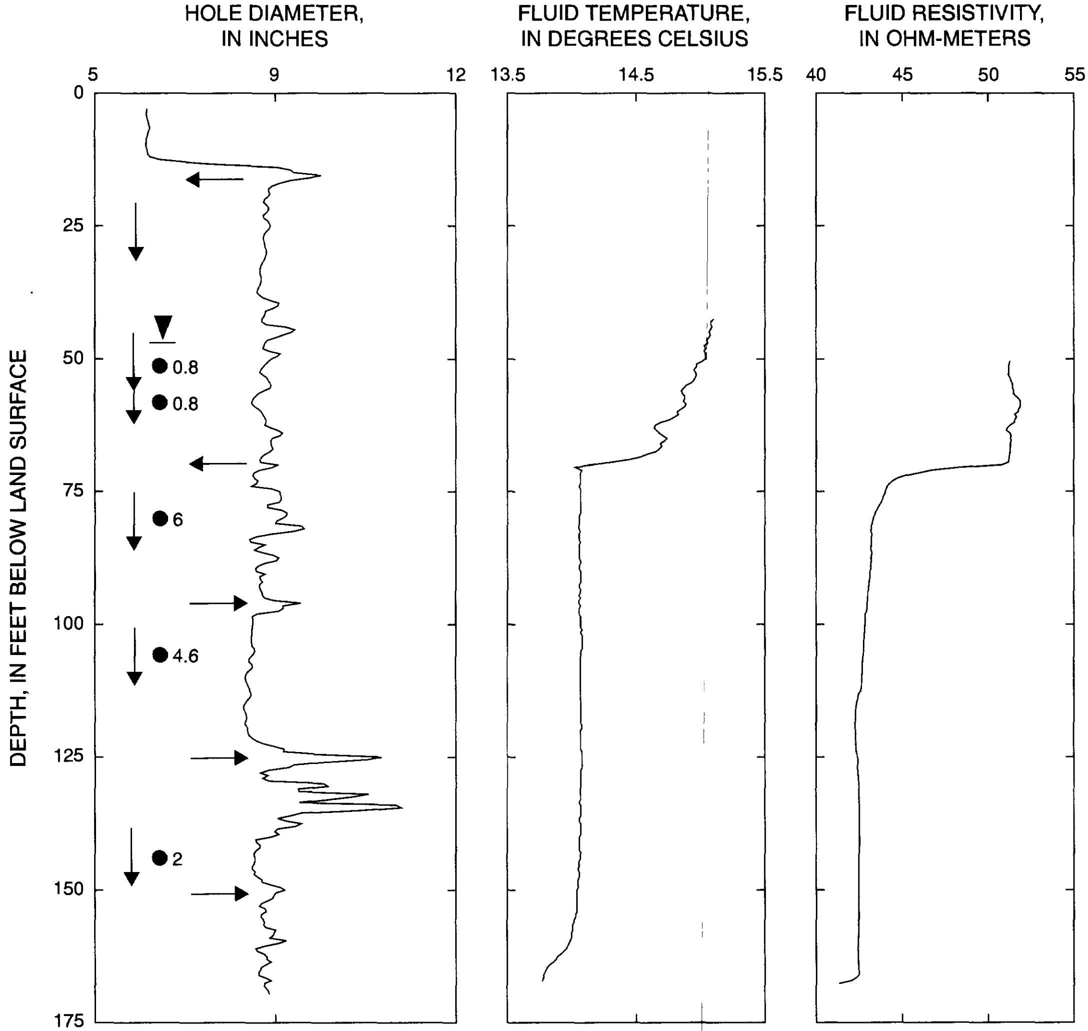
The predominant direction of vertical borehole flow measured in Hatboro Borough and in Warminster Township near the Fischer and Porter Site is downward, primarily caused by a downward head gradient formed in response to the pumping of public supply wells in the area. Downward flow was measured in 36 boreholes, not including those boreholes in which two directions of flow were measured. These boreholes ranged from 149 to 510 ft in depth. Generally, fluid movement is downward from fractures in the siltstone and sandstone units in the upper part of the aquifer system, which is unconfined, to fractures in the sandstone units in the lower part of the aquifer system, which is semiconfined or confined. The fluid movement measured in borehole MG–1236 is shown in figure 16. Water cascades into the borehole at 0.8 gal/min from a fracture at 16.5 ft bls, which is above the water level. An additional 5.2 gal/min of water enters the borehole through a fracture at 70 ft bls and moves downward. Water exits the borehole through fractures at 96 ft (1.4 gal/min), 125 ft (2.6 gal/min), and 150 ft (2 gal/min) bls.

Upward vertical flow was measured in 23 boreholes, which ranged from 71 to 591 ft deep. Many of these boreholes are just northwest of the topographic divide between the Pennypack and Little Neshaminy Creek drainage basins. The divide approximately parallels the strike of the Stockton Formation, and boreholes northwest of the divide penetrate younger beds that crop out in upsection, upgradient areas. The fluid movement measured in borehole BK–2600 is shown in figure 17. Water enters the borehole at a rate of 4.4 gal/min through fractures at 126–129 ft bls and moves upward. An additional 0.3 gal/min enters the borehole through a fracture at 93 ft bls. Water exits the borehole through fractures at 50.5 ft (3.5 gal/min) and 28 ft (1.2 gal/min) bls.

Both upward and downward vertical flow was measured in six boreholes. These boreholes ranged from 396 to 470 ft deep and were among the deepest boreholes logged. Fluid movement was upward in the upper part of the borehole and downward in the lower part of the borehole in two boreholes. The fluid movement measured in borehole BK–1845 is shown in figure 18. Borehole BK–1845 is about 100 ft from Little Neshaminy Creek, and the expected head gradient would be upward in a discharge area. Water enters the borehole at a rate of 1.9 gal/min through a fracture at 340 ft bls and moves upward at a rate of 1.2 gal/min and downward at a rate of 0.7 gal/min. Water exits the borehole through a fracture at the bottom of the borehole. Additional water enters the borehole through fractures at 236 ft (1.7 gal/min) and about 165 ft (2.1 gal/min) bls and moves upward. Water exits the borehole at a rate of 5 gal/min through a fracture at 49 ft bls, just below the casing.

Fluid movement was downward in the upper part of the borehole and upward in the lower part of the borehole in three boreholes. The fluid movement measured in borehole BK–949 is shown in figure 19. In the upper part of the borehole, water enters at a rate of 2 gal/min through a fracture at 126 ft bls and moves downward. An additional 2.9 gal/min of water enters the borehole through fractures at 169–174 ft bls. Water exits the borehole through fractures at 188 ft (1.5 gal/min) and 220 ft (3.4 gal/min) bls. In the lower part of the borehole, water enters at a rate of 1.4 gal/min through a fracture at 384 ft bls, moves upward, and exits the borehole through fractures at 303–307 ft bls. A zone of no borehole flow between 220 and 303 ft bls separates the two zones of flow.

Fluid movement in some boreholes is very complex. The fluid movement in borehole BK–2794 was measured by use of a heat-pulse flowmeter (fig. 20). The heat-pulse-flowmeter measurements show two zones of upward flow with a zone of downward flow between them. Water enters the borehole at a rate of 0.26 gal/min through a fracture at 111 ft bls and moves upward at a rate of 0.18 gal/min and downward at a rate of 0.8 gal/min. Water also enters the borehole at a rate of 0.02 gal/min through a fracture at 212 ft bls and moves upward. Water moving downward from the fracture at 111 ft bls and upward from the fracture at 212 ft bls exits the borehole through a fracture at 147 ft bls. Water moving upward from the fracture at 111 ft bls exits the borehole through fractures at 70 ft (0.11 gal/min), 60 ft (0.06 gal/min), and 28 ft (0.03 gal/min) bls.



EXPLANATION

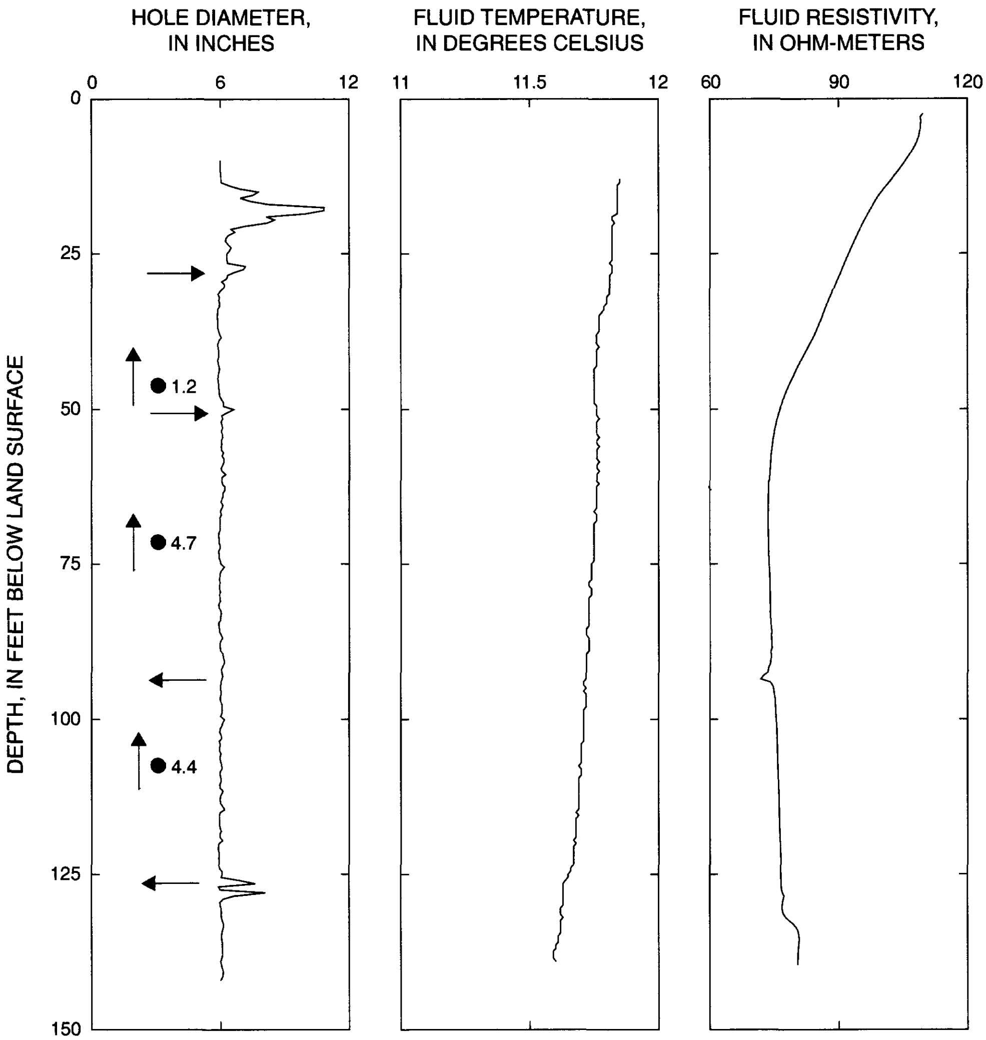
● 6 BOREHOLE-FLOW MEASUREMENT—Circle at depth of slug injection. Number is measured flow in gallons per minute

DIRECTION OF VERTICAL BOREHOLE FLOW—Arrow indicates downward flow

FLOW INTO OR OUT OF BOREHOLE—Arrow pointing away from caliper log indicates flow into borehole. Arrow pointing toward caliper log indicates flow out of borehole

MEASURED WATER LEVEL

Figure 16. Caliper, fluid-temperature, and fluid-resistivity logs from borehole MG–1236, Hatboro Borough, Pennsylvania, showing borehole-flow measurements.



EXPLANATION

● 4.7 BOREHOLE-FLOW MEASUREMENT—Circle at depth of slug injection. Number is measured flow in gallons per minute

↑ DIRECTION OF VERTICAL BOREHOLE FLOW—Arrow indicates upward flow

→ FLOW INTO OR OUT OF BOREHOLE—Arrow pointing away from caliper log indicates flow into borehole. Arrow pointing toward caliper log indicates flow out of borehole

Figure 17. Caliper, fluid-temperature, and fluid-resistivity logs from borehole BK–2600, Warminster Township, Pennsylvania, showing borehole-flow measurements.

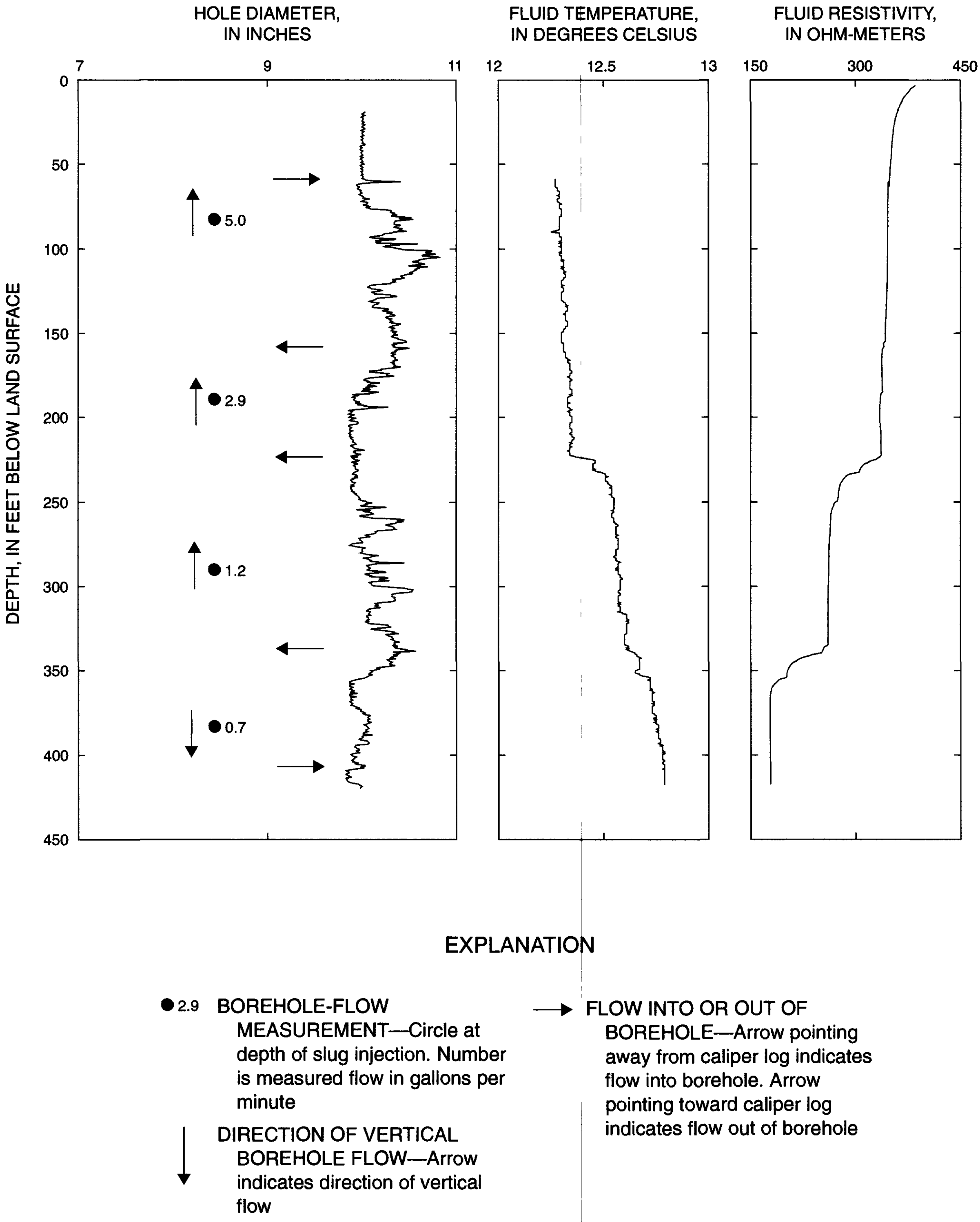
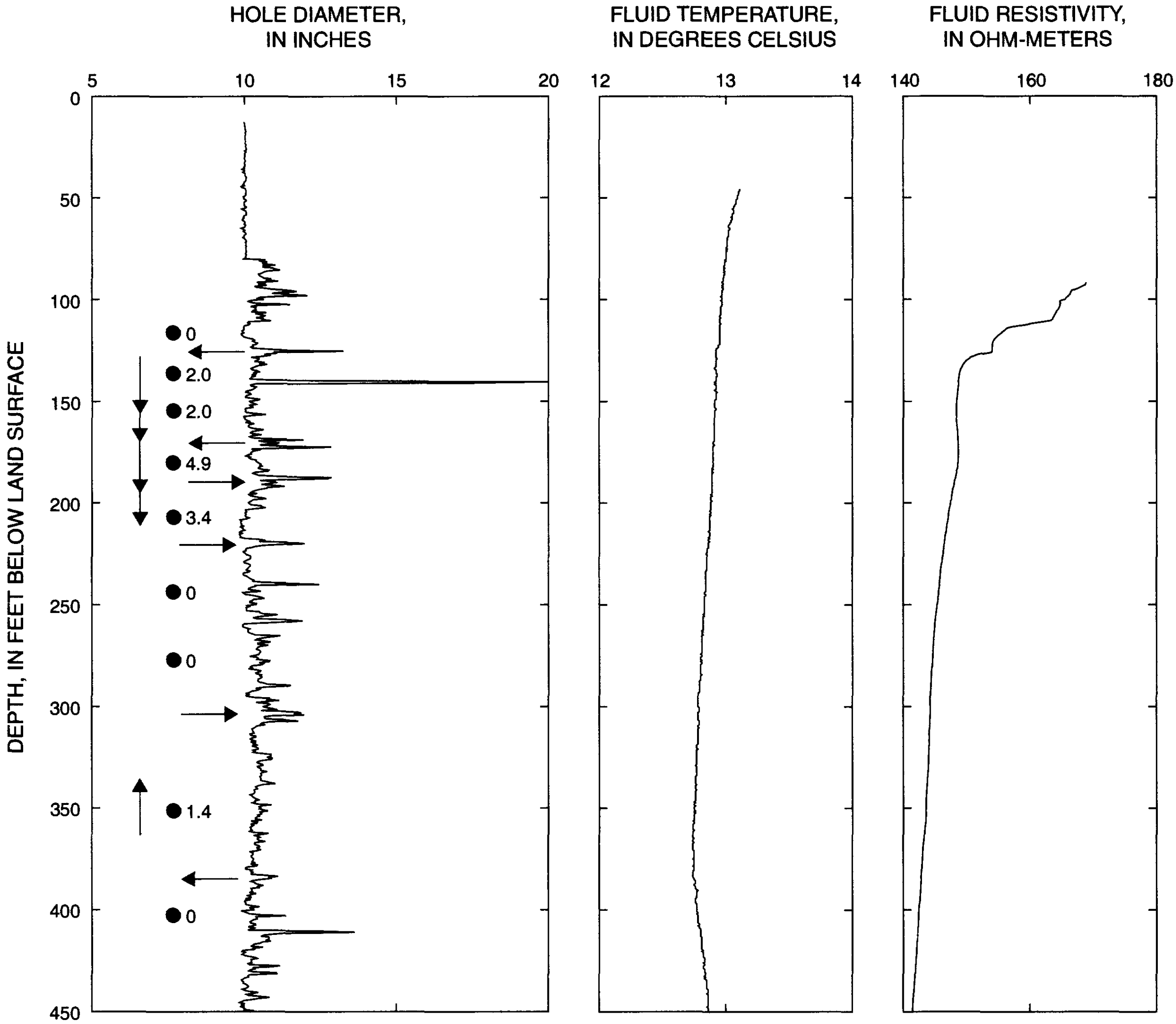


Figure 18. Caliper, fluid-temperature, and fluid-resistivity logs from borehole BK–1845, Warwick Township, Pennsylvania, showing borehole-flow measurements.



EXPLANATION

3.4 BOREHOLE-FLOW MEASUREMENT—Circle at depth of slug injection. Number is measured flow in gallons per minute

DIRECTION OF VERTICAL BOREHOLE FLOW—Arrow indicates direction of vertical flow

FLOW INTO OR OUT OF BOREHOLE—Arrow pointing away from caliper log indicates flow into borehole. Arrow pointing toward caliper log indicates flow out of borehole

Figure 19. Caliper, fluid-temperature, and fluid-resistivity logs from borehole BK–949, Warminster Township, Pennsylvania, showing borehole-flow measurements.

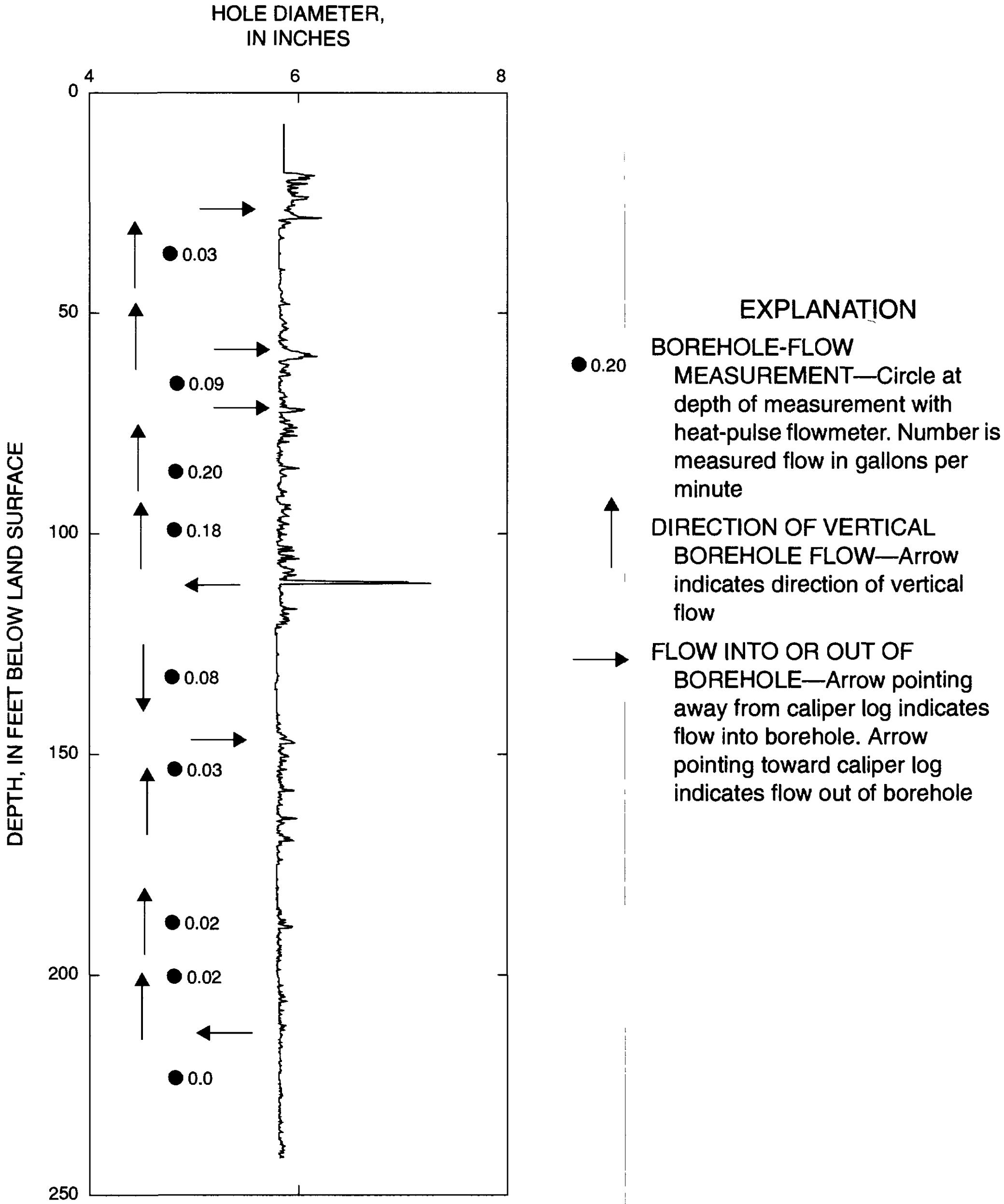


Figure 20. Caliper log from borehole BK–2794, Warminster Township, Pennsylvania, showing borehole-flow measurements made with a heat-pulse flowmeter.

Ground-Water Quality

Water samples were collected for field and laboratory analysis from 24 boreholes with measurable borehole flow. More than one depth interval was sampled in four boreholes. Water samples also were collected from 14 pumping wells, mostly active public supply wells in the Hatboro Authority water system. Well MG–1235 was sampled after 47 hours of pumping during a 48-hour aquifer test. Well-construction data are listed in table 6 at the back of this report. Water samples were analyzed for some chemical and physical properties (pH, temperature, specific conductance, alkalinity, and dissolved oxygen) in the field. Samples were analyzed for selected dissolved inorganic constituents, nutrients, and radon and total VOC's by the USGS National Water-Quality Laboratory in Arvada, Colo. Results of field determinations and chemical analyses are listed in tables 7–9 at the back of this report.

Inorganic Constituents

Ground-water samples were grouped by shallow borehole-flow samples (samples collected at depths less than 85 ft bls, 13 samples), deep borehole-flow samples (samples collected at depths greater than 90 ft bls, 12 samples), and pumping-well samples (active public supply wells, 15 samples). Shallow borehole-flow samples were assumed to represent ground water with a short flow path and residence time. Deep borehole-flow samples were assumed to represent ground water with an intermediate flow path and residence time. Pumping-well samples were assumed to represent ground water with a long flow path and residence time.

Ground water in the Stockton Formation is predominantly of the calcium bicarbonate type; shallow borehole-flow samples contain less calcium and bicarbonate than the other samples (fig. 21), probably because calcite ($CaCO_3$) has been leached from the shallow part of the aquifer system. The water sample from borehole MG–1240 plots as a sodium chloride type of water because the borehole is at a former road-salt storage site, and the water from this borehole is contaminated with road de-icing salt; the concentration of chloride is 240 mg/L. Water from public supply wells MG–946 (Hatboro-16) and MG–947 (Hatboro-17), near MG–1240, also contains elevated concentrations of chloride (93 mg/L and 83 mg/L, respectively), suggesting that part of the source area for water pumped from wells MG–946 and MG–947 is updip to the southeast.

The interaction between water and the rocks of the Stockton Formation was evaluated by use of the SOLMINEQ.88 geochemical modeling computer program of Kharaka and others (1988). The model computes the equilibrium distribution of inorganic aqueous species generally present in ground water by use of interpolated disassociation constants and computed activity coefficients. States of reaction of the aqueous solution with respect to 220 solid phases (minerals) are computed from the distribution of aqueous species by use of a consistent set of thermodynamic data.

Model results showed little difference between shallow and deep borehole-flow samples or between borehole-flow samples and pumping-well samples. These results indicate that most cations and anions in ground water probably have their source in the weathered upper few feet or tens of feet of the formation. Nearly all ground-water samples were saturated with respect to minerals of the smectite group (illite, kaolinite, dickite, and pyrophyllite), gibbsite, and halloysite. These minerals are predominant in the soil of the study area. Soil analyses in the study area give the average mineral composition as 33–36 percent illite, 30–32 percent montmorillonite (a smectite group mineral), 21–24 percent kaolinite, 14–17 percent vermiculite, and 5 percent chlorite (Tompkins, 1975). Gibbsite and halloysite are secondary minerals derived from the weathering of aluminum silicates.

Nearly all ground-water samples also were saturated with respect to albite, microcline, quartz, potassium feldspar, muscovite, and paragonite (sodium-rich mica). The average composition of nine arkose samples from the Stockton Formation given by Rima and others (1962, p. 17) was 62 percent quartz, 34 percent feldspar, and 1 percent mica. Feldspar minerals from the Stockton Formation, in order of decreasing abundance, are orthoclase, microcline, albite, oligoclase, perthite, and microperthite. Matrixes are of three distinct types: (1) kaolinite-illite and hematite; (2) chlorite, sericite (fine-grained muscovite), and pulverized quartz grains; and (3) finely disseminated sericite. The cementing materials are authigenic quartz, authigenic feldspar, and carbonates, chiefly calcite (Rima and others, 1962, p. 20).

Volatile Organic Compounds

Trichloroethylene (TCE), tetrachloroethylene (PCE), and 1,1,1-trichloroethane (TCA) are among the most commonly used industrial solvents. Besides these compounds, several other organic compounds not commonly used in the study area

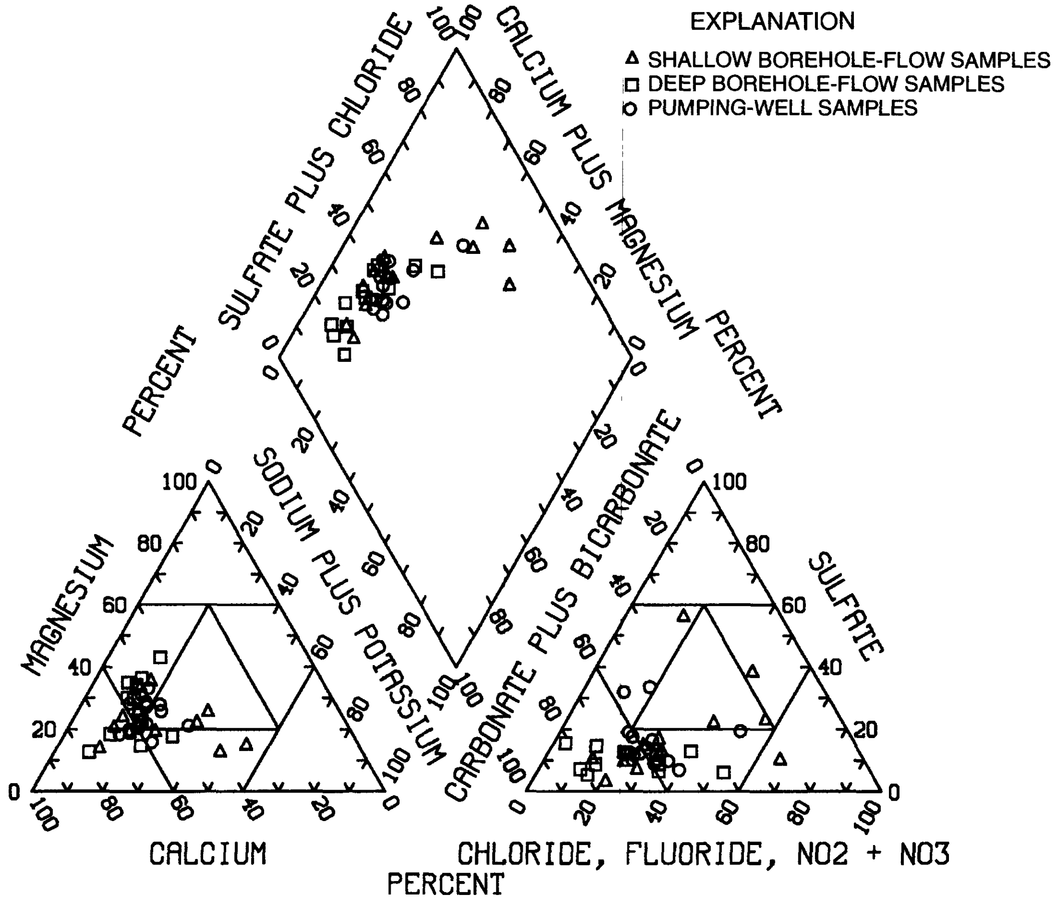


Figure 21. Piper diagram of cation-anion percentages for pumping-well, shallow borehole-flow, and deep borehole-flow water samples, Hatboro Borough and Warminster Township, Pennsylvania.

are found in ground water. Compounds, such as trans-1,2-dichloroethene (DCE), 1,1-dichloroethane (DCA), and vinyl chloride (VC), are degradation products of other VOC's. Under anaerobic conditions, PCE successively degrades by reductive dehalogenation to TCE; cis-1,2-DCE, trans-1,2-DCE, and (or) 1,1-DCE; chloroethane; and VC (Parsons and others, 1985; Vogel and McCarty, 1985; Freedman and Gossett, 1989). TCA anaerobically degrades to DCA. A typical reaction pathway for anaerobic degradation of PCE and TCE by reductive dehalogenation is shown in figure 22.

Ground-water contamination by VOC's is widespread in the study area. Detectable concentrations of VOC's were present in water samples from all 24 wells sampled in Hatboro Borough and in water samples from 10 of 14 wells (71 percent) sampled in Warminster Township (fig. 23). The VOC's detected in water samples are summarized in table 3. Of 43 VOC's analyzed for, 20 compounds (47 percent) were detected. Chloroform was the most commonly detected VOC (28 wells or 74 percent of wells sampled), followed by TCE (26 wells or 68 percent), and PCE and TCA (24 wells or 63 percent). Chloroform is a common laboratory contaminant, and if it is present in ground water, the source may be leaking water-distribution and sewer lines. Most of the study area is supplied with public water and sewers.

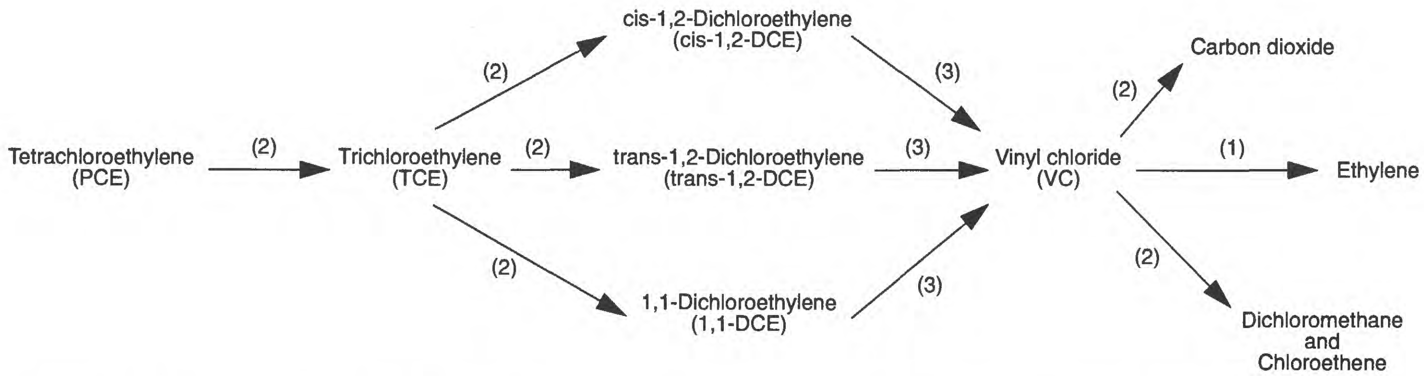
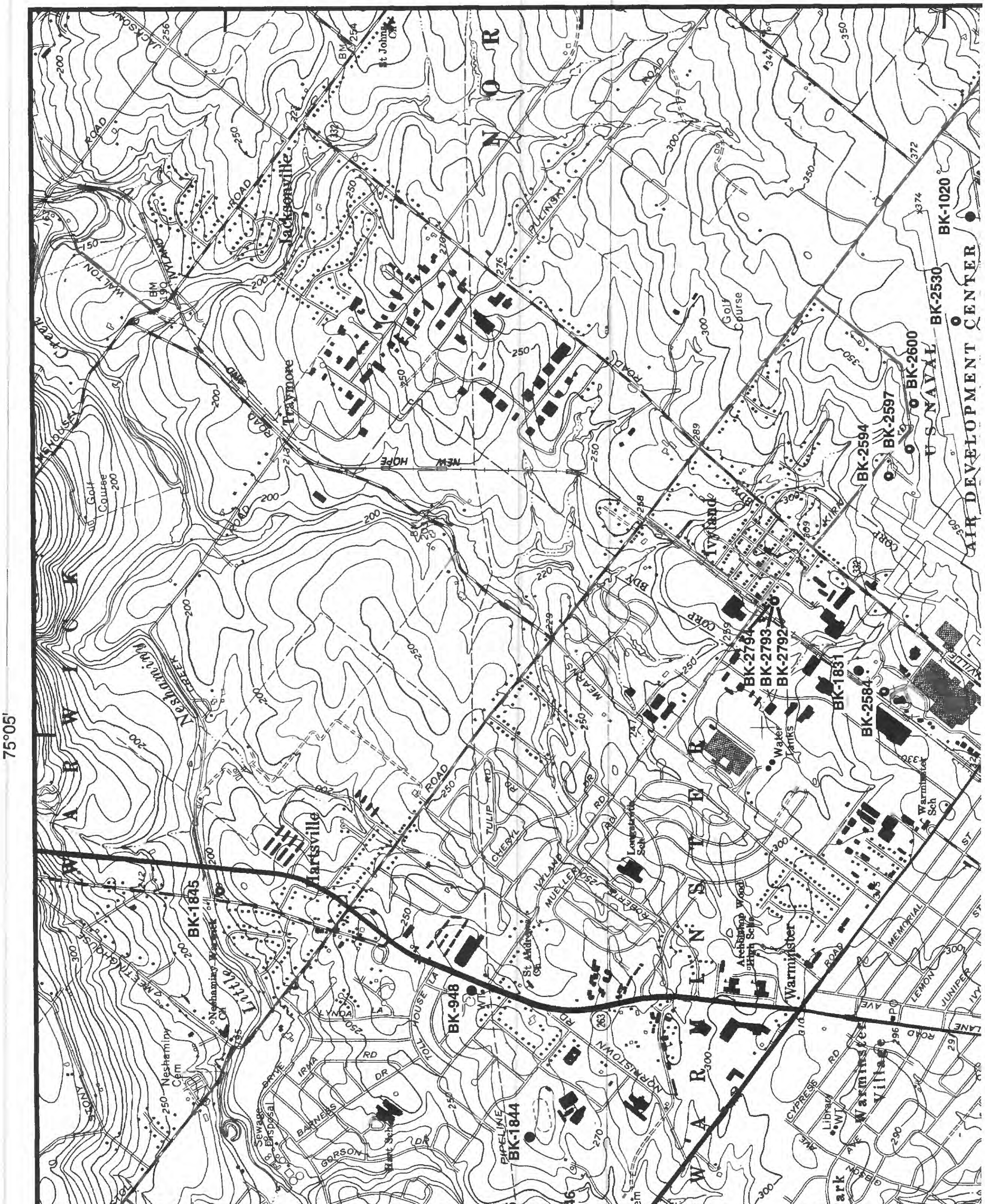


Figure 22. Typical reaction pathways for the anaerobic degradation of tetrachloroethylene and trichloroethylene by reductive dehalogenation. Reactions from: (1) Freedman and Gossett (1989); (2) Parsons and others (1985); and (3) Vogel and McCarty (1985).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Jacksonville
Traymore
Hartsville
Ivyland
Warminster
Warminster Village
Rosewood Park
Neshaminy Creek
Little Neshaminy Creek
BK-1845
BK-948
BK-1844
BK-1145
BK-1146
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BK-2530
BK-1020

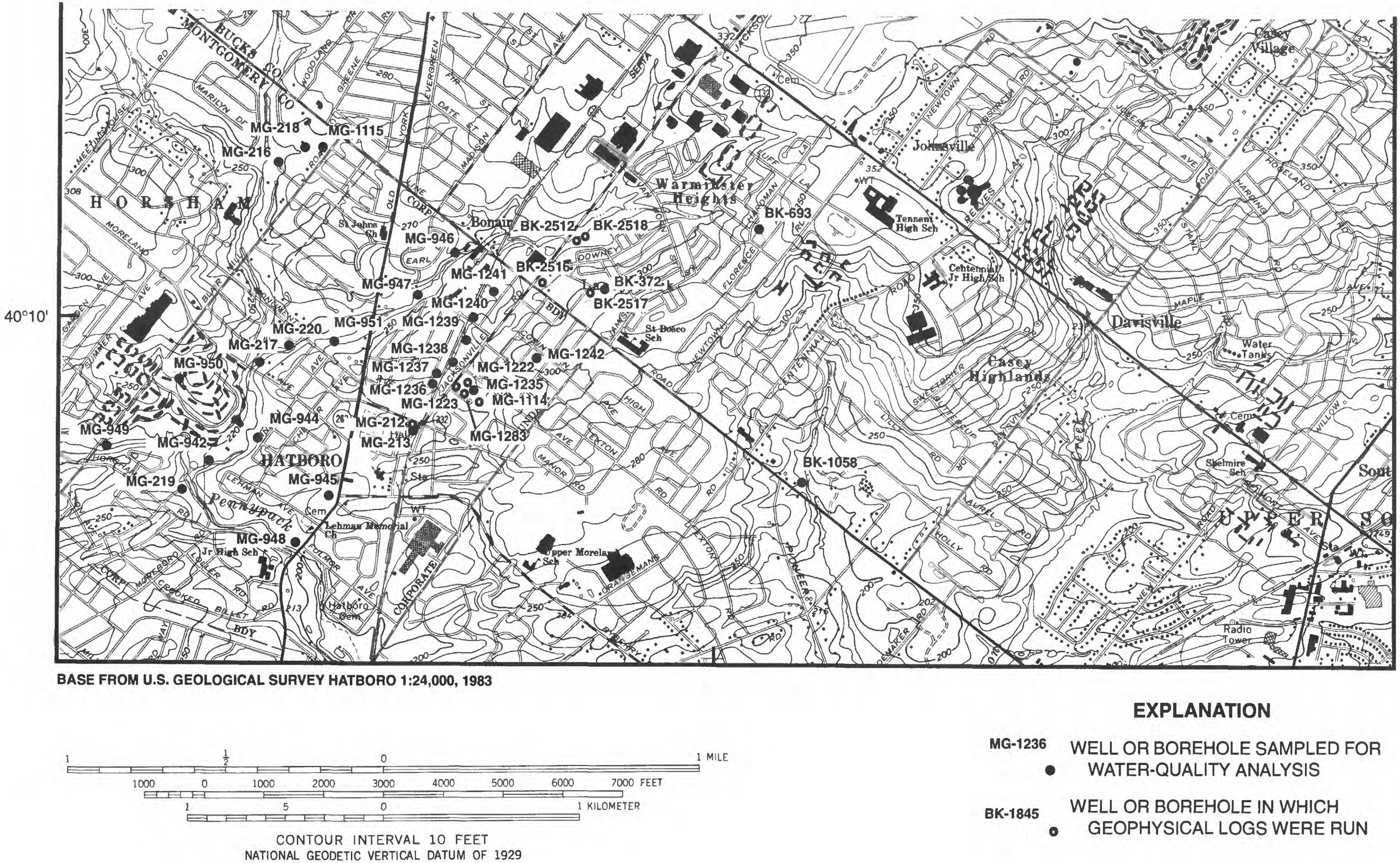


Figure 23. Location of boreholes and wells sampled for chemical analysis and selected boreholes and wells in which geophysical logs were run, Hatboro Borough and Warminster Township, Pennsylvania.

Table 3. Volatile organic compounds detected in ground water, Hatboro Borough and Warminster Township, Pennsylvania

[Concentrations in micrograms per liter]

Compound	Number of wells in which compound was detected	Maximum concentration detected
Benzene	2	0.5
Bromoform	2	2.1
Carbon tetrachloride	5	25
Chlorodibromomethane	2	1.6
Chloroform	28	15
Dichlorobromomethane	4	.6
Dichlorodifluoromethane	1	.2
1,1-Dichloroethane	11	14
1,2-Dichloroethane	2	5.6
1,1-Dichloroethylene	11	260
trans-1,2-Dichloroethylene[1]	17	72
1,2-Dichloropropane	2	60
Methylene chloride	2	.4
Tetrachloroethylene	24	170
Toluene	5	1.2
1,1,1-Trichloroethane	24	1,400
1,1,2-Trichloroethane	3	.4
Trichloroethylene	26	5,800
Trichlorofluoromethane	3	.9
Vinyl chloride	3	1.4

[1]trans-1,2-Dichloroethylene and cis-1,2-dichloroethylene reported as trans-1,2-dichloroethylene.

CROSS-CONTAMINATION THROUGH OPEN BOREHOLES

Extent of Cross-Contamination

In the industrial area of northern Hatboro along and to the west of Jacksonville Road, samples of borehole fluid moving in nine boreholes (fig. 24) were collected for laboratory analysis to quantify aquifer cross-contamination. None of the boreholes sampled were on an NPL site. After intervals of borehole flow were determined from the geophysical logs, a sample of the moving fluid was extracted with a nitrogen-driven bladder pump at a rate less than that of the measured borehole flow and was analyzed for VOC's. Downward flow was measured in all of the boreholes; the samples represent water moving from the shallow to the deeper part of the aquifer.

Water samples from all nine boreholes contained detectable concentrations of VOC's. TCE and PCE were detected in samples from all of the boreholes, and chloroform, TCA, and trans-1,2-DCE were detected in samples from eight of the nine boreholes. Concentrations of TCE, TCA, and 1,1-DCE as great as 5,800, 1,400, and 260 µg/L, respectively, show that some water moving downward in the aquifer through these open boreholes is highly contaminated and that open boreholes may contribute substantially to the movement of ground-water contamination. Concentrations of VOC's detected in the borehole-flow samples are summarized in table 4. Because these water samples represent water moving through open boreholes from the shallow to the deeper part of the aquifer system, sample data can be used to show the extent of aquifer cross-contamination in this area.

The rate of borehole flow is known; therefore, concentrations of VOC's in the water samples can be used to estimate the downward mass flux and the extent of aquifer cross-contamination. The mass of each compound moving downward in the aquifer through an open borehole annually was estimated from the measured borehole-flow rate and results of chemical analysis of the fluid by

$$M = 1.99\, Q\, C,$$

where

- M is the quantity of a compound moving down a borehole annually, in grams per year;
- Q is the measured borehole flow, in gallons per minute; and
- C is the concentration of the compound in the borehole fluid, in micrograms per liter.

Because most of the boreholes were sampled once and concentrations of VOC's vary temporally, the mass flux estimates should be considered an approximation. The data can be used to provide an estimate of the amount of cross-contamination.

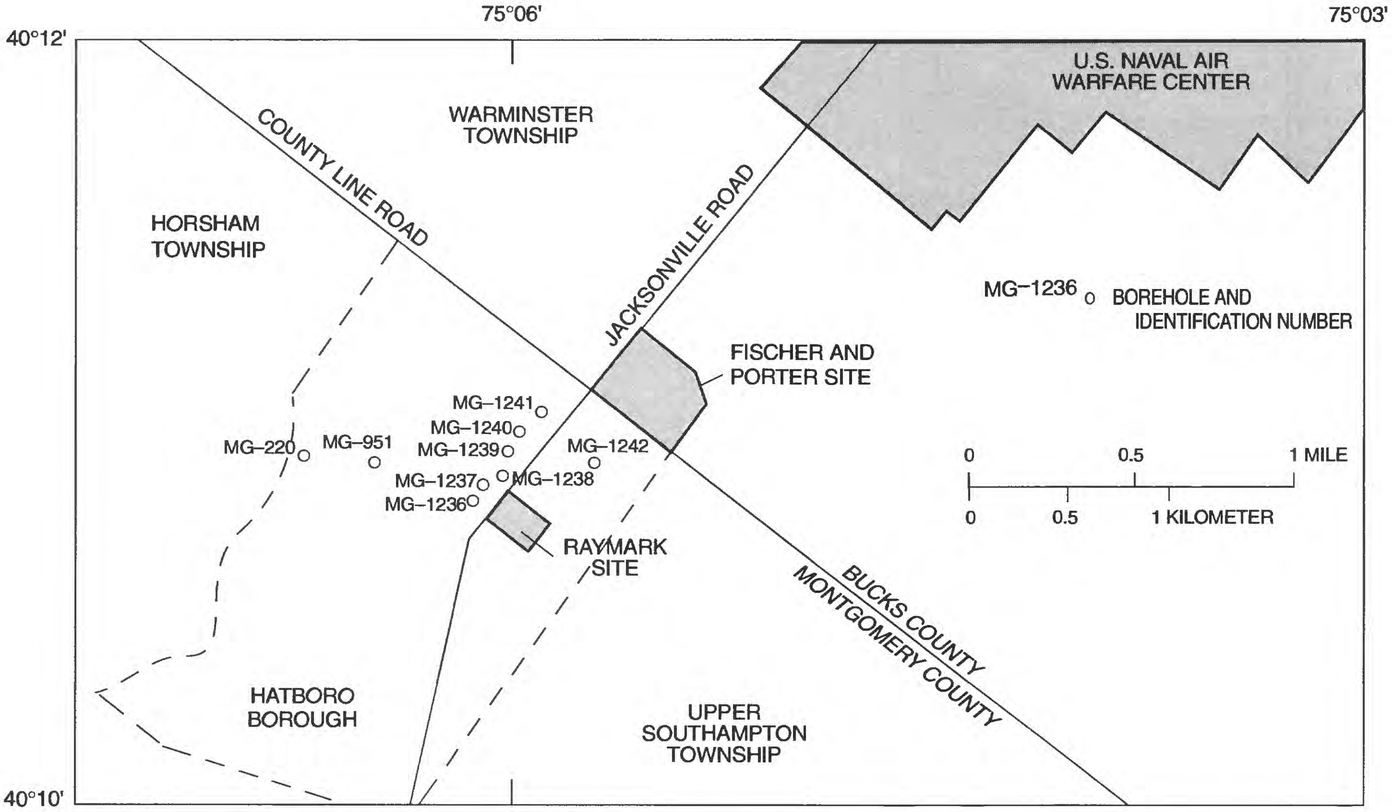


Figure 24. Boreholes sampled for volatile organic compounds in the Jacksonville Road area, Hatboro Borough, Pennsylvania.

An estimated 80.6 kg/yr (14.7 gal/yr) of VOC's (table 5) were moving downward through the nine open boreholes sampled from the contaminated, upper part of the aquifer to the lower part. TCE accounted for 94 percent and TCA accounted for 3 percent of the compounds by mass.

Borehole MG–1239 is at the site of the former Roberts and Mander Stove Company, which manufactured gas kitchen ranges from the late 1800's to the early 1950's. The borehole is behind the former foundry building. Borehole-flow samples show concentrations of TCE and TCA as high as 5,800 and 1,400 μg/L, respectively (table 9). The pumping of public supply well MG–947 (Hatboro-17), 1,100 ft downdip, causes a daily water-level change of approximately 3.3 ft in borehole MG–1239, indicating a strong hydraulic connection. On the basis of borehole geophysical logs and borehole-flow measurements, water containing elevated concentrations of VOC's enters borehole MG–1239 between 50 and 60 ft bls and moves downward at 0.7 gal/min to a fluid-receiving zone about 136 ft bls. Water then moves through the deeper part of the aquifer to well MG–947.

In response to a verbal presentation of study results by the USGS in 1993, the USEPA Superfund Removal Branch plugged or reconstructed five of the sampled boreholes (MG–220, MG–951, MG–1238, MG–1239, and MG–1240). Boreholes MG–1236, MG–1237, MG–1241, and MG–1242 were reconstructed by the USGS so that they are now open only to a single water-bearing zone. The aquifer cross-contamination problem caused by known open boreholes in the Jacksonville Road area of Hatboro has been eliminated.

Prevention of Ground-Water Cross-Contamination

Borehole geophysical logs were used as a guide to design and construct monitor-well networks at all three NPL sites. Generally, a deep (150–350 ft) borehole was drilled at each monitor-well cluster site, and a suite of geophysical logs was run. Interpretation of geophysical logs enabled the identification of water-bearing zones that produce and receive water; these zones should not be connected. From the logs, discrete intervals to be monitored were selected.

The monitor-well network at the Raymark Site serves as an example of how geophysical logs were used as a guide to design and construct monitor wells that do not cause cross-contamination. The USEPA's investigation of the Raymark Site included the drilling and construction of nine monitor wells (three cluster locations with three wells in each cluster) and the reconstruction of an existing open borehole to eliminate cross-contamination.

Table 4. Volatile organic compounds detected in borehole-flow samples from nine sampled boreholes in the Jacksonville Road area, Hatboro Borough, Pennsylvania

[Concentrations in micrograms per liter]

Compound	Number of boreholes in which compound was detected	Maximum concentration detected
Benzene	1	0.5
Bromoform	1	.4
Carbon tetrachloride	4	25
Chlorodibromomethane	1	.2
Chloroform	8	15
Dichlorobromomethane	2	.4
1,1-Dichloroethane	6	14
1,2-Dichloroethane	2	5.6
1,1-Dichloroethylene	6	260
trans-1,2-Dichloroethylene[1]	8	72
1,2-Dichloropropane	2	60
Methylene chloride	2	.4
Tetrachloroethylene	9	57
Toluene	1	.2
1,1,1-Trichloroethane	8	1,400
1,1,2-Trichloroethane	2	.4
Trichloroethylene	9	5,800
Trichlorofluoromethane	1	.9
Vinyl chloride	2	1.4

[1]trans-1,2-dichloroethylene and cis-1,2-dichloroethylene reported as trans-1,2-dichloroethylene.

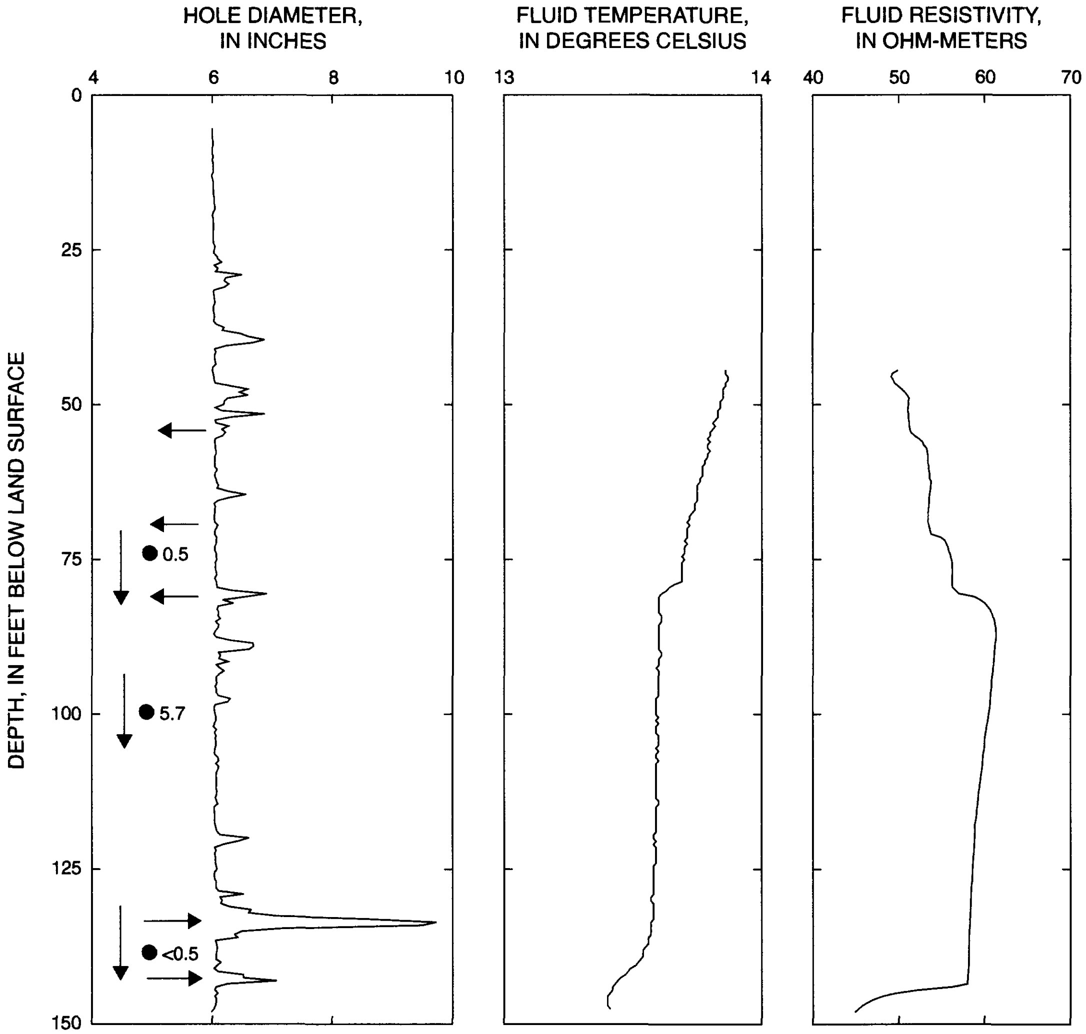
Table 5. Estimated quantity of volatile organic compounds moving downward in the Stockton Formation through nine sampled boreholes in the Jacksonville Road area, Hatboro Borough, Pennsylvania

Compound	Quantity moving downward in the aquifer through open boreholes (grams per year)
Carbon tetrachloride	570
1,1-Dichloroethane	200
1,2-Dichloroethane	8
Chloroform	36
1,1-Dichloroethylene	730
trans-1,2-Dichloroethylene[1]	250
1,2-Dichloropropane	450
Tetrachloroethylene	450
1,1,1-Trichloroethane	2,050
1,1,2-Trichloroethane	1
Trichloroethylene	75,860
Total	80,600

[1]trans-1,2-dichloroethylene and cis-1,2-dichloroethylene reported as trans-1,2-dichloroethylene.

Before drilling, an existing open-hole monitor well (MG–1114) was logged to determine hydrogeological conditions at the site. Borehole-flow measurements made in borehole MG–1114 showed that water moved downward from shallow to deep water-bearing zones under nonpumping conditions (fig. 25). Slugs of high-conductance fluid injected at 75, 100, and 140 ft bls moved downward at rates of 0.5, 5.7, and less than 0.5 gal/min, respectively. The caliper, fluid-temperature, and fluid-resistivity geophysical logs and borehole-flow measurements showed that water enters the borehole at a rate of 0.5 gal/min through fractures at 57 and 71 ft bls and moves downward. An additional 5.2 gal/min of water enters the borehole through a fracture at 81 ft bls and flows downward. Water exits the borehole through fractures at 131–135 and 142–144 ft bls.

The caliper log was used to determine smooth sections of borehole MG–1114 to set straddle packers and intervals to isolate for discrete-zone sampling for VOC's. The concentrations of TCE in water from the interval isolated above 75 ft bls was 11,000 µg/L, the concentration of TCE in water from the interval isolated between 75 and 95 ft bls was 530 µg/L,



EXPLANATION

● 5.7 BOREHOLE-FLOW MEASUREMENT—Circle at depth of slug injection. Number is measured flow in gallons per minute

↓ DIRECTION OF VERTICAL BOREHOLE FLOW—Arrow indicates downward flow

→ FLOW INTO OR OUT OF BOREHOLE—Arrow pointing away from caliper log indicates flow into borehole. Arrow pointing toward caliper log indicates flow out of borehole

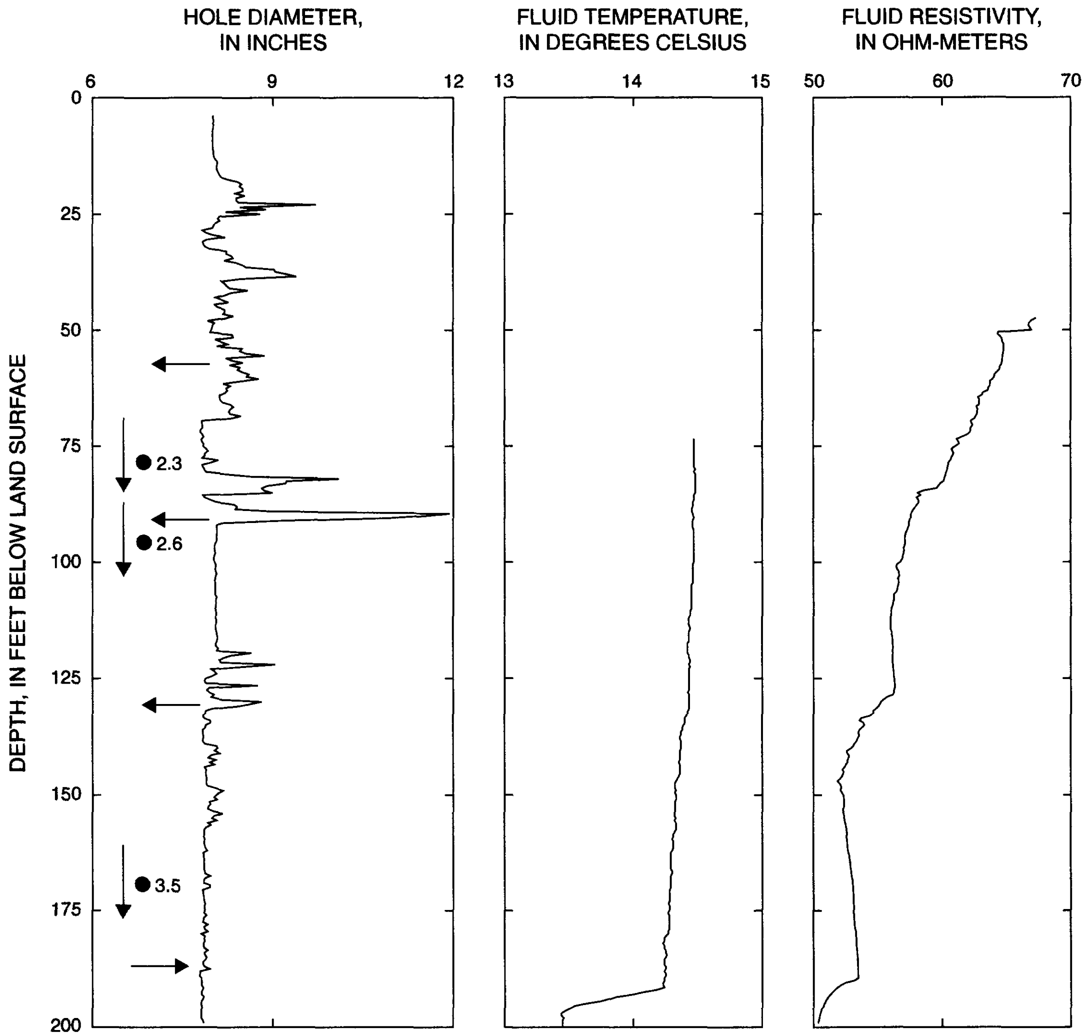
Figure 25. Caliper, fluid-temperature, and fluid-resistivity logs from borehole MG–1114, Hatboro Borough, Pennsylvania, showing borehole-flow measurements.

and the concentrations of TCE in water from the interval isolated between 125 and 148 ft bls was 1,100 µg/L. On the basis of the chemical, geophysical, and borehole-flow measurement data, water (0.5 gal/min) with elevated concentrations of TCE (11,000 µg/L) entered the borehole through fractures at 57 and 71 ft bls and moved downward. It was diluted by water (5.2 gal/min) with a much lower concentration of TCE (530 µg/L) that entered the borehole through the fracture at 81 ft bls, and it was further diluted to a concentration of 1,100 µg/L by water in the water-receiving zone. Borehole MG–1114 was constructed as a monitor well open from 138 to 148 ft bls, thus eliminating the cross-connection between the shallow, contaminated water-producing zones and the deeper water-receiving zones. The water level in the deep-screened zone of well MG–1114 responds in the same way that the water level in deep-screened monitor well MG–1222 (fig. 14) responds to the pumping of public supply well MG–944 (Hatboro-14).

The construction of a cluster of three monitor wells at the location of 200-ft-deep borehole MG–1222 shows how geophysical logs (fig. 26) were used to design and construct a well cluster to monitor multiple discrete intervals in the aquifer and to avoid a cross-connection among the monitored intervals. The caliper log shows that the major fractures in borehole MG–1222 are at 24, 43–44, 56, 83–86, 90–92, 121, 123, 128, and 131–132 ft bls. The fluid-resistivity log shows sharp decreases in fluid resistance at 83, 128, 146, and 189 ft bls, indicating water-producing or water-receiving zones. The fluid-temperature log shows intervals of nearly constant temperature at depths of about 74–80, 80–130, and 130–192 ft bls. Slugs of high-conductance fluid injected at 80, 95, and 170 ft bls moved downward at rates of 2.3, 2.6, and 3.5 gal/min, respectively. The geophysical logs and borehole-flow measurements show that water-producing fractures from 56 to 63 ft bls in a silty, fine-grained sandstone unit produce 2.3 gal/min of water under nonpumping conditions. An additional 0.3 gal/min of water enters the borehole from a water-producing fracture in the same unit at 82–86 ft bls. An additional 0.9 gal/min of water enters the borehole from a water-producing fracture in a fine-grained sandstone unit at 130–132 and 144 ft bls. Water exits the borehole through a water-receiving fracture in a medium- to coarse-grained sandstone unit at 189 ft bls. Borehole flow does not occur below 189 ft bls.

The 200-ft-deep borehole was reconstructed as a monitor well open from 185 to 195 ft bls to monitor the fluid-receiving zone at 188 ft bls. Two additional monitor wells open to a shallow and an intermediate-depth zone were constructed next to the deep well. The monitor well open to the intermediate interval (118–138 ft bls) monitors the fluid-producing zone at 128 ft bls. The monitor well open to the shallow interval (33–63 ft bls) monitors the upper, unconfined part of the aquifer system, which includes the fluid-producing zones at 56–63 ft bls. Three monitor wells in the cluster monitor the major water-producing and water-receiving zones above 200 ft bls without allowing a cross-connection between these zones (fig. 13).

In the Stockton Formation, depth of water-bearing zones in an area cannot be determined from one borehole. Each borehole should be logged and evaluated separately. The same water-bearing zone may not be intersected in adjacent boreholes, especially if it is a vertical fracture with a different orientation than that of the adjacent boreholes. The caliper and natural-gamma logs of three adjacent boreholes drilled about 15 ft from each other are shown in figure 27. Despite their closeness, each borehole penetrates different water-bearing zones in different beds. Lithology is generalized and is correlated from the natural-gamma logs. Borehole BK–2793 penetrated a water-bearing fracture in bed C at 72 ft bls; the other two boreholes did not penetrate a water-bearing fracture in bed C (fig. 27). Borehole BK–2794 penetrated water-bearing fractures in bed E at 111 ft bls and in bed G at 164–170 ft bls (fig. 27); the driller reported a water-bearing zone at 215 ft bls, but the caliper log does not show a fracture, and heat-pulse-flowmeter measurements did not indicate a water-bearing fracture at that depth. Borehole BK–2792, drilled to the same depth as borehole BK–2794, penetrated only one water-bearing fracture in bed L at 224 ft bls (fig. 27); heat-pulse-flowmeter measurements showed upward flow from this fracture under nonpumping conditions.



EXPLANATION

3.5 BOREHOLE-FLOW MEASUREMENT—Circle at depth of slug injection. Number is measured flow in gallons per minute

DIRECTION OF VERTICAL BOREHOLE FLOW—Arrow indicates downward flow

FLOW INTO OR OUT OF BOREHOLE—Arrow pointing away from caliper log indicates flow into borehole. Arrow pointing toward caliper log indicates flow out of borehole

Figure 26. Caliper, fluid-temperature, and fluid-resistivity logs from borehole MG–1222, Hatboro Borough, Pennsylvania, showing borehole-flow measurements.

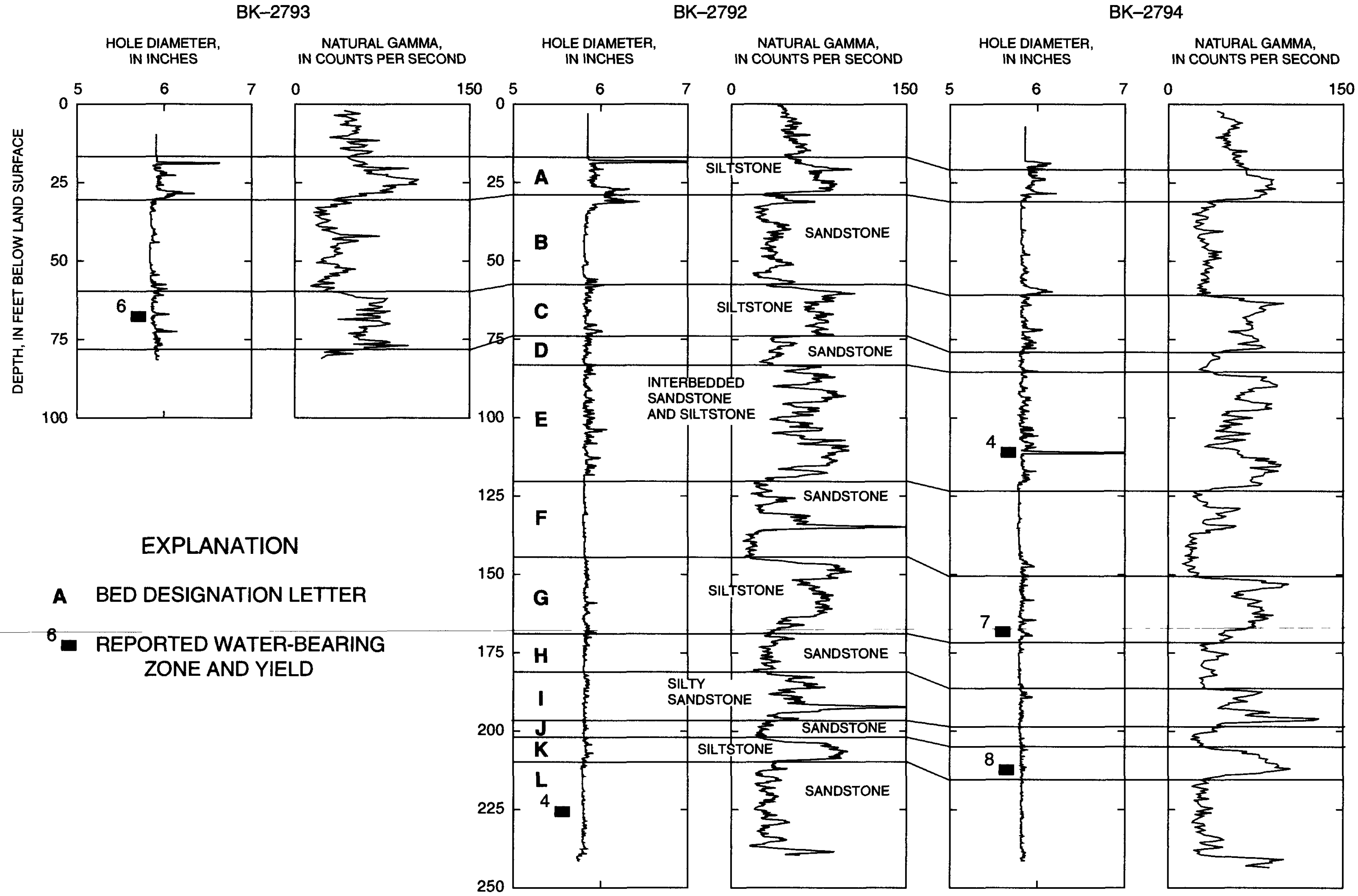


Figure 27. Caliper, natural-gamma, and generalized lithologic logs from boreholes BK–2792, BK–2793, and BK–2794, Warminster Township, Pennsylvania.

SUMMARY AND CONCLUSIONS

The study area is a 9-mi^2 area in Hatboro Borough, Montgomery County, and Warminster Township, Bucks County, Pa., underlain by sedimentary rocks of the Stockton Formation of Upper Triassic age. Rocks that underlie the study area belong to the middle arkose member of the Stockton Formation; some deep boreholes may penetrate the lower arkose member. In the Hatboro area, the Stockton Formation strikes approximately N. 65° E. and dips approximately 9° NW. The rocks are chiefly arkosic sandstone and siltstone. The Stockton Formation includes alluvial fans, fluvial and lacustrine sandstones, and fluvial and near-shore lacustrine siltstones. From visual identification of five rock cores collected in the study area, eight lithologies were identified:

1. Siltstone, reddish-brown or dark purple-gray, sometimes micaceous.
2. Sandstone, pinkish-gray, silty, fine-grained.
3. Sandstone, dark-gray, very fine-grained.
4. Sandstone, gray, fine-grained.
5. Sandstone, gray, poorly sorted, fine- to medium-grained.
6. Sandstone, gray, medium-grained.
7. Sandstone, light-gray, medium- to coarse-grained.
8. Conglomerate, light-gray or brown.

Rocks of the Stockton Formation form a complex, heterogeneous, multiaquifer system consisting of a series of gently dipping lithologic units with different hydraulic properties. The beds, a few inches to a few feet thick, act as a series of alternating aquifers and confining or semiconfining units that form a leaky, multiaquifer system. Most ground water in the unweathered zone moves through a network of interconnecting secondary openings—fractures, bedding planes, and joints. Beds within the Stockton Formation are hydraulically connected by vertical joints that cross each other at various angles throughout the beds; therefore, ground water may move across beds, particularly in the direction of dip, rather than through individual beds. Primary porosity that may have originally existed has been almost eliminated by compaction and cementation. Overall, the sandstone units are the principle water-bearing units, but some finer grained units may contain water-bearing zones. Ground water is unconfined in the shallower part of the aquifer and semiconfined or confined in the deeper part of the aquifer. Ground water is confined by overlying, less permeable lithologic units. Differences in the ratio of vertical to horizontal hydraulic conductivity and differences in vertical hydraulic conductivity within and among lithologic units create confining conditions.

Nearly all deep wells in the Stockton Formation are open to several water-bearing zones and are multiaquifer wells. Each water-bearing zone usually has a different hydraulic head. The hydraulic head in a deep, open-hole well is the composite of the heads in the several water-bearing zones penetrated. 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. In the Hatboro area, water moves downward through the aquifer system in response to a downward head gradient, which is caused in part by the pumping of deep public supply wells.

Determination of the potential for borehole flow was based on caliper, natural-gamma, single-point-resistance, fluid-resistivity, and (or) fluid-temperature logs that were run in 162 boreholes 31 to 655 ft deep. Upon completion of geophysical logging, the suite of logs was evaluated in the field to determine the potential for borehole flow and to choose zones of potential borehole flow. Direction and rate of borehole-fluid movement were determined in 83 wells by the brine-tracing method; the lower limit of flow measurement is about 0.5 gal/min in a 6-in.-diameter borehole. The rate and direction of borehole-fluid movement were determined in 10 boreholes by use of a heat-pulse flowmeter; the range of flow measurement is 0.01 to 1 gal/min.

The potential is great for borehole flow and cross-contamination in open-hole boreholes in the Stockton Formation. Borehole flow was measurable in 65 of 93 boreholes (70 percent). No flow was measurable in 19 boreholes. The direction and rate of borehole flow was not determinable for nine boreholes by use of the brine-tracing method. Fluid movement at rates up to 17 gal/min was measured. Downward flow was measured in 36 boreholes, not including those boreholes in which two directions of flow were measured. The predominant direction of vertical borehole flow measured in Hatboro Borough and in Warminster Township near the Fischer and Porter Site is downward. Upward vertical flow was measured in 23 boreholes. Many of these boreholes are just northwest of the surface-water divide between the Pennypack and Little Neshaminy Creek drainage basins. The divide parallels the strike of the Stockton Formation, and boreholes to the northwest of the divide penetrate beds that crop out in updip, upgradient areas.

Fluid movement under nonpumping conditions in some boreholes may be very complex. Both upward and downward vertical flow was measured in six boreholes. These boreholes ranged from 396 to 470 ft deep and were among the deepest boreholes logged. Fluid movement was upward in the upper part of the borehole and downward in the lower part of the borehole in two boreholes. Fluid movement was downward in the upper part of the borehole and upward in the lower part of the borehole in three boreholes.

Ground-water contamination by VOC's is widespread in the study area. Detectable concentrations of VOC's were present in water samples from all 24 wells sampled in Hatboro Borough and in water samples from 10 of 14 wells (71 percent) sampled in Warminster Township. However, concentrations of VOC's in many water samples did not exceed the USEPA maximum contaminant levels. Chloroform was the most commonly detected VOC (28 wells or 74 percent of wells sampled), followed by TCE (26 wells or 68 percent), and PCE and TCA (24 wells or 63 percent).

To estimate the quantity of VOC's in borehole flow, samples of borehole flow from nine boreholes in the industrial area of Hatboro along and to the west of Jacksonville Road were collected for laboratory analysis. None of the boreholes sampled were on an NPL site, but they were near the Raymark NPL site and the site of the former Roberts and Mander Stove Company. Downward flow was measured in all of the boreholes; the samples represent water moving from the contaminated, shallow part of the aquifer to the deeper part of the aquifer, which is tapped by public supply wells. Water samples from all nine boreholes contained detectable concentrations of VOC's. Concentrations of TCE, TCA, and 1,1-DCE as great as 5,800, 1,400, and 260 µg/L, respectively, show that some water moving downward in the aquifer through these open boreholes is highly contaminated and that open boreholes may contribute substantially to movement of ground-water contamination. An estimated 80.6 kg/yr (14.7 gal/yr) of VOC's was moving downward through the nine open boreholes sampled from the contaminated, upper part of the aquifer to the lower part. TCE accounted for 94 percent and TCA accounted for 3 percent of the compounds by mass.

Borehole geophysical logs were used as a guide to design and construct monitor-well networks at three NPL sites. An open borehole was drilled, and a suite of geophysical logs was run. Interpretation of geophysical logs enabled the identification of water-bearing zones that produce and receive water; these are zones that should not be connected. From the geophysical logs, discrete intervals to be monitored were selected. In the Stockton Formation, the same water-bearing zone may not be intersected in adjacent boreholes, especially if it is a vertical fracture with a different orientation than that of the adjacent boreholes. In most areas of the Stockton Formation, depth of water-bearing zones in an area cannot be determined from one borehole. Each borehole should be logged and evaluated separately.

A combination of borehole geophysical methods, measurements of vertical borehole flow, and analyses of borehole-fluid samples provided effective methods to identify and assess an aquifer cross-contamination problem. Borehole geophysical methods were used to identify zones of fluid movement. Borehole-flow measurements provided data on the direction and rate of borehole-fluid movement. Sampling and analysis of moving borehole fluid provided concentrations of VOC's that enable estimations of quantities of VOC's moving through sampled open boreholes.

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Table 6. Record of wells

[Latitude and longitude are given in degrees, minutes, and seconds. Casing length: first number is inner casing, second number is outer casing. Casing diameter: first number is inner casing, second number is outer casing. Use of site: Z, destroyed; P, public supply; U, unused; O, observation or monitor well; --, no data]

Well identification number	Latitude	Longitude	Owner or site location	Year drilled	Depth drilled (feet)	Diameter (inches)	Casing length (feet)	Casing diameter (inches)	Use of site
			Bucks County						
BK–372	401059	0750523	Fischer & Porter Company	1952	600	8	50	8	Z
BK–693	401116	0750450	Warminster Municipal Authority	1955	324	10	50/40	10/14	P
BK–948	401308	0750509	Warminster Municipal Authority	1963	516	10	88/50	10/14	P
BK–949	401158	0750704	Warminster Municipal Authority	1962	466	10	80/50	10/14	U
BK–1020	401155	0750307	U.S. Naval Air Warfare Center	1968	400	6	57/52	10/14	O
BK–1058	401030	0750440	Warminster Municipal Authority	--	500	8	58	8	U
BK–1145	401308	0750644	Warminster Municipal Authority	1980	350	6	20	6	U
BK–1146	401304	0750649	Warminster Municipal Authority	1981	460	12	132/20	12/20	P
BK–1831	401215	0750445	U.S. Naval Air Warfare Center	1980	300	6	59	6	O
BK–1832	401235	0750711	Warminster Municipal Authority	1991	393	6	38	6	U
BK–1833	401232	0750706	Warminster Municipal Authority	1991	400	6	37	6	U
BK–1834	401247	0750709	Warminster Municipal Authority	1991	360	6	39	6	U
BK–1843	401301	0750703	Warminster Municipal Authority	1985	325	6	20	6	U
BK–1844	401308	0750630	Warminster Municipal Authority	1985	514	6	20	6	U
BK–1845	401403	0750505	Warminster Municipal Authority	1991	421	10	60	10	U
BK–2512	401115	0750531	Fischer & Porter Company	1993	303	8	87/5	8/12	O
BK–2516	401107	0750541	Fischer & Porter Company	1993	262	2	14	4	Z
BK–2517	401107	0750526	Fischer & Porter Company	1993	277	2	20	4	Z
BK–2518	401115	0750530	Fischer & Porter Company	1993	266	2	9	4	Z
BK–2530	401157	0750334	U.S. Naval Air Warfare Center	1993	153	8	11.5	8	O
BK–2536	401145	0750328	U.S. Naval Air Warfare Center	1993	163	12/8	7/135	8/4	O
BK–2595	401209	0750410	U.S. Naval Air Warfare Center	1994	158	6	14	6	O
BK–2600	401205	0750352	U.S. Naval Air Warfare Center	1994	143	6	14	6	O
BK–2792	401225	0750434	U.S. Naval Air Warfare Center	1995	240	6	18	6	O
BK–2793	401225	0750434	U.S. Naval Air Warfare Center	1995	82	6	18	6	O
BK–2794	401225	0750434	U.S. Naval Air Warfare Center	1995	241	6	18	6	O
			Montgomery County						
MG–212	401040	0750609	Hatboro Authority	--	250	12	38	14	U
MG–213	401041	0750609	Hatboro Authority	--	250	--	38	10	U
MG–216	401126	0750640	Hatboro Authority	--	299	10	40	10	P
MG–217	401051	0750643	Hatboro Authority	1948	288	10	30	10	P
MG–218	401131	0750631	Hatboro Authority	--	306	--	--	--	P
MG–219	401030	0750705	Hatboro Authority	1953	300	10	40	10	P
MG–220	401056	0750638	Hatboro Authority	1956	475	10	43	10	Z
MG–942	401034	0750655	Hatboro Authority	1959	300	10	40/11	10/14	P
MG–944	401038	0750645	Hatboro Authority	1964	300	10	41/20	10/14	P
MG–945	401030	0750628	Hatboro Authority	1964	300	10	41/20.5	10/14	P
MG–946	401111	0750558	Hatboro Authority	1969	300	10	40/30	10/14	U
MG–947	401103	0750608	Hatboro Authority	--	300	--	--	--	P
MG–948	401019	0750635	Hatboro Authority	1971	301	10	47/30	10/14	P
MG–949	401037	0750720	Hatboro Authority	1972	300	10	40/40	10/16	P
MG–950	401048	0750701	Hatboro Authority	1972	375	10	70	10	P
MG–951	401055	0750625	Hatboro Authority	1971	335	10	70/30	10/14	Z
MG–1114	401045	0750555	Raymark	1981	151	6	20	6	O
MG–1115	401130	0750630	Hatboro Authority	1959	404	10	50	10	O
MG–1222	401048	0750557	Raymark	1990	200	8	20	8	O
MG–1223	401046	0750559	Raymark	1990	196	8	6	8	O
MG–1235	401046	0750556	Raymark	1990	143	6	--	6	O
MG–1236	401048	0750603	U.S. Environmental Protection Agency	--	170	6	14	4	O
MG–1237	401050	0750602	U.S. Environmental Protection Agency	1990	169	6	36	4	O
MG–1238	401051	0750557	U.S. Environmental Protection Agency	1984	200	6	28	6	O
MG–1239	401055	0750600	U.S. Environmental Protection Agency	--	166	6	31	4	O
MG–1240	401059	0750554	U.S. Environmental Protection Agency	1984	159	6	17	4	O
MG–1241	401103	0750549	Fischer & Porter Company	--	175	6	21	6	O
MG–1242	401053	0750540	Fischer & Porter Company	--	-178	6	19	6	O
MG–1283	401045	0750558	Raymark	1992	300	6	240	6	O

Table 7. Results of field determinations

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; --, no data]

U.S. Geological Survey well number	Date	Sampling depth (feet)	pH (standard units)	Specific conductance (µS/cm)	Temperature (degrees Celsius)	Alkalinity (mg/L as $CaCO_3$)	Dissolved oxygen (mg/L)
			Bucks County				
BK–372	03–04–91	241	7.0	275	15.5	154	7.4
BK–693	12–10–90	85	5.8	220	13.5	22	8.6
BK–948	05–14–74	--	6.9	--	--	87	--
	11–29–90	--	7.7	500	13.0	171	4.2
BK–949	05–14–74	--	7.4	--	--	112	--
	03–20–91	--	7.0	380	14.0	146	3.0
	03–20–91	--	7.0	400	13.0	152	3.2
BK–1020	04–18–91	70	5.6	140	11.5	18	12.0
BK–1058	03–20–91	105	7.6	340	12.5	124	4.9
BK–1145	08–16–91	50	6.9	280	13.5	144	1.1
BK–1146	07–17–91	--	7.6	480	13.0	132	3.5
BK–1831	06–20–91	--	7.5	370	19.0	120	1.2
BK–1832	07–17–91	100	7.8	460	13.0	189	3.8
BK–1833	06–21–91	60	7.5	435	19.5	164	4.1
BK–1834	07–17–91	75	6.7	405	17.0	100	7.3
BK–1843	07–18–91	45	6.9	435	14.0	130	3.7
BK–1844	07–18–91	130	7.2	1,110	15.5	97	4.2
	07–18–91	70	5.4	200	18.5	13	8.5
			Montgomery County				
MG–213	06–20–91	--	6.0	460	14.5	50	7.1
MG–216	06–27–56	--	8.4	343	13.0	120	--
	06–10–91	--	7.1	435	14.5	148	5.3
MG–217	06–27–56	--	7.6	403	14.0	113	--
	06–10–91	--	7.5	545	15.0	194	4.0
MG–218	06–27–56	--	8.2	407	12.0	115	--
	01–18–91	120	6.3	360	12.0	104	5.8
	06–10–91	--	7.2	480	14.5	172	6.5
MG–219	06–27–56	--	8.0	286	13.0	112	--
	10–23–79	--	6.6	395	12.0	110	--
	06–20–91	--	6.7	475	14.0	116	5.0
MG–220	11–15–90	130	7.7	490	12.5	184	2.1
MG–942	06–10–91	--	7.0	470	15.0	136	3.9
MG–944	06–10–91	--	7.4	600	14.5	206	3.7
MG–945	08–16–91	--	6.9	505	14.5	177	4.3
MG–946	04–16–92	--	7.3	650	13.5	204	3.3
MG–947	06–20–91	--	7.2	670	14.0	170	4.5
	06–10–91	--	7.3	690	15.0	170	4.8
MG–948	08–16–91	--	6.8	560	20.0	174	2.1
MG–949	08–16–91	--	7.0	360	15.0	152	2.9
MG–950	08–16–91	--	7.4	515	14.0	140	4.0
MG–951	12–10–90	55	6.9	550	14.0	160	5.6
	12–10–90	105	7.0	550	14.0	158	5.6
MG–1115	11–14–90	248	6.4	530	--	74	5.5
	11–14–90	100	6.3	375	--	70	6.5
MG–1235	05–17–91	--	6.4	425	15.0	106	4.0
MG–1236	11–16–90	85	6.5	390	16.5	78	5.6
	06–05–91	85	6.3	345	14.5	63	6.7
MG–1237	11–15–90	60	7.0	480	15.5	160	4.2
	11–15–90	85	7.1	510	14.5	156	3.2
MG–1238	11–16–90	110	6.4	470	12.5	112	3.4
MG–1239	11–30–90	60	7.5	580	11.5	201	4.0
	11–30–90	80	7.6	560	12.5	198	2.0
MG–1240	11–29–90	90	6.4	1180	13.5	116	3.2
	11–29–90	60	6.4	1120	12.0	120	3.8
MG–1241	12–13–90	110	6.6	600	14.0	176	3.6
MG–1242	12–13–90	90	6.7	500	13.0	150	8.0

Table 8. Results of chemical analyses for inorganic constituents

[mg/L, milligrams per liter; µg/L, micrograms per liter; pCi/L, picoCuries per liter; <, less than; --, no data; total dissolved solids is residue on evaporation at 180 degrees Celsius]

U.S. Geological Survey well number	Date	Sampling depth (feet)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Silica, dissolved (mg/L as SiO_2)	Total dissolved solids (mg/L)
					Bucks County					
BK–372	03–04–91	241	28	8.8	5.8	1.3	13	12	11	134
BK–693	12–10–90	85	16	5.2	15	.9	24	31	25	128
BK–948	05–14–74	--	--	--	--	--	110	--	--	420
	11–29–90	--	45	28	17	1.8	25	34	18	272
BK–949	05–14–74	--	--	--	--	--	24	12	--	278
	03–20–91	--	47	15	13	.9	16	21	29	225
	03–20–91	--	47	15	12	1.0	17	27	29	223
BK–1020	04–18–91	70	9.4	4.0	10	1.2	36	4.5	24	101
BK–1058	03–20–91	105	56	5.6	7.3	1.4	24	11	17	197
BK–1145	08–16–91	50	48	9.0	15	1.2	20	14	20	205
BK–1146	07–17–91	--	55	9.1	27	2.1	72	16	18	279
BK–1831	06–20–91	--	36	9.5	12	1.7	22	3.3	24	164
BK–1832	07–17–91	100	52	20	9.7	1.1	12	17	23	252
BK–1833	06–21–91	60	45	18	12	2.6	7.5	27	20	232
BK–1834	07–17–91	75	46	11	11	.8	31	25	28	216
BK–1843	07–18–91	45	57	11	12	.9	32	34	25	235
BK–1844	07–18–91	130	180	21	43	2.1	500	28	20	856
	07–18–91	70	13	2.6	17	.9	29	20	31	119
					Montgomery County					
MG–213	06–20–91	--	30	8.5	25	1.2	31	48	25	199
MG–216	06–27–56	--	38	11	--	--	25	14	32	264
	06–10–91	--	43	14	16	.9	26	34	23	240
MG–217	06–27–56	--	31	10	--	--	70	8.5	24	279
	06–10–91	--	53	18	26	2.0	36	46	20	306
MG–218	06–27–56	--	41	10	--	--	64	11	29	274
	01–18–91	120	42	10	16	1.0	15	35	23	205
	06–10–91	--	52	16	20	1.3	30	33	24	275
MG–219	06–27–56	--	40	5.2	--	--	23	10	26	197
	10–23–79	--	44	9.2	16	1.5	27	19	23	220
	06–20–91	--	52	10	16	1.5	17	36	21	232
MG–220	11–15–90	130	55	24	15	1.7	34	41	18	282
MG–942	06–10–91	--	58	9.8	15	1.0	31	40	23	258
MG–944	06–10–91	--	73	16	28	1.3	61	45	22	355
MG–945	08–16–91	--	77	14	25	1.3	50	52	22	348
MG–946	04–16–92	--	85	25	22	1.2	35	93	22	388
MG–947	06–20–91	--	68	24	22	1.1	21	83	24	359
	06–10–91	--	68	23	22	1.1	29	96	25	405
MG–948	08–16–91	--	60	14	25	1.8	48	39	21	302
MG–949	08–16–91	--	45	18	16	1.3	28	30	22	255
MG–950	08–16–91	--	55	17	28	2.7	94	33	21	316
MG–951	12–10–90	55	64	18	21	1.3	35	53	25	361
	12–10–90	105	64	19	21	1.3	35	53	25	335
MG–1115	11–14–90	248	58	11	29	1.4	69	50	22	232
	11–14–90	100	<36	7.5	24	1.3	9.9	53	22	209
MG–1235	05–17–91	--	48	10	18	.9	20	22	32	253
MG–1236	11–16–90	85	42	8.9	19	1.3	33	38	25	233
	06–05–91	85	38	8.2	19	1.3	38	42	26	237
MG–1237	11–15–90	60	72	8.5	13	.8	18	41	28	298
	11–15–90	85	74	8.6	14	.9	8.9	42	27	295
MG–1238	11–16–90	110	59	8.5	25	1.3	30	62	37	308
MG–1239	11–30–90	60	64	29	23	1.6	29	43	28	353
	11–30–90	80	53	29	22	1.9	23	44	26	319
MG–1240	11–29–90	90	66	19	130	2.8	53	240	22	624
	11–29–90	60	68	20	130	2.8	53	240	22	620
MG–1241	12–13–90	110	86	14	18	1.0	35	63	30	384
MG–1242	12–13–90	90	54	21	14	.9	16	50	24	277

Table 8. Results of chemical analyses for inorganic constituents—Continued

[mg/L, milligrams per liter; µg/L, micrograms per liter; pCi/L, picoCuries per liter; <, less than; --, no data; total dissolved solids is residue on evaporation at 180 degrees Celsius]

U.S. Geological Survey well number	Date	Fluoride, dissolved (mg/L as F)	Bromide, dissolved (mg/L as Br)	Nitrogen, NO_2+NO_3, dissolved (mg/L as N)	Nitrogen, nitrate, dissolved (mg/L as N)	Nitrogen, nitrite, dissolved (mg/L as N)	Phosphorus, dissolved (mg/L as P)	Phosphorus, ortho, dissolved (mg/L as P)
				Bucks County				
BK–372	03–04–91	0.10	0.03	1.50	--	<0.01	0.04	0.02
BK–693	12–10–90	<.10	.03	4.20	--	<.01	.04	.04
BK–948	05–14–74	.10	--	--	2.60	--	--	--
	11–29–90	<.10	.10	3.90	--	<.01	.03	.03
BK–949	05–14–74	.12	--	--	1.80	--	--	.02
	03–20–91	<.10	.12	--	--	--	--	--
	03–20–91	<.10	.12	--	--	--	--	--
BK–1020	04–18–91	<.10	.03	1.10	--	<.01	.04	.02
BK–1058	03–20–91	<.10	.06	1.70	--	<.01	.07	.06
BK–1145	08–16–91	<.10	.05	1.60	--	<.01	.07	.06
BK–1146	07–17–91	.10	.05	1.40	1.38	.02	.01	.01
BK–1831	06–20–91	.10	.03	.068	--	<.01	.05	.04
BK–1832	07–17–91	<.10	.05	3.10	--	<.01	.07	.08
BK–1833	06–21–91	.10	<.01	2.00	--	<.01	.04	.04
BK–1834	07–17–91	<.10	.04	5.10	--	<.01	.05	.07
BK–1843	07–18–91	<.10	.06	2.30	--	<.01	.06	.04
BK–1844	07–18–91	<.10	.04	4.60	--	<.01	.10	.08
	07–18–91	<.10	.03	1.70	--	<.01	.03	<.01
				Montgomery County				
MG–213	06–20–91	<.10	.08	4.70	--	<.01	.02	.02
MG–216	06–27–56	.10	--	--	2.90	--	--	--
	06–10–91	<.10	.05	2.80	--	<.01	.04	.05
MG–217	06–27–56	.10	--	--	1.50	--	--	--
	06–10–91	<.10	.07	1.90	--	<.01	.02	.02
MG–218	06–27–56	.10	--	--	2.50	--	--	--
	01–18–91	<.10	.06	2.90	--	<.01	.07	.08
	06–10–91	<.10	.07	3.40	--	<.01	.05	.05
MG–219	06–27–56	0.10	--	--	2.90	--	--	--
	10–23–79	.10	--	3.70	3.69	0.01	0.05	0.04
	06–20–91	<.10	<0.01	3.20	--	<.01	.04	.03
MG–220	11–15–90	<.10	.07	.600	--	<.01	.04	.04
MG–942	06–10–91	<.10	.06	2.10	--	<.01	.05	.02
MG–944	06–10–91	<.10	.10	.590	--	<.01	.02	<.01
MG–945	08–16–91	<.10	.10	3.70	--	<.01	.07	.06
MG–946	04–16–92	.10	.24	--	--	--	--	--
MG–947	06–20–91	<.10	.10	2.70	--	<.01	.07	.05
	06–10–91	<.10	.10	2.80	--	<.01	.06	.05
MG–948	08–16–91	<.10	.04	1.70	--	<.01	.06	.05
MG–949	08–16–91	<.10	.06	3.00	--	<.01	.06	.05
MG–950	08–16–91	<.10	.08	1.70	--	<.01	.04	.02
MG–951	12–10–90	.10	.07	3.60	--	<.01	.14	.15
	11–14–90	<.10	.05	3.80	--	<.01	.08	.07
MG–1115	11–14–90	.10	--	4.00	--	<.01	.07	.07
	05–16–91	<.10	.08	3.80	3.79	.01	.09	.07
MG–1235	11–16–90	<.10	.08	4.10	--	<.01	.16	.16
MG–1236	06–05–91	<.10	.07	3.70	--	<.01	.14	.15
	11–15–90	.10	.13	3.00	--	<.01	.23	.24
MG–1237	11–15–90	.10	.13	3.00	--	<.01	.22	.24
	11–16–90	<.10	.09	2.30	--	<.01	2.90	.03
MG–1238	11–30–90	<.10	.07	2.10	--	<.01	.35	.29
MG–1239	11–30–90	.10	.07	2.00	1.99	.01	.42	.36
	11–29–90	<.10	.10	1.80	--	<.01	.16	.11
MG–1240	11–29–90	<.10	.10	1.80	--	<.01	.15	.11
	12–13–90	.10	.25	1.70	--	<.01	.15	.15
MG–1241	12–13–90	.10	.05	4.50	--	<.01	.04	.05
MG–1242	07–01–92	.10	.080	3.40	--	<.01	.18	.17

Table 8. Results of chemical analyses for inorganic constituents—Continued

[mg/L, milligrams per liter; µg/L, micrograms per liter; pCi/L, picoCuries per liter; <, less than; --, no data; total dissolved solids is residue on evaporation at 180 degrees Celsius]

U.S. Geological Survey well number	Date	Aluminum, dissolved (µg/L as Al)	Barium, dissolved (µg/L as Ba)	Iron, dissolved (µg/L as Fe)	Lead, dissolved (µg/L as Pb)	Manganese, dissolved (µg/L as Mn)	Strontium, dissolved (mg/L as Sr)	Radon, total (pCi/L)
				Bucks County				
BK–372	03–04–91	20	99	8	<1	5	150	610
BK–693	12–10–90	<10	150	8	<1	4	38	1,400
BK–948	05–14–74	--	--	110	--	<10	--	--
	11–29–90	<10	250	<3	<1	23	850	1,000
BK–949	05–14–74	--	--	30	--	<10	--	--
	03–20–91	<10	460	7	<1	3	96	1,600
	03–20–91	20	460	10	<1	4	97	1,500
BK–1020	04–18–91	<10	21	100	<1	3	34	2900
BK–1058	03–20–91	20	380	6	<1	1	81	1,700
BK–1145	08–16–91	<10	260	35	<1	10	420	4,100
BK–1146	07–17–91	10	120	6	2	10	1,500	2,100
BK–1831	06–20–91	<10	260	6	2	36	290	2,500
BK–1832	07–17–91	<10	450	12	<1	8	190	2,200
BK–1833	06–21–91	1	520	12	1	3	600	3,100
BK–1834	07–17–91	<10	66	4	<1	3	470	2,400
BK–1843	07–18–91	<10	73	9	<1	5	730	4,100
BK–1844	07–18–91	<10	120	7	<1	64	5,000	3,900
	07–18–91	<10	160	4	<1	3	37	3,400
				Montgomery County				
MG–213	06–20–91	<10	82	280	1	12	70	2,100
MG–216	06–27–56	--	--	100	--	--	--	--
	06–10–91	<10	310	<3	1	<1	130	1,700
MG–217	06–27–56	--	--	200	--	--	--	--
	06–10–91	<10	190	<3	1	<1	490	1,400
MG–218	06–27–56	--	--	40	--	--	--	--
	01–18–91	<10	450	7	<1	2	--	1,700
	06–10–91	<10	340	6	<1	2	230	1,400
MG–219	06–27–56	--	--	110	--	--	--	--
	10–23–79	--	--	0	0	4	--	--
	06–20–91	<1	350	<3	1	<1	200	1,900
MG–220	11–15–90	<10	220	23	<1	4	250	2,000
MG–942	06–10–91	<10	260	<3	1	5	170	1,200
MG–944	06–10–91	<10	77	22	1	98	930	1,000
MG–945	08–16–91	10	140	6	2	7	250	1,100
MG–946	04–16–92	10	250	23	<1	5	290	1,400
MG–947	06–20–91	<10	360	3	2	2	110	--
	06–10–91	<10	370	5	<1	2	110	1,600
MG–948	08–16–91	<10	170	<3	1	4	310	1,700
MG–949	08–16–91	<10	350	<3	<1	2	100	1,200
MG–950	08–16–91	<10	160	<3	1	1	750	1,500
MG–951	12–10–90	<10	210	10	<1	5	74	1,400
	12–10–90	<10	230	7	1	2	78	1,300
MG–1115	11–14–90	<10	130	<3	<1	14	120	170
	11–14–90	<10	160	4	<1	12	55	170
MG–1235	05–17–91	<10	110	11	1	<1	55	1,900
MG–1236	11–16–90	<10	160	15	1	3	42	1,400
	06–05–91	<10	160	16	<1	3	45	1,500
MG–1237	11–15–90	<10	420	4	1	<1	43	--
	11–15–90	<10	440	3	<1	8	44	--
MG–1238	11–16–90	<10	370	5	<1	8	56	1,500
MG–1239	11–30–90	<10	360	<3	<1	2	230	--
	11–30–90	<10	410	<3	<1	1	250	--
MG–1240	11–29–90	<10	95	5	<1	270	180	--
	11–29–90	10	100	5	<1	280	180	--
MG–1241	12–13–90	20	300	14	<1	4	70	1,100
MG–1242	12–13–90	10	400	7	<1	<1	100	1,200

Table 9. Results of chemical analysis for volatile organic compounds

[All results are total concentrations in micrograms per liter; <, less than; --, no data]

U.S. Geological Survey well number	Date	Sampling depth (feet)	Benzene	Bromoform	1,2-Dibromoethane	Carbon tetrachloride	Chlorobenzene	1,2-Dichlorobenzene	1,3-Dichlorobenzene	1,4-Dichlorobenzene	Chlorodibromomethane	Chloroethane	2-Chloroethylvinylether
Bucks County													
BK–372	03–04–91	241	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
BK–693	12–10–90	85	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK–948	11–29–90	120	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK–949	03–20–91	135	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
	03–20–91	135	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK–1020	04–18–91	70	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK–1058	03–20–91	105	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK–1145	08–16–91	50	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK–1146	07–17–91	--	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK–1831	06–20–91	--	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK–1832	07–17–91	100	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK–1833	06–21–91	60	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK–1834	07–17–91	75	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK–1843	07–18–91	45	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK–1844	07–18–91	130	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
Montgomery County													
MG–213	06–20–91	--	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG–216	06–10–91	--	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG–217	06–10–91	--	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG–218	01–18–91	120	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
	06–10–91	--	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG–219	06–20–91	--	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG–220	11–15–90	130	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG–942	06–10–91	--	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG–944	06–10–91	--	.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG–945	08–16–91	--	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG–946	04–16–92	--	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<1.0
MG–947	06–10–91	--	<.2	<.2	<.2	.3	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG–948	08–16–91	--	<.2	2.1	<.2	<.2	<.2	<.2	<.2	<.2	1.6	<.2	<.2
MG–949	08–16–91	--	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG–950	08–16–91	--	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG–951	12–10–90	55	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
	12–10–90	105	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG–1115	11–14–90	248	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
	11–14–90	100	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG–1235	05–17–91	--	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG–1236	11–16–90	85	<2.0	<2.0	<2.0	2.6	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0
	06–05–91	85	<.2	<.2	<.2	2.0	<.2	<.2	<.2	<.2	<.2	<.2	<.2
	06–16–92	60	<.2	.4	<.2	.2	<.2	<.2	<.2	<.2	.2	<.2	<.2
	06–16–92	85	<.2	<.2	<.2	1.5	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG–1237	11–15–90	60	<.2	<.2	<.2	20	<.2	<.2	<.2	<.2	<.2	<.2	<.2
	11–15–90	85	<.2	<.2	<.2	19	<.2	<.2	<.2	<.2	<.2	<.2	<.2
	06–16–92	85	<.2	<.2	<.2	15	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG–1238	11–16–90	110	<.2	<.2	<.2	2.7	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG–1239	11–30–90	60	.4	<.2	<.2	25	<.2	<.2	<.2	<.2	<.2	<.2	<.2
	11–30–90	80	.5	<.2	<.2	14	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG–1240	11–29–90	90	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
	11–29–90	60	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG–1241	12–13–90	110	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG–1242	12–13–90	90	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2

Table 9. Results of chemical analysis for volatile organic compounds—Continued

[All results are total concentrations in micrograms per liter; <, less than; --, no data]

U.S. Geological Survey well number	Date	Chloroform	Dichloro-bromo-methane	Dichloro-difluoro-methane	1,1-Dichloro-ethane	1,2-Dichloro-ethane	1,1-Dichloro-ethylene	trans-1,2-Dichloro-ethene	1,2-Dichloro-propane	1,3-Dichloro-propene	cis-1,3-Dichloro-propene	trans-1,3-Dichloro-propene	Ethyl benzene	Methyl-bromide
							Bucks County							
BK-372	03-04-91	1.9	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
BK-693	12-10-90	.8	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK-948	11-29-90	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK-949	03-20-91	.2	<.2	<.2	.7	<.2	.4	16	<.2	<.2	<.2	<.2	<.2	<.2
	03-20-91	.2	<.2	<.2	.7	<.2	.5	17	<.2	<.2	<.2	<.2	<.2	<.2
BK-1020	04-18-91	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK-1058	03-20-91	.9	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK-1145	08-16-91	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK-1146	07-17-91	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK-1831	06-20-91	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK-1832	07-17-91	.7	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK-1833	06-21-91	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK-1834	07-17-91	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK-1843	07-18-91	.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK-1844	07-18-91	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
							Montgomery County							
MG-213	06-20-91	.3	<.2	<.2	<.2	<.2	<.2	.3	<.2	<.2	<.2	<.2	<.2	<.2
MG-216	06-10-91	.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG-217	06-10-91	3.8	.2	<.2	<.2	<.2	<.2	.2	<.2	<.2	<.2	<.2	<.2	<.2
MG-218	01-18-91	<.2	<.2	.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
	06-10-91	.2	<.2	<.2	<.2	<.2	<.2	.4	<.2	<.2	<.2	<.2	<.2	<.2
MG-219	06-20-91	.3	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG-220	11-15-90	.2	<.2	<.2	<.2	<.2	<.2	1.6	<.2	<.2	<.2	<.2	<.2	<.2
MG-942	06-10-91	.7	<.2	<.2	<.2	<.2	<.2	.8	<.2	<.2	<.2	<.2	<.2	<.2
MG-944	06-10-91	.3	<.2	<.2	.4	<.2	.2	9.4	<.2	<.2	<.2	<.2	<.2	<.2
MG-945	08-16-91	.4	<.2	<.2	.2	<.2	.3	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG-946	04-16-92	.3	<.2	<.2	.2	<.2	<.2	<.2	<.2	--	<.2	<.2	<.2	<.2
MG-947	06-10-91	1.0	<.2	<.2	.8	<.2	6.8	33	<.2	<.2	<.2	<.2	<.2	<.2
MG-948	08-16-91	.3	.6	<.2	<.2	<.2	<.2	.4	<.2	<.2	<.2	<.2	<.2	<.2
MG-949	08-16-91	.4	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG-950	08-16-91	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG-951	12-10-90	.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
	12-10-90	.3	<.2	<.2	<.2	<.2	<.2	.2	<.2	<.2	<.2	<.2	<.2	<.2
MG-1115	11-14-90	.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
	11-14-90	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
MG-1235	05-17-91	1.9	<.2	<.2	<.2	<.2	.4	13	<.2	<.2	<.2	<.2	<.2	<.2
MG-1236	11-16-90	<2.0	<2.0	<2.0	<2.0	<2.0	28	<2.0	60	<2.0	<2.0	<2.0	<2.0	<2.0
	06-05-91	.7	.2	<.2	.6	<.2	8.4	43	<.2	<.2	<.2	<.2	<.2	<.2
	06-16-92	.2	<.2	<.2	.6	<.2	9.0	5.8	<.2	<.2	<.2	<.2	<.2	<.2
	06-16-92	.6	<.2	<.2	.5	<.2	8.3	32	<.2	<.2	<.2	<.2	<.2	<.2
MG-1237	11-15-90	3.1	<.2	<.2	.5	<.2	9.6	21	<.2	<.2	<.2	<.2	<.2	<.2
	11-15-90	3.0	<.2	<.2	.5	<.2	9.8	22	<.2	<.2	<.2	<.2	<.2	<.2
	06-16-92	2.8	<.2	<.2	.5	<.2	12	22	<.2	<.2	<.2	<.2	<.2	<.2
MG-1238	11-16-90	1.7	<.2	<.2	3.0	.2	2.3	2.7	<.2	<.2	<.2	<.2	<.2	<.2
MG-1239	11-30-90	15	.2	<.2	8.4	3.9	190	69	<.2	<.2	<.2	<.2	<.2	<.2
	11-30-90	15	.4	<.2	14	5.6	260	29	<.2	<.2	<.2	<.2	<.2	<.2
MG-1240	11-29-90	<.2	<.2	<.2	.4	<.2	.2	71	<.2	<.2	<.2	<.2	<.2	<.2
	11-29-90	<.2	<.2	<.2	.3	<.2	.2	72	<.2	<.2	<.2	<.2	<.2	<.2
MG-1241	12-13-90	.6	<.2	<.2	.8	<.2	1.8	1.7	.3	<.2	<.2	<.2	<.2	<.2
MG-1242	12-13-90	.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2

Table 9. Results of chemical analysis for volatile organic compounds—Continued

[All results are total concentrations in micrograms per liter; <, less than; --, no data]

U.S. Geological Survey well number	Date	Methyl-chloride	Methylene chloride	Styrene	1,1,2,2-Tetra-chloro-ethane	Tetra-chloro-ethylene	Toluene	1,1,1-Trichloro-ethane	1,1,2,-Trichloro-ethane	Tri-chloro-ethylene	Tri-chloro-fluoro-methane	Vinyl chloride	Xylene
						Bucks County							
BK–372	03–04–91	<0.2	<0.2	<0.2	<0.2	0.4	<0.2	1.9	<0.2	0.7	<0.2	<0.2	<0.2
BK–693	12–10–90	<.2	<.2	<.2	<.2	.2	<.2	<.2	<.2	.7	<.2	<.2	<.2
BK–948	11–29–90	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	2.2	<.2	<.2	<.2
BK–949	03–20–91	<.2	<.2	<.2	<.2	160	<.2	1.0	<.2	12	.2	<.2	<.2
	03–20–91	<.2	<.2	<.2	<.2	170	<.2	1.1	<.2	13	.2	<.2	<.2
BK–1020	04–18–91	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK–1058	03–20–91	<.2	<.2	<.2	<.2	.6	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK–1145	08–16–91	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK–1146	07–17–91	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK–1831	06–20–91	<.2	<.2	<.2	<.2	1.6	<.2	<.2	<.2	.7	<.2	<.2	<.2
BK–1832	07–17–91	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK–1833	06–21–91	<.2	<.2	<.2	<.2	.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK–1834	07–17–91	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK–1843	07–18–91	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
BK–1844	07–18–91	<.2	<.2	<.2	<.2	<.2	<.2	.2	<.2	<.2	<.2	<.2	<.2
						Montgomery County							
MG–213	06–20–91	<.2	<.2	<.2	<.2	.3	<.2	.2	<.2	73	<.2	<.2	<.2
MG–216	06–10–91	<.2	<.2	<.2	<.2	.2	<.2	.2	<.2	.3	<.2	<.2	<.2
MG–217	06–10–91	<.2	<.2	<.2	<.2	.4	.2	.2	<.2	7.4	<.2	<.2	<.2
MG–218	01–18–91	<.2	<.2	<.2	<.2	.9	<.2	.2	<.2	.2	<.2	<.2	<.2
	06–10–91	<.2	<.2	<.2	<.2	.6	<.2	.4	<.2	1.1	<.2	<.2	<.2
MG–219	06–20–91	<.2	<.2	<.2	<.2	<.2	<.2	.5	<.2	<.2	<.2	<.2	<.2
MG–220	11–15–90	<.2	<.2	<.2	<.2	.4	<.3	.3	<.2	33	<.2	<.2	<.2
MG–942	06–10–91	<.2	<.2	<.2	<.2	<.2	.4	<.2	<.2	7.6	<.2	<.2	<.2
MG–944	06–10–91	<.2	<.2	<.2	<.2	.3	<.2	.6	<.2	340	<.2	.3	<.2
MG–945	08–16–91	<.2	<.2	<.2	<.2	.2	<.2	2.3	<.2	.2	<.2	<.2	<.2
MG–946	04–16–92	<.2	<.2	<.2	<.2	2.9	<.2	.3	<.2	12	<.2	<.2	<.2
MG–947	06–10–91	<.2	<.2	<.2	<.2	5.3	.2	42	<.2	270	.3	<.2	<.2
MG–948	08–16–91	<.2	<.2	<.2	<.2	3.1	<.2	<.2	<.2	.4	<.2	<.2	<.2
MG–949	08–16–91	<.2	<.2	<.2	<.2	1.1	<.2	.2	<.2	<.2	<.2	<.2	<.2
MG–950	08–16–91	<.2	<.2	<.2	<.2	<.2	<.2	.2	<.2	.3	<.2	<.2	<.2
MG–951	12–10–90	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	9.2	<.2	<.2	<.2
	12–10–90	<.2	<.2	<.2	<.2	<.2	<.2	.2	<.2	13	<.2	<.2	<.2
MG–1115	11–14–90	<.2	<.2	<.2	<.2	<.2	<.4	.3	<.2	<.2	<.2	<.2	<.2
	11–14–90	<.2	<.2	<.2	<.2	<.2	<.4	.3	<.2	<.2	<.2	<.2	<.2
MG–1235	05–17–91	<.2	<.2	<.2	<.2	.7	.2	.3	.2	1,400	<.2	<.2	<.2
MG–1236	11–16–90	<2.0	<2.0	<2.0	<2.0	2.6	<2.0	<2.0	<2.0	5,500	<2.0	<2.0	<2.0
	06–05–91	<.2	<.2	<.2	<.2	1.8	.2	15	.4	3,900	<.2	.2	<.2
	06–16–92	<.2	.2	<.2	<.2	<.2	<.2	17	<.2	280	<.2	<.2	<.2
	06–16–92	<.2	<.2	<.2	<.2	1.7	<.2	9.5	.4	3,400	<.2	<.2	<.2
MG–1237	11–15–90	<.2	<.2	<.2	<.2	.6	<.2	11	.3	570	<.2	<.2	<.2
	11–15–90	<.2	<.2	<.2	<.2	.6	<.2	11	.3	660	<.2	<.2	<.2
	06–16–92	<.2	<.2	<.2	<.2	.8	<.2	6.5	.3	670	<.2	<.2	<.2
MG–1238	11–16–90	<.2	<.2	<.2	<.2	10	<.2	34	<.2	480	<.2	<.2	<.2
MG–1239	11–30–90	<.2	.3	<.2	<.2	44	<.2	1,000	<.2	4,900	<.2	.8	<.2
	11–30–90	<.2	.4	<.2	<.2	57	<.2	1,400	<.2	5,800	<.2	1.4	<.2
MG–1240	11–29–90	<.2	<.2	<.2	<.2	31	<.2	.2	<.2	110	<.2	<.2	<.2
	11–29–90	<.2	<.2	<.2	<.2	25	<.2	<.2	<.2	110	<.2	<.2	<.2
MG–1241	12–13–90	<.2	<.2	<.2	<.2	1.3	<.2	2.7	<.2	12	.9	<.2	<.2
MG–1242	12–13–90	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	1.2	<.2	<.2	<.2