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

Geohydrology and Ground-Water Quality of Warwick Township, Bucks County, Pennsylvania

by Philip H. Bird

Water-Resources Investigations Report 97-4267

prepared in cooperation with
WARWICK TOWNSHIP

Lemoyne, Pennsylvania
1998

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

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

For additional information
write to:

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

Copies of this report may be
purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286, Building 810
Denver, Colorado 80225-0286

CONTENTS

ILLUSTRATIONS

TABLES

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

MULTIPLY	BY	TO OBTAIN
	LENGTH	
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	AREA	
acre	4,047	square meter
square mile (mi^2)	2.590	square kilometer
	FLOW	
gallon per minute (gal/min)	0.06309	liter per second
gallon per day (gal/d)	0.003785	cubic meter per day
million gallon per day (Mgal/d)	0.04381	cubic meter per second
	TEMPERATURE	
degree Fahrenheit (°F)	°C=5/9 (°F-32)	degree Celsius
	SPECIFIC CAPACITY	
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter
	TRANSMISSIVITY	
foot squared per day (ft^2/d)	0.09290	meter squared per day

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

Abbreviated water-quality units used in report:

- milligrams per liter (mg/L)
- micrograms per liter (µg/L)
- picocuries per liter (pCi/L)
- microsiemens per centimeter at 25 degrees Celsius (µS/cm)

GEOHYDROLOGY AND GROUND-WATER QUALITY OF WARWICK TOWNSHIP, BUCKS COUNTY, PENNSYLVANIA

by Philip H. Bird

ABSTRACT

Warwick Township is an 11.14-square-mile area located in the Newark Basin. Ninety-nine percent of the area is underlain by Triassic-age sedimentary rocks of the Stockton and Lockatong Formations. Ground water in the sedimentary rocks moves through interconnected secondary openings—joints, fractures, and bedding-plane separations. High transmissivity beds are separated by low transmissivity beds, forming a leaky multiaquifer ground-water system. Water in the shallow part of the aquifer is unconfined and is semiconfined or confined in the deeper part. Most deep wells are multiaquifer wells and penetrate several water-bearing zones.

The frequency of occurrence of water-bearing zones decreases with depth. Sixty-seven percent of the water-bearing zones in the Stockton Formation and 37 percent of the water-bearing zones in the Lockatong Formation are within 200 feet of land surface. On the basis of the median specific capacity of domestic and nondomestic wells, the Stockton Formation is the more productive of the two hydrogeologic units. The Stockton Formation also has higher median well yields than the Lockatong Formation.

A water budget for an unnamed tributary to Little Neshaminy Creek was calculated for calendar years 1994-95. Average annual precipitation was 48 inches, average annual evapotranspiration and other losses were 32.1 inches, average annual streamflow was 15.2 inches, and the average annual change in ground-water storage was an increase of 0.1 inch. The average estimated recharge for the period was 7.4 inches or 0.36 million gallons per day per square mile.

The median pH of water from wells in the Stockton Formation (6.7) is slightly acidic; the median pH of water from wells in the Lockatong Formation (7.0) is neutral. The median concentration of dissolved oxygen in water from wells in the Stockton Formation (2.2 mg/L) is lower than water from wells in the Lockatong Formation (5.2 mg/L). Median total concentrations of dissolved solids in the Stockton Formation (234 mg/L) and the Lockatong Formation (240 mg/L) are similar. Water from only 1 of 16 wells sampled exceeds the U.S. Environmental Protection Agency (USEPA) secondary maximum contaminant level (SMCL) for total dissolved solids. One of 16 samples exceeds the USEPA action level for lead, and 1 of 16 samples exceeds the SMCL for sulfate; these wells are in the Stockton Formation. The median nitrate concentration of water from wells in both formations is similar, 2.8 mg/L for the Stockton Formation and 2.0 mg/L for the Lockatong Formation. Of 16 water samples from wells, none exceeds the USEPA maximum contaminant level (MCL) for nitrate. Volatile organic compounds were detected in four of five wells sampled; the most commonly detected compound was methyl tert butyl ether (four of five wells). One of five samples exceeded the USEPA MCL for trichloroethylene.

INTRODUCTION

Warwick Township is in south-central Bucks County (fig. 1), which has one of the fastest growing populations in Pennsylvania. The Bucks County Planning Commission (1984) estimated that the township population would increase as much as 416 percent between 1980 and 2000. Because of the rapidly increasing population, demand for water for public, commercial, and industrial uses also has increased greatly in recent years. Increased withdrawals from wells may lead to a decline in ground-water levels and may cause reductions in ground-water availability and streamflow, as are now occurring in other areas of southern Bucks County (Sloto and Davis, 1983). In response to the need for information about the ground-water resources in Warwick Township, the U.S. Geological Survey (USGS), in cooperation with Warwick Township, conducted the study described in this report.

Purpose and Scope

This report provides data and analysis on the geology and ground-water resources in Warwick Township, Bucks County, Pa. It presents a statistical analysis of hydrologic data from 114 wells and chemical analyses from 16 wells. This report describes the hydrogeologic system, a water-budget analysis of a small representative basin, and ground-water/surface-water relations. It also presents statistical summaries of water-quality data.

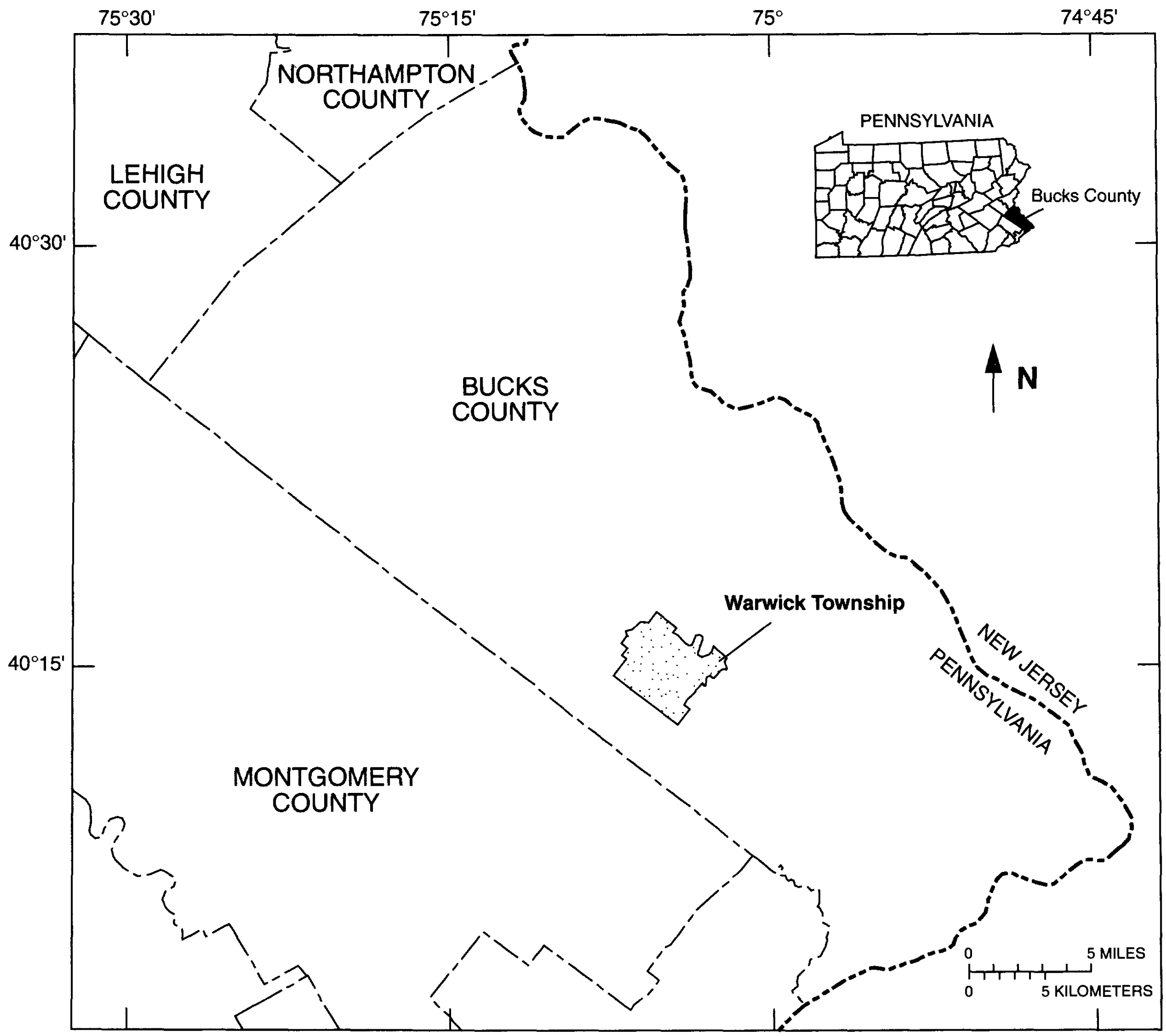


Figure 1. Location of study area.

LOCATION AND PHYSIOGRAPHY

Warwick Township (fig. 1) is an 11.14-mi^2 area in south-central Bucks County. It is drained by the Neshaminy and Little Neshaminy Creeks and their tributaries. The Neshaminy Creek forms most of the township's northern border, and the Little Neshaminy Creek forms the northern half of the eastern border. The floodplain of Neshaminy Creek is bordered by steep hillsides. Little Neshaminy Creek flows through the southern half of the township. It is bordered by hills to the north and east and by gently rolling fields to the south. These streams are tributaries to the Delaware River.

Warwick Township is in the Mesozoic-age Newark Basin of the Piedmont Physiographic Province. It is underlain by the Triassic-age sedimentary rocks of the Lockatong and Stockton Formations. The Stockton Formation is intruded in the northwest by a Jurassic-age diabase dike. The Lockatong Formation forms the higher, northeastern half of the township.

CLIMATE

Warwick Township has a humid continental climate with warm summers and moderately cold winters. The normal mean annual temperature (1961-90) at Neshaminy Falls, Pa., 7 mi. southeast of the township, is 51.7°F (Owenby and Ezell, 1992). For the coldest month, January, the normal mean temperature is 28.3°F, and for July, the warmest month, the normal mean temperature is 73.8°F.

The normal annual precipitation (1961-90) at Neshaminy Falls is 47.47 in. (Owenby and Ezell, 1992). Precipitation is nearly evenly distributed throughout the year; thunderstorms account for slightly higher precipitation in July and August.

WELL-NUMBERING SYSTEM

Well-identification numbers used in this report consist of a county abbreviation prefix preceding a sequentially assigned well number. The prefix BK denotes a well located in Bucks County. Well locations are shown on figure 2. Data for these wells are given in table 13 at the end of the report.

BOREHOLE GEOPHYSICAL LOGGING

Caliper, natural-gamma, single-point-resistance, fluid-temperature, and fluid-resistivity logging was conducted at seven wells (table 1). The locations of these wells are shown on figure 2. The geophysical logs provide information on well construction, formation properties, and fluid properties within the well. Keys (1990) discussed the application of borehole geophysical methods to water-resources investigations. Fluid-velocity measurements were made when fluid-temperature and fluid-resistivity logs indicated flow in the well. A borehole television survey was conducted in one well (BK-1845).

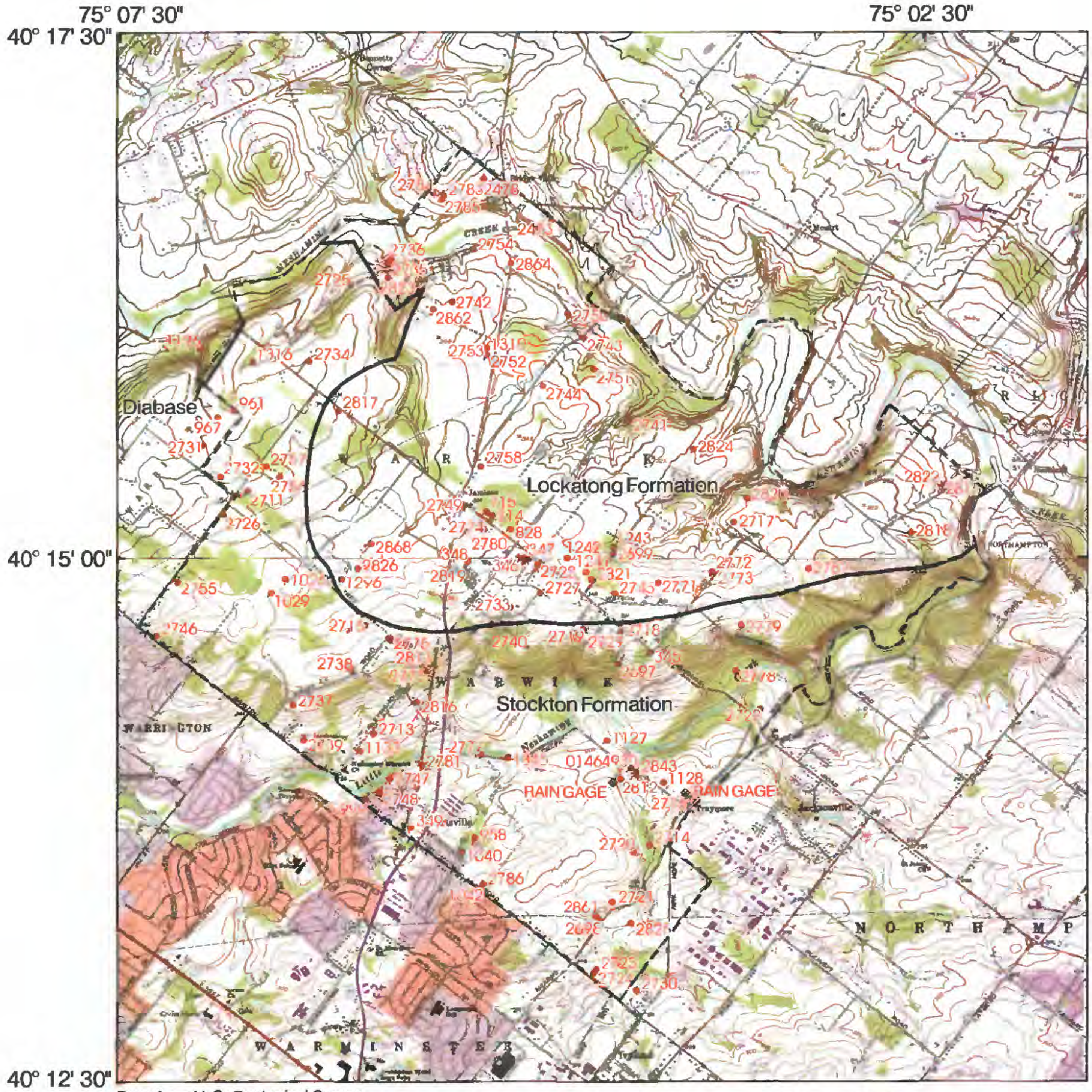
The caliper log provides a record of borehole (well) diameter, which is determined by drilling technique, lithology, and fracturing. The log is used to identify fractures and possible fluid-bearing openings, to correlate lithostratigraphy, and to adjust other geophysical logs for variations caused by changes in well diameter.

Natural-gamma logs record gamma-ray emissions from the decay of naturally occurring radioactive isotopes in rocks penetrated by the borehole. Uranium-238, thorium-232, their daughter isotopes, and potassium-40 are the most common natural-gamma emitting isotopes. These elements are commonly found associated with clay because of ion-exchange and adsorption. Therefore, fine-grained sedimentary rocks

Table 1. *Wells in which geophysical logging was conducted in Warwick Township, Bucks County, Pennsylvania*

[C, caliper; J, natural-gamma; E, electric; F, fluid-resistivity; T, temperature; V, fluid-velocity; P, television survey]

U.S. Geological Survey identification number	Owner and identification number	Geologic unit	Depth logged (feet)	Geophysical logs run
BK-1845	Warminster Township Municipal Authority 29	Stockton Formation	420	C, J, E, F, T, V, P
BK-2697	M. Young	Stockton Formation	400	C, J, E, F, T
BK-2698	Warwick Water and Sewer Authority	Stockton Formation	222	C, J, E, F, T
BK-2699	Warwick Water and Sewer Authority	Lockatong Formation	427	C, J, E, F, T
BK-2861	Warwick Water and Sewer Authority 11	Stockton Formation	158	C, J, E, F, T
BK-2862	Camp Neumann	Lockatong Formation	305	C, J, E, F, T
BK-2864	Creek Wood Estates	Lockatong Formation	265	C, J, E, F, T, V



Base from U. S. Geological Survey
Buckingham 1:24,000 1980, Contour interval 20 feet,
Hatboro 1:24,000 1983, Contour interval 10 feet

SCALE

0 0.2 0.4 0.6 0.8 1 MILE

0 1 KILOMETER

EXPLANATION

- - - - TOWNSHIP BOUNDARY

——— GEOLOGIC CONTACT WITHIN TOWNSHIP

•2730 WELL LOCATION WITH IDENTIFICATION NUMBER -- Prefix BK for Bucks County omitted

RAIN GAGE ◆ RAIN GAGE

01464930 ▲ STREAMFLOW-MEASUREMENT STATION WITH IDENTIFICATION NUMBER

Figure 2. Geology and locations of wells and streamflow-measurement stations in Warwick Township, Bucks County, Pennsylvania.

such as shale, siltstone, and argillite generally emit more natural-gamma radiation than do sandstones or conglomerates.

Single-point-resistance logs, also known as electric logs, record the electrical resistance measured between an electrode placed in the ground near the wellhead and an electrode lowered into the borehole. A water-filled borehole is required, and the logs are only valid for the saturated zone below the casing. Resistance generally decreases with density of water-bearing fractures, borehole diameter, and increasing dissolved solids concentration in the borehole fluid. Single-point-resistance logs aid in the identification of water-bearing zones and, with natural-gamma logs, in the correlation of lithostratigraphy.

Fluid-temperature logs record borehole fluid temperature for the length of the borehole. These logs are used to locate intervals of vertical borehole flow and possible water-producing and water-receiving zones. Vertical fluid flow is identified by zones of little or no temperature change. Boreholes with no vertical flow generally show decreasing fluid temperature in the upper part of the well and an increasing temperature gradient in the lower part of the well as a function of the geothermal gradient.

Fluid-resistivity logs record changes in the electrical resistance of the borehole fluid along the length of the borehole. This log measures changes in the concentration of dissolved solids in the borehole fluid and is used to help identify intervals of fluid flow and to locate water-producing and water-receiving zones. Sharp changes in fluid resistivity indicate zones of water production and water reception, and intervals of fluid flow are identified by a low fluid-resistivity gradient between water-producing and water-receiving zones.

Direction and rate of borehole fluid flow are measured with a heat-pulse flowmeter. All flow is diverted through the tool, and the fluid is heated instantaneously by an electrified grid within the tool. The heated fluid is subsequently detected at one of two thermistors located above and below the heating grid. The interval between heating and detection is recorded by the analysis software, which calculates flow rate and direction. The range of flow measurement with this method is approximately 0.05-1.5 gal/min in a 2- to 8-in. well.

Direction and rate of borehole fluid flow also can be determined by the “brine-tracing” method, where the vertical movement of a high-conductance fluid slug is monitored with the fluid-resistivity tool. The lower limit of flow measurement with this method is approximately 0.5 gal/min in a 6-in. well.

A borehole television survey was conducted with a waterproof video camera with a very wide angle lens. Images were recorded on tape with a standard video cassette recorder, and selected features were “captured” onto a personal computer to produce the images in this report.

Previous Investigations

The geology and mineral resources of Bucks County were discussed and mapped by Willard and others (1959). The geology of much of the area also was described by Bascom and others (1931). The area is included on the geologic map of Lyttle and Epstein (1987). Rima and others (1962) described the geology and hydrology of the Stockton Formation.

A study was done on the effect of urbanization on the water resources of adjacent Warminster Township by Sloto and Davis (1983). A map of the potentiometric surface in Warwick Township was done for this study by Rowland (1997). Hydrologic and water-quality data were collected for adjacent townships in northern Bucks County by Schreffler and others (1994), and the hydrogeology and ground-water quality of northern Bucks County were described by Sloto and Schreffler (1994). Geohydrology and open borehole cross-contamination in the Stockton Formation were studied in Hatboro Borough and adjacent Warminster Township by Sloto and others (1996). Geohydrology and vertical distribution of organic compounds in ground water at the Fischer and Porter Company Superfund Site in adjacent Warminster Township were studied by Sloto and others (1995).

Acknowledgments

The author gratefully acknowledges the individuals and companies that allowed access to their wells for measurements, sampling, and geophysical logging and streams for streamflow measurements. Thanks also to Dick Raab, Joe DiPasquale, Tom Courduff, Kevin Grazul, and Cindi Rowland for all their help. Special thanks go to Curt Schreffler for his invaluable assistance.

GEOLOGY

Warwick Township is underlain by Upper Triassic-age sedimentary rocks of the Newark Basin. A dike of Jurassic-age diabase, an intrusive crystalline rock composed mostly of calcic plagioclase and augite, covers about 7 acres along the northwestern border of the township (fig. 2). The diabase has no primary porosity and is highly resistant to weathering; therefore it is not an important source of ground water. This dike will not be discussed in this report.

STOCKTON FORMATION

The Stockton Formation (fig. 2) underlies the southern and western areas of the township. It is the oldest of the Newark Basin sediments and forms its basal unit. The Stockton lies unconformably over crystalline rocks of Paleozoic and Precambrian age. The formation includes alluvial fans, fluvial and lacustrine sandstones, mudstones, and siltstones (Turner-Peterson and Smoot, 1985). The rocks contain mudcracks, channels, ripple marks, and minor burrows. The bedding of the strata is not uniform; crossbeds and pinch-and-swell structures are common. Beds in the formations are commonly lens-shaped and discontinuous.

The Stockton Formation dips from 10° to 15° to the north-northwest in the southern part of the township and 5° to 15° to the east-southeast near the western edge. The Stockton is estimated to be 6,000 ft thick in the center of the basin at the Bucks-Montgomery County border (Rima and others, 1962).

The Stockton Formation is lithologically diverse; the rocks differ in texture, color, and bedding. The common characteristic of Stockton rocks is their high arkose content, although lesser amounts occur in the upper several hundred feet (Willard and others, 1959). The rocks include interbedded conglomerate, arkose, arkosic sandstone, siltstone, and shale. Texture generally grades from coarse conglomerates in the lower half to fine-grained sandstones and shale in the upper half. Color ranges from light gray to yellow, brown, and red. Rapid lithologic changes are common, and beds may grade from fine to coarse grained in a few yards (Willard and others, 1959).

The Stockton Formation interfingers with and is overlain conformably by the Lockatong Formation. The Stockton-Lockatong boundary is considered to be the base of the lowest continuous black siltstone bed (Olsen, 1980).

LOCKATONG FORMATION

The Lockatong Formation (fig. 2) underlies the northern and eastern areas of the township. It conformably overlays and interfingers with the Stockton Formation. The lithology of the Lockatong Formation is fairly homogenous and includes detrital and chemical-lacustrine sediments. The detrital rocks are dark gray to black, calcareous, pyritic siltstone and shale in the lower part overlain by dark gray, calcareous siltstone and fine-grained sandstone (Van Houten, 1962). The chemical-lacustrine rocks are dark gray to black, dolomitic siltstone and marlstone with lenses of pyritic limestone in the lower part, overlain by red or gray analcime- and carbonate-rich siltstone. These rocks are non-fissile and are very resistant to weathering. Willard and others (1959) refer to these rocks as argillite, a term meaning a tough, firmly cemented, non-fissile, argillaceous (composed of clay or clay sized particles) rock. Dark red shale, siltstone, and marlstone interfinger with gray beds, especially in the upper and western parts, but differ from the gray beds mainly in color. Pyrite and calcite crystals up to 1/4-in. long are scattered throughout the beds. Rock containing sufficient calcite to be considered an argillaceous limestone occurs in beds up to a few feet thick (Willard and others, 1959). The rocks contain shrinkage cracks, mudcracks, ripple marks, root disruptions, and burrows. Bedding is generally even and commonly about a foot thick, although some beds may be massive. In some places, the contact between red and gray beds is sharp; in most others, there is a brownish- to purplish-gray transition rock, which is a few inches to a few feet thick. Where the contact is sharp, the gray is commonly suncracked, and the cracks are filled with red sediment (Willard and others, 1959). No examples of cracked red shale filled with gray have been found.

The Lockatong Formation dips from 3° to 30° to the east-northeast in the Jamison-Bridge Valley area; the lowest dip is just west of Jamison and the highest dip is east of Bridge Valley. In the northeast area, dip varies from 5° to 19° to the north-northeast. The maximum thickness of the formation is estimated to be 3,900 ft (Lyttle and Epstein, 1987).

HYDROLOGY

Both the Stockton and Lockatong Formations are aquifers. Most wells in both formations have their casing set several feet into unweathered bedrock and are completed as open holes.

RELATION OF GEOLOGY TO GROUND-WATER FLOW

The hydraulic properties of aquifers and the characteristics of ground-water-flow systems are related to the subsurface geology. In the weathered zone, ground water moves through intergranular openings resulting from weathering. Permeability of the weathered zone may be reduced locally because of increased amounts of clay resulting from weathering. Below the weathered zone, ground water moves through interconnected secondary openings—joints, fractures, and bedding-plane separations. Permeability may be higher in zones where cementation has been partially removed, but this is generally restricted to conglomerates and some sandstones.

The ground-water system consists of a series of beds with differing hydraulic properties. Soft shale beds deform rather than break under pressure and act as confining units; harder sandstone and conglomerate beds fracture and thus become more permeable. This results in a series of high-transmissivity beds separated by confining or semiconfining units. Ground water in the high-transmissivity beds may be under different pressures, resulting in different hydraulic heads. Because most deep wells penetrate several of these units, the hydraulic head in deep wells is a composite head. If the composite head in a well is above the land surface, the well will flow; if it is below an upper water-bearing zone, water in the well will cascade. When head differences exist in the well, water will flow under non-pumping conditions from zones of higher head to zones of lower head. If the flow is downward, a cone of depression may form, lowering water levels locally.

Ground-water flow in the Triassic-age formations is anisotropic; flow is generally in the direction of strike (Sloto and Schreffler, 1994). Increased compression with depth closes many water-bearing openings, so that continuity of the water-bearing network is along strike, where depth to individual beds is constant. Wells drilled along strike will intersect the same beds, whereas wells drilled along dip will seldom penetrate the same units. Therefore, pumping influence on nearby wells is greatest for wells along strike, and cones of depression in the Triassic formations are usually elliptical, with the long axis along strike (Sloto and Schreffler, 1994). In some cases, ground-water flow may not be normal to lines of equal hydraulic head but may trend toward strike because of the decrease of water-bearing openings with depth along dip.

STOCKTON FORMATION

The Stockton Formation underlies 51.3 percent of Warwick Township. The conglomerates and sandstones of the Stockton are poorly cemented and easily fractured, resulting in higher well yields than those obtained in the Lockatong Formation, which is largely siltstone. Recharge to the Stockton is aided by its generally lower elevations than the Lockatong and lesser amounts of clay in the weathered zone.

Borehole geophysical logging was conducted in wells BK-1845, BK-2697, BK-2698, and BK-2861 in the Stockton Formation in Warwick Township (fig. 2). A borehole television survey was conducted in well BK-1845 (figs. 3 and 4). This well was originally drilled as a 6-in.-diameter well and later reamed to a 10-in.-diameter well. Television surveys and geophysical logging were conducted for both well diameters; geophysical logs for the 10-in.-diameter borehole are shown in fig. 5. Upward flow in the 10-in.-diameter well at a rate of 5.0, 2.9, and 1.2 gal/min was measured at 80, 180, and 280 ft below land surface (bls), respectively, and downward flow at a rate of 0.7 gal/min was measured at 380 ft bls (fig. 6). Water enters the well through fractures at 184, 221, 231, and 331 ft bls. Water-receiving fractures were located at 60 and 405 ft bls. The television survey of the 10-in.-diameter well showed turbulence in particles suspended in the borehole fluid at 184.5, 221.8, 231.0, and 332.2 ft bls. No particles were seen in the borehole fluid in the television survey of the 6-in.-diameter well. The television survey of the 6-in.-diameter well showed horizontal fractures at the depths of turbulence in the 10-in.-diameter well, but these fractures were not observed in the television survey of the 10-in.-diameter well because they had become obscured during re-drilling to increase the borehole diameter.

Well BK-2697 was drilled to a depth of 400 ft bls. The caliper log showed that the only major fracture in the well was at 192 ft bls (fig. 7). The natural-gamma and single-point-resistance logs indicate shale from 103 to 192 ft bls, sandstone from 192 to 296 ft bls, shale from 296 to 354 ft bls, and sandstone from 354 to 396 ft bls. The fluid-resistivity and fluid-temperature logs indicate possible zones of horizontal flow at 319 and 359 ft bls. No vertical flow was indicated by the fluid-temperature or fluid-resistivity logs.

The caliper log of well BK-2698 shows numerous small fractures from 60 to 180 ft bls (fig. 8). The natural-gamma and single-point-resistance logs indicate shale to 124 ft bls, sandstone from 124 to 151 ft bls, shale from 151 to 176 ft bls, and sandstone from 176 to 220 ft bls. Irregular inflections at 98 ft and 149 ft appear in the fluid-resistivity log but not in the fluid-temperature log; this indicates influence from a nearby pumping well, rather than vertical or horizontal flow under ambient conditions. The pump in BK-2861, 75 ft northwest, was disconnected during logging; the nearest pumping wells are BK-2721, a domestic well approximately 600 ft northeast of BK-2698, and BK-2825, a nondomestic well approximately 900 ft east. It is uncertain which of these wells is influencing well BK-2698. Potential water-producing zones in well BK-2698 are at 60, 97, and 150 ft bls.

Well BK-2861 is cased with 10-in.-diameter steel to 82 ft bls and is open to 158 ft bls. The caliper log shows major fractures at 119, 138, and 145 ft bls (fig. 9). The natural-gamma and single-point resistance logs show alternating shale and sandstone beds to 129 ft bls and sandstone from 129 to 158 ft bls. The fluid-resistivity and fluid-temperature logs do not indicate horizontal or vertical flow.

Wells BK-2698 and BK-2861 are approximately 75 ft apart along strike. A correlation of natural-gamma and single-point-resistance logs from both wells shows that they penetrate the same beds, although well BK-2698 is deeper (fig. 10). The driller reported that development of wells BK-2698 and BK-2861 showed that pumping one had no effect on the other.

LOCKATONG FORMATION

The Lockatong Formation underlies 48.6 percent of Warwick Township. It has little permeability, and ground water moves through a poorly interconnected system of joints and fractures. The Lockatong weathers to clay, which plugs fractures in the weathered zone and causes ground water to be confined. The filled fractures impede recharge, as do the higher elevations common in areas underlain by this formation (Sloto and Schreffler, 1994). Well yields in the Lockatong Formation are generally lower than well yields in the Stockton Formation. Borehole geophysical logs were run in wells BK-2699, BK-2862, and BK-2864 in Warwick Township.

BK-2699 is a 427-ft-deep test well approximately 200 ft stratigraphically updip from Warwick Water and Sewer Authority Well 4 (BK-1243), which is 510 ft deep. The natural-gamma log of well BK-2699 indicates that the well starts in the Lockatong Formation and appears to enter the Stockton Formation at a depth of approximately 290 ft bls (fig. 11). This depth-to-contact is near to the depth expected from strike-and-dip measurements in the area (Willard and others, 1959). The caliper log shows numerous fractures from 12 to 70 ft bls. From 70 to 260 ft bls, only minor fractures occur. Major fractures are at 264, 289, 316, 385, and 407 ft bls. An obstruction at 402 ft bls is shown on the caliper log. The natural-gamma and single-point-resistance logs show a change in lithology from shale to sandstone at 394 ft bls. Assuming a dip of 8° (Willard and others, 1959) and an elevation difference of 5 ft, BK-1243 would penetrate the Stockton Formation at approximately 410 ft bls. The fluid-resistivity and fluid-temperature logs of well BK-2699 show the effect of pumping well BK-1243 by showing changes in slope at 225 ft, 260 ft, 305 ft, 325 ft, and 410 ft bls. Cessation of pumping in well BK-1243 resulted in a water-level rise in BK-2699 of 164 ft in 97 minutes; the approximate recharge rate was 2.5 gal/min.

Well BK-2864 is drilled 265 ft into the Lockatong Formation. The natural-gamma and single-point-resistance logs indicate that the lithology is entirely shale, suggesting this well is entirely in the Lockatong Formation (fig. 12). The fluid-temperature and fluid-resistivity logs indicate no borehole flow under ambient conditions. The heat-pulse flowmeter measured no flow at 47 ft bls. The caliper log shows few fractures below the casing, but several constrictions within the casing. These constrictions are probably the result of damage to the casing caused by land-grading operations at the site.

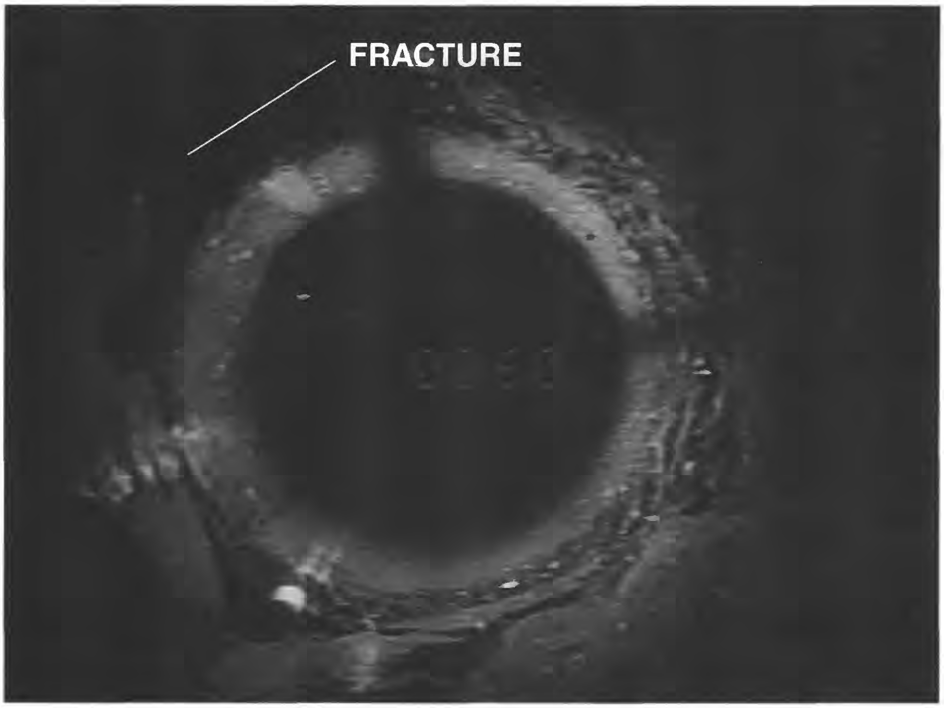


Figure 3. Photograph from borehole television survey of borehole BK–1845, Warwick Township, Bucks County, Pennsylvania, showing horizontal, water-receiving fracture at 60 feet below land surface.

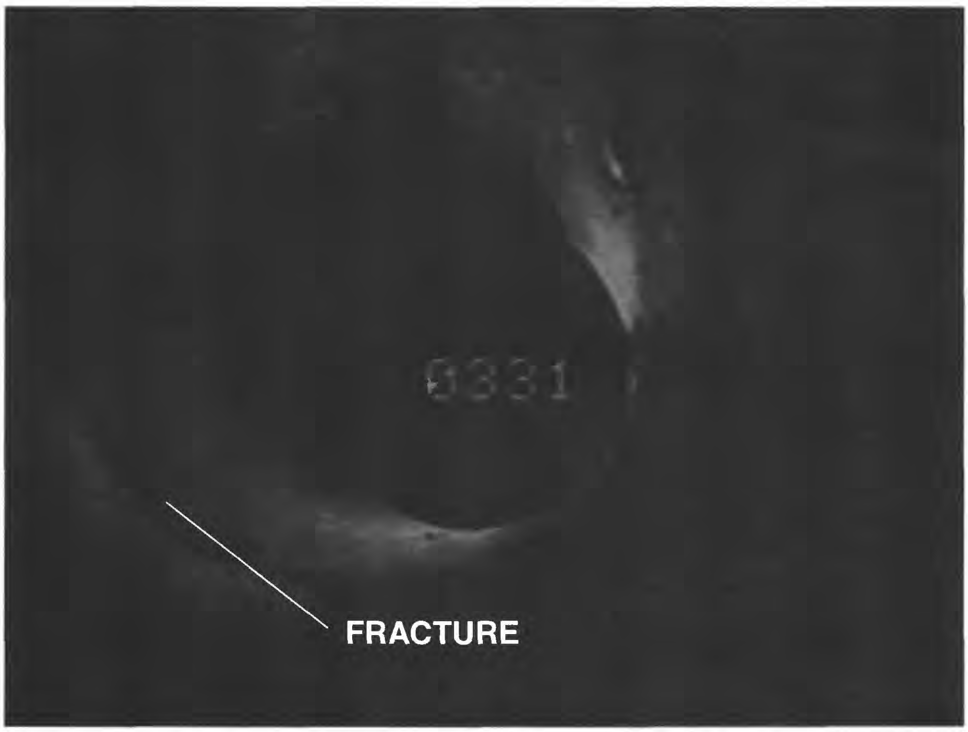


Figure 4. Photograph from borehole television survey of borehole BK–1845, Warwick Township, Bucks County, Pennsylvania, showing horizontal, water-producing fracture at 331 feet below land surface.

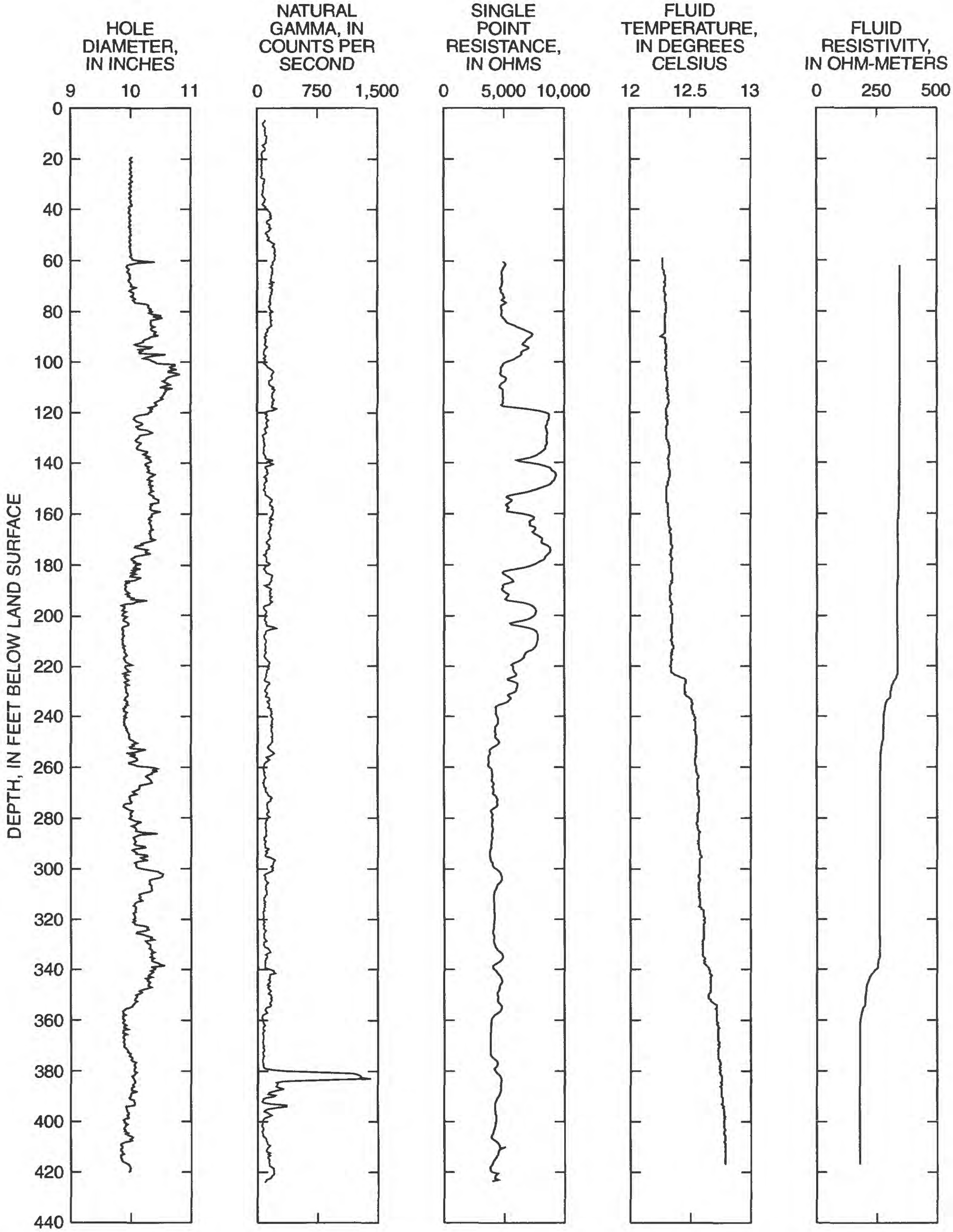


Figure 5. Caliper, natural-gamma, single-point-resistance, fluid-temperature, and fluid-resistivity logs from borehole BK–1845 (10-in. well), Warwick Township, Bucks County, Pennsylvania.

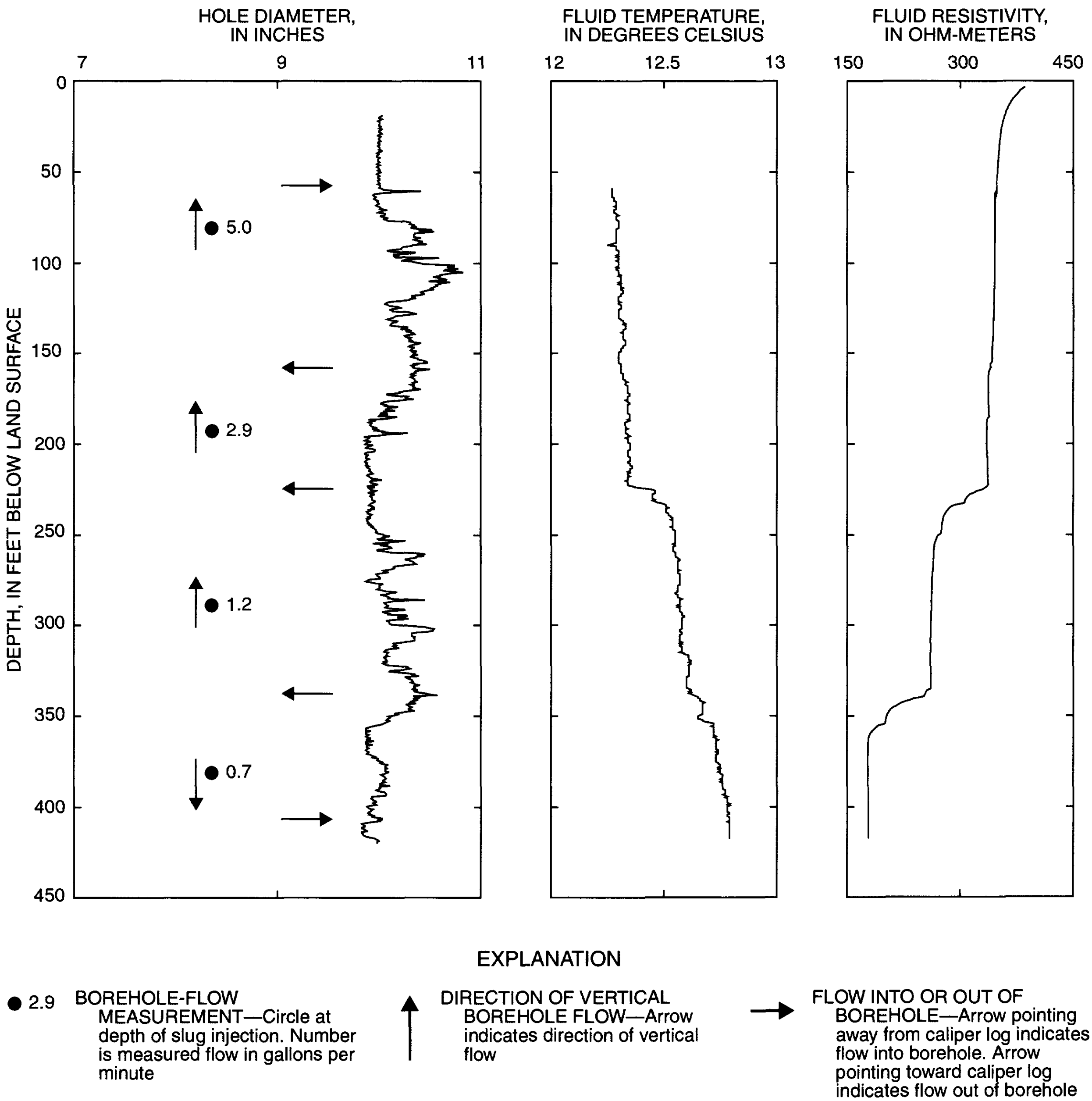


Figure 6. Caliper, fluid-temperature, and fluid-resistivity logs from borehole BK-1845, Warwick Township, Bucks County, Pennsylvania, showing borehole-flow measurements in 10-in. well (from Sloto, Macchiaroli, and Towle, 1996).

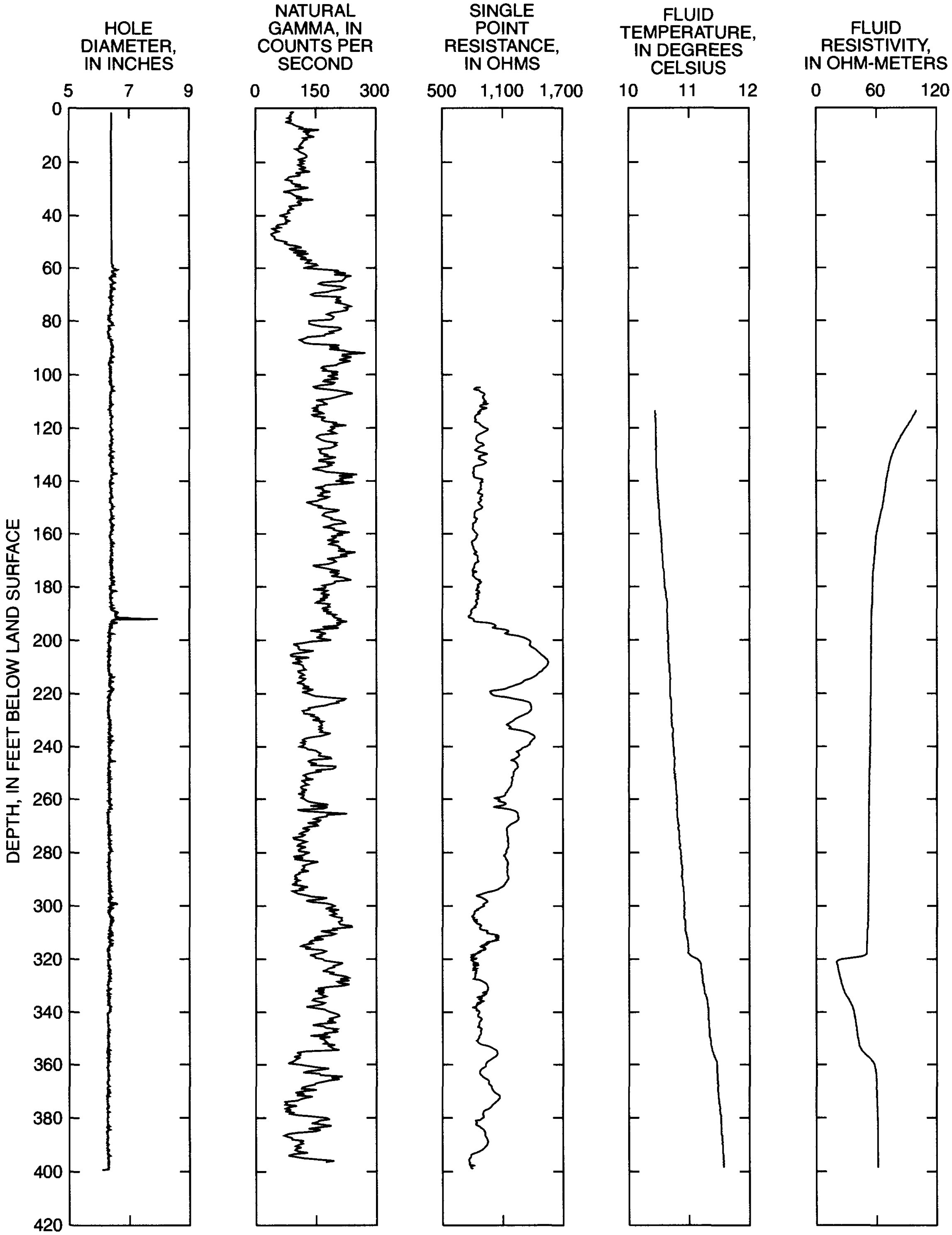


Figure 7. Caliper, natural-gamma, single-point-resistance, fluid-temperature, and fluid-resistivity logs from borehole BK–2697, Warwick Township, Bucks County, Pennsylvania.

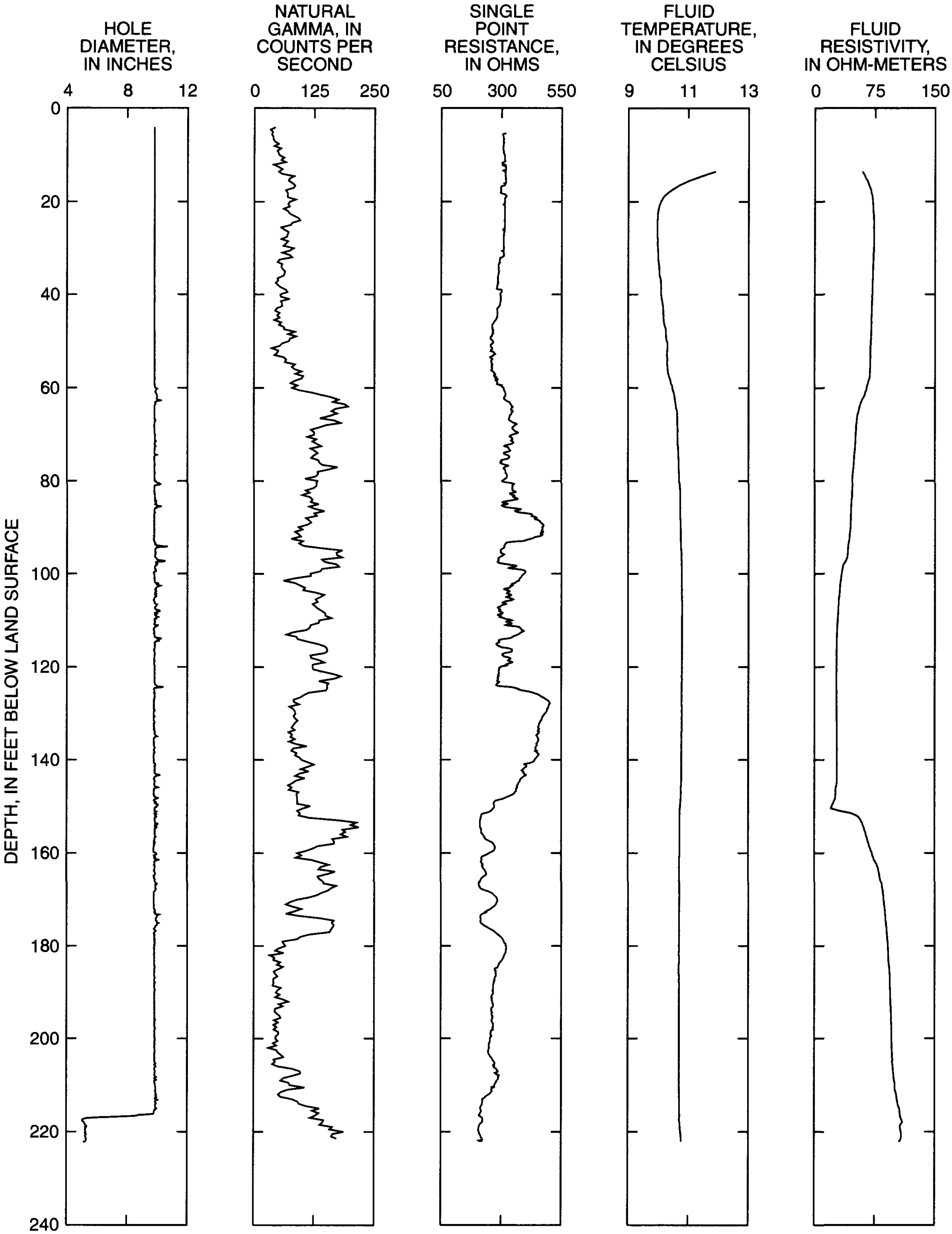


Figure 8. Caliper, natural-gamma, single-point-resistance, fluid-temperature, and fluid-resistivity logs from borehole BK–2698, Warwick Township, Bucks County, Pennsylvania.

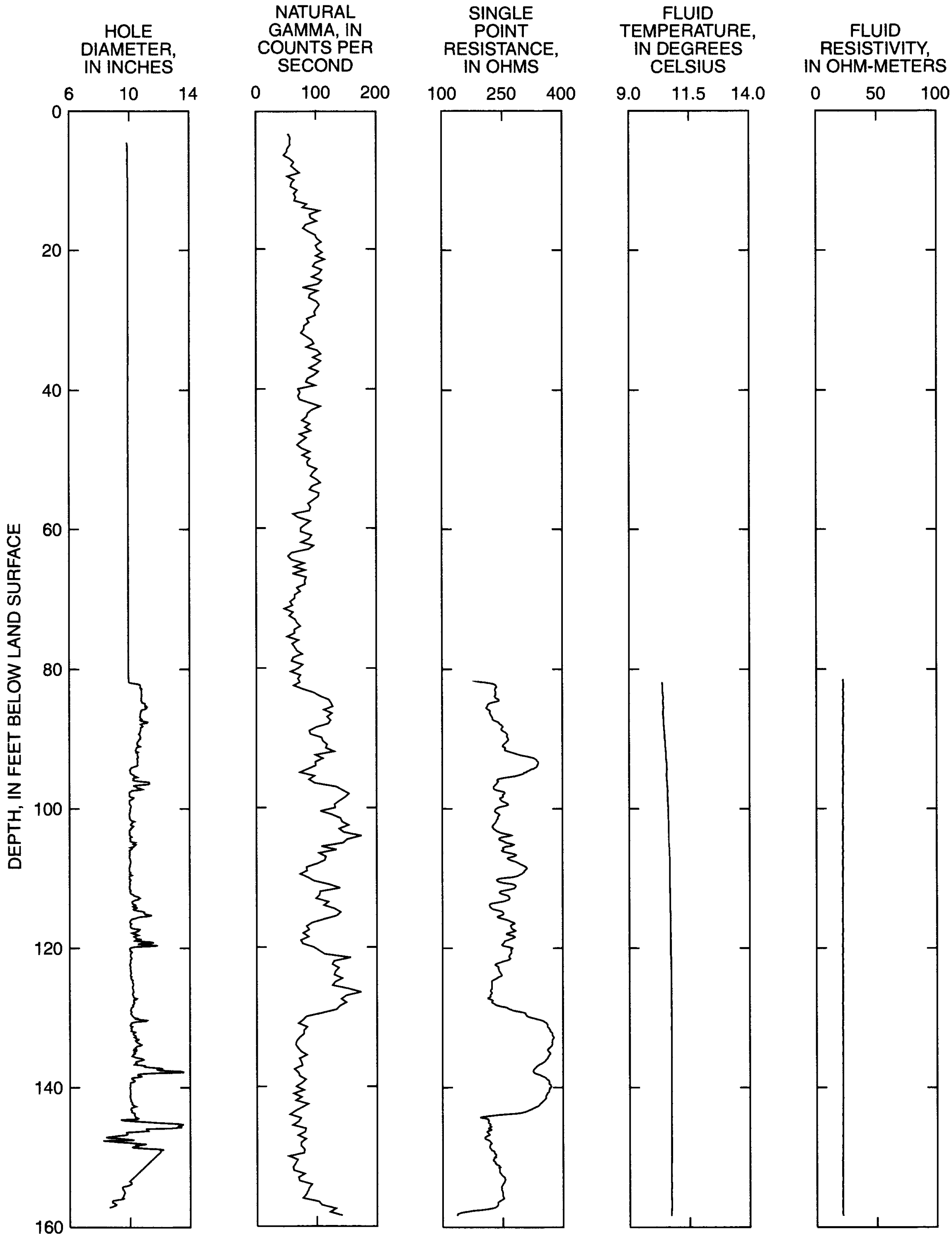


Figure 9. Caliper, natural-gamma, single-point-resistance, fluid-temperature, and fluid-resistivity logs from borehole BK–2861, Warwick Township, Bucks County, Pennsylvania.

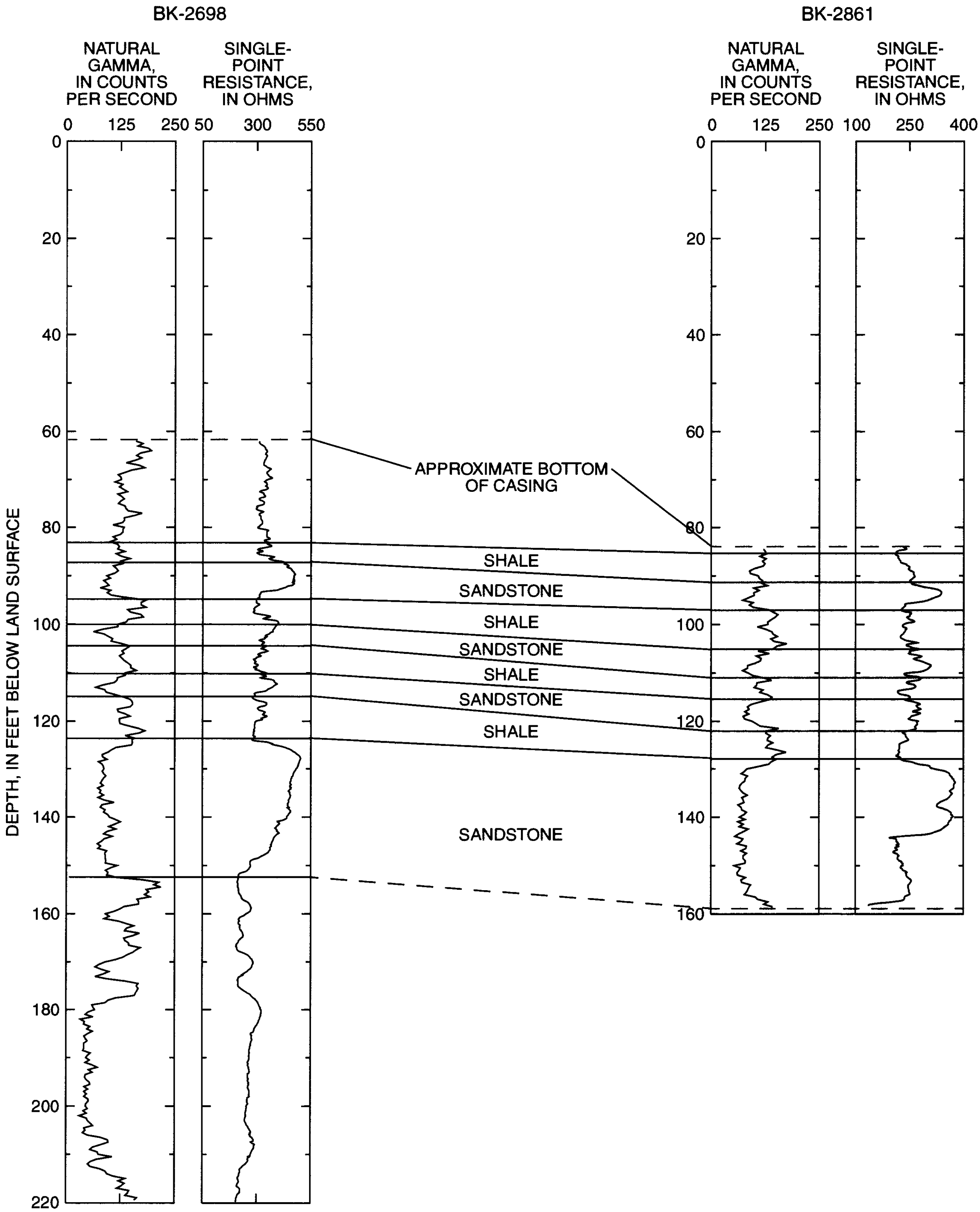


Figure 10. Interpreted geologic section approximately along strike penetrated by wells BK-2698 and BK-2861, Warwick Township, Bucks County, Pennsylvania.

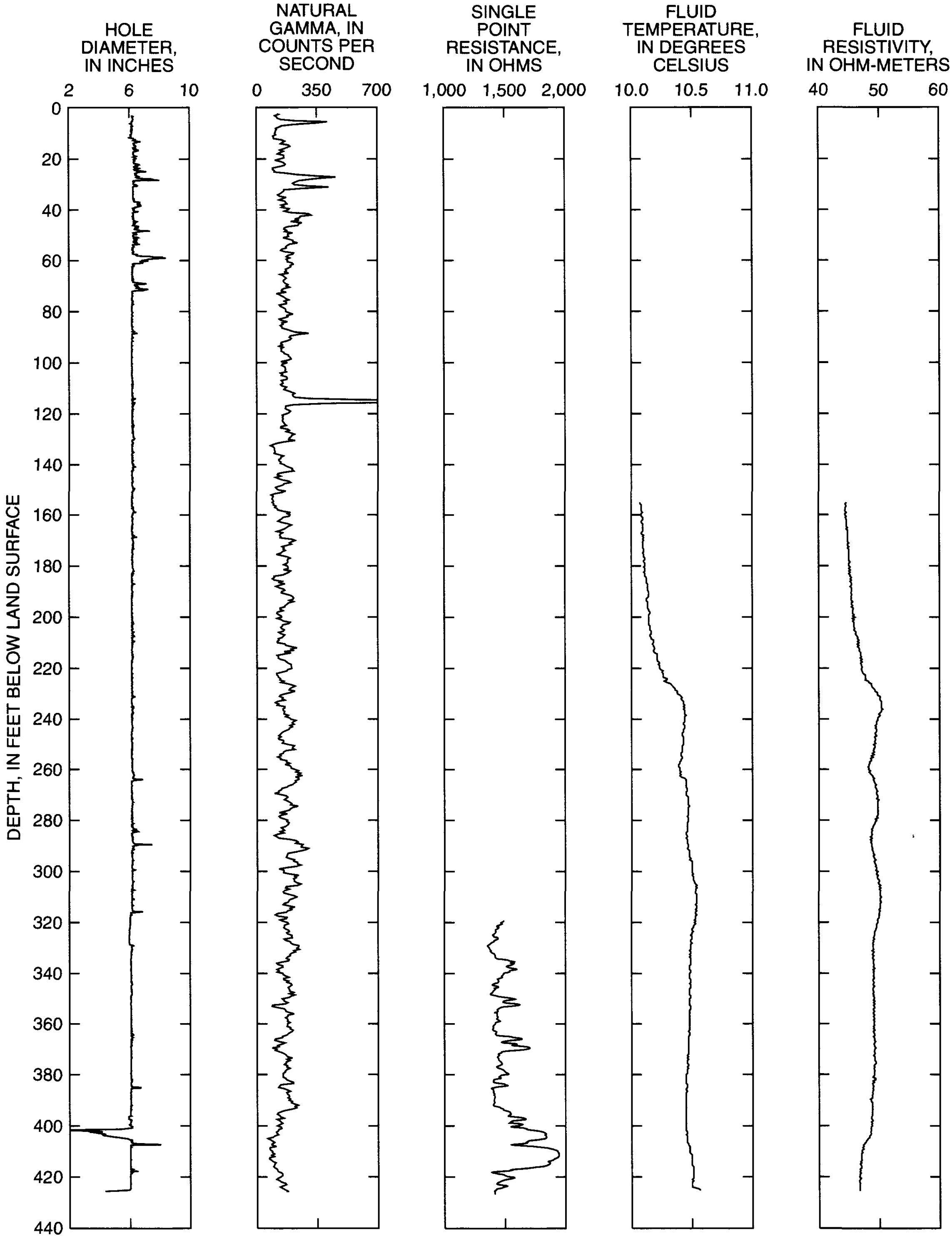


Figure 11. Caliper, natural-gamma, single-point-resistance, fluid-temperature, and fluid-resistivity logs from borehole BK–2699, Warwick Township, Bucks County, Pennsylvania.

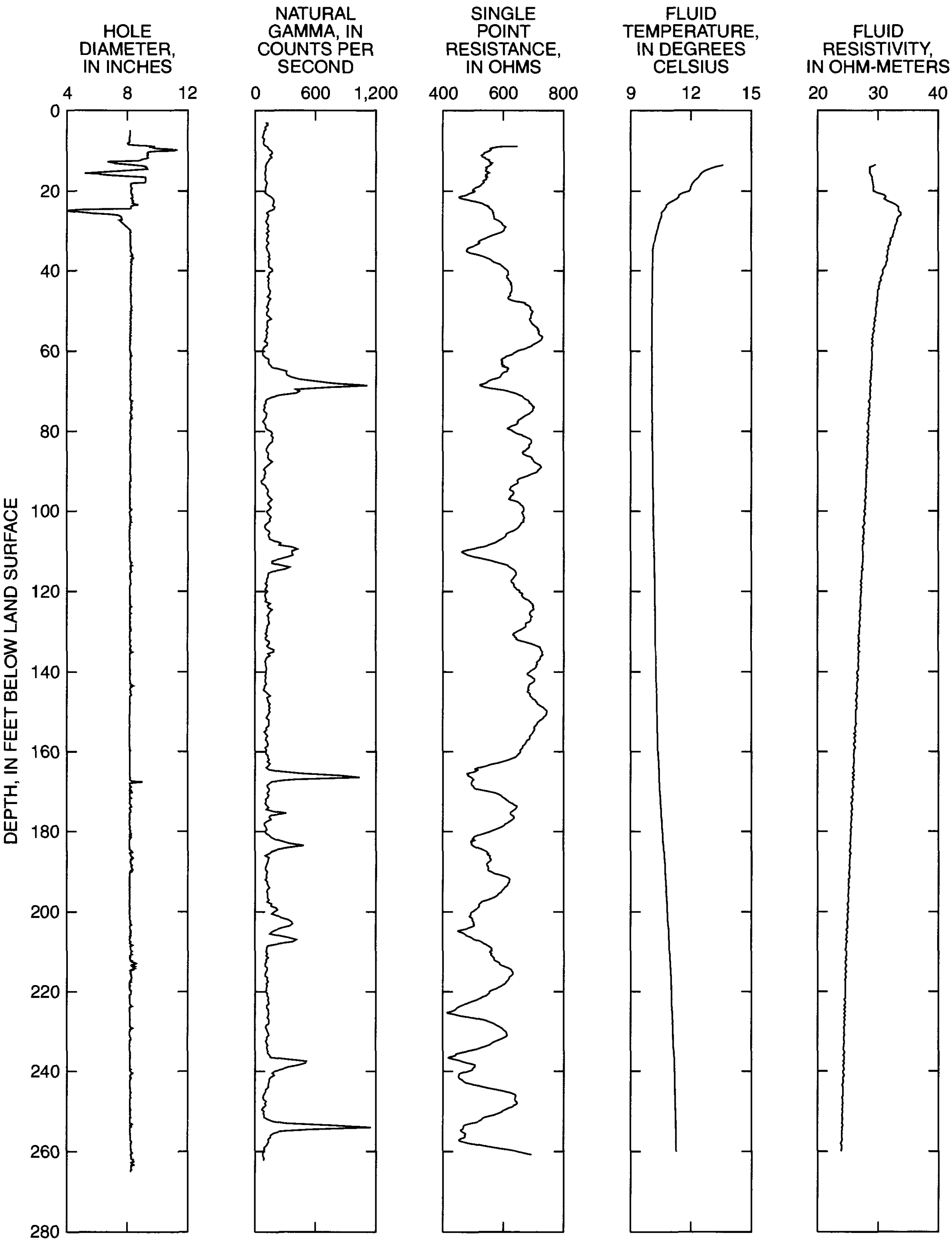


Figure 12. Caliper, natural-gamma, single-point-resistance, fluid-temperature, and fluid-resistivity logs from borehole BK–2864, Warwick Township, Bucks County, Pennsylvania.

Aquifer and Well-Construction Characteristics

The hydrologic properties of the Stockton and Lockatong Formations are discussed in the following sections.

Water-Bearing Zones

Primary porosity below the weathered zone is practically nonexistent in Triassic-age sedimentary rocks. Ground water moves through interconnected secondary openings. The size and number of these openings determines secondary porosity; the extent of interconnection determines permeability. Where a formation is highly fractured, well yields will be high.

Data on 119 water-bearing zones in 36 wells reported by drillers are summarized in table 2. Wells are as deep as 600 ft, and 9,323 ft of uncased borehole are represented. The data are expressed in units of water-bearing zones per 100 ft of uncased borehole. For 23 wells in the Stockton Formation, 84 water-bearing zones were reported in 5,169 ft of uncased borehole; 64 percent of the water-bearing zones are within 200 ft of land surface. For 13 wells in the Lockatong Formation, 35 water-bearing zones were reported in 4,154 ft of uncased borehole; 34 percent of the water-bearing zones are within 200 ft of land surface. The Stockton Formation has nearly twice as many water-bearing zones per 100 ft of uncased borehole (1.63) as the Lockatong Formation (0.84) in Warwick Township.

Well Yield

Well yields reported for wells in Warwick Township are given in table 3. Yield is reported in gallons per minute. Aquifer characteristics that determine well yield are porosity and permeability of the rock, and the number, size, and interconnection of water-bearing zones penetrated. A yield of 6 gal/min is considered adequate for most domestic uses; public supply and irrigation may require hundreds of gallons per minute (Paulachok and Wood, 1988). Wells drilled in the Stockton Formation yield more water than do wells drilled in the Lockatong Formation. The median yield of nondomestic wells in the Stockton Formation is 125 gal/min, and the median yield of nondomestic wells in the Lockatong Formation is 32.5 gal/min. The median yield of domestic wells in the Stockton Formation is 19 gal/min, and the median yield of domestic wells in the Lockatong Formation is 15 gal/min.

Some wells in Warwick Township are drilled through the Lockatong Formation into the underlying Stockton Formation. Warwick Water and Sewer Authority public-supply wells 4, 5, 6, and 8 (BK-1243, BK-1241, BK-1296, and BK-1242, respectively) are started in the Lockatong Formation and are reported to be completed

Table 2. *Number of water-bearing zones per 100 feet of uncased borehole, Warwick Township, Bucks County, Pennsylvania*

Depth interval (feet)	Stockton Formation (23 wells)			Lockatong Formation (13 wells)		
	Number of water-bearing zones		Footage drilled (feet)	Number of water-bearing zones		Footage drilled (feet)
	Penetrated	Per 100 feet of borehole		Penetrated	Per 100 feet of borehole	
0-50	3	5.00	60	0	0	30
51-100	13	2.20	590	2	.58	346
101-150	25	2.99	835	7	1.12	626
151-200	13	1.67	778	3	.50	600
201-250	10	1.30	770	5	.91	550
251-300	5	.68	730	6	1.13	530
301-350	8	1.40	570	2	.47	430
351-400	4	.93	430	2	.50	400
401-450	3	1.30	230	2	.74	270
451-500	0	0	110	3	1.50	200
501-550	0	0	56	2	1.48	135
551-600	0	0	10	1	2.70	37
Greater than 600	0	0	0	0	0	0
Total (mean)	84	(1.63)	5,169	35	(.84)	4,154

in the Stockton Formation. Geophysical logs of test well BK-2699 (fig. 11), drilled between wells BK-1243 and BK-1241, support this conclusion. The Lockatong-Stockton contact is reported to be at 248 ft bls in well BK-1241, and the natural-gamma log of well BK-2699 shows the contact to be at approximately 394 ft. Primary water contribution to these wells is probably from the Stockton Formation; therefore, these four wells are considered to be in the Stockton Formation.

SPECIFIC CAPACITY

The specific capacity of a well is calculated by dividing the pumping rate by the drawdown in water level and is reported in gallons per minute per foot of drawdown. Because it takes drawdown into account, it is a better measure of productivity than yield alone. Specific-capacity data for wells in Warwick Township were from the records of consultants and drillers (table 13). The specific capacity of wells drilled in the Stockton Formation is higher than that of wells drilled in the Lockatong Formation. The median specific capacity of nondomestic wells in the Stockton Formation is 1.3 (gal/min)/ft (table 3), and the median specific capacity of nondomestic wells in the Lockatong Formation is 0.18 (gal/min)/ft. The median specific capacity for domestic wells in the Stockton Formation is 0.20 (gal/min)/ft, and the median specific capacity for domestic wells in the Lockatong Formation is 0.12 (gal/min)/ft.

TRANSMISSIVITY

Transmissivity is the rate at which water is transmitted through an aquifer under a hydraulic gradient. It is usually determined by an aquifer test. An aquifer test measures drawdown and recovery rates in a well pumped at a constant rate and nearby observation wells. Most aquifer tests, however, are based on assumptions that do not apply to fractured-rock aquifers. Median transmissivity of the Stockton Formation in northern Bucks County, on the basis of analyses of seven aquifer tests, is 410 ft^2/d; the median transmissivity of the Lockatong Formation in northern Bucks County, on the basis of three aquifer tests, is 820 ft^2/d (Sloto and Schreffler, 1994). This high median transmissivity for the Lockatong may be a consequence of the small sample size and because only high-yielding wells were tested. This shows that high-yielding production wells can be drilled in the Lockatong Formation, even though well-yield and specific-capacity data show it to be a low-yielding aquifer.

WELL DEPTH AND CASING LENGTH

The drilling of a well normally ends when the well yields sufficient water for the planned use. Casing is usually set a few feet into unweathered bedrock. Casing lengths and well depths for wells inventoried in Warwick Township are shown in table 4.

Table 3. *Reported specific capacity and yield of wells in Warwick Township, Bucks County, Pennsylvania*

Hydrogeologic unit	Nondomestic wells			Domestic wells		
	Minimum	Median	Maximum	Minimum	Median	Maximum
	Specific capacity (gallons per minute per foot of drawdown)					
Stockton Formation	0.14	1.3	4.9	0.02	0.20	5
Lockatong Formation	.07	.18	.31	.01	.12	1.5
	Yield (gallons per minute)					
Stockton Formation	25	125	480	6	19	100
Lockatong Formation	2	32.5	60	6	15	30

Table 4. *Reported well depths and casing lengths in feet for wells in Warwick Township, Bucks County, Pennsylvania*

Hydrogeologic unit	Nondomestic wells			Domestic wells		
	Minimum	Median	Maximum	Minimum	Median	Maximum
	Well depth					
Stockton Formation	107	400	605	30	190	460
Lockatong Formation	150	400	577	15.5	290	560
	Casing length					
Stockton Formation	22.6	60	120	26	41.5	79
Lockatong Formation	10	42	85	20	41	80

WATER LEVELS

Water levels were measured in approximately 80 wells on a one-time basis to construct a potentiometric-surface map (Rowland, 1997). The potentiometric surface represents the level to which water in a well will rise; this is the static hydraulic head in the well. The hydraulic head is a composite where a well penetrates more than one water-bearing zone. The water table is the potentiometric surface for an unconfined aquifer. Six wells were measured monthly from January 1994 to December 1995. The measurements were used in determining change in ground-water storage.

WATER-LEVEL FLUCTUATIONS

Water levels in an aquifer fluctuate in response to recharge from precipitation and discharge to pumping wells, streams, and evapotranspiration. Water-level changes are seasonal. Water levels usually rise in late fall, winter, and early spring when evapotranspiration is low and recharge from precipitation is high. Water levels usually decline in late spring, summer, and early fall when evapotranspiration is high and recharge is low (fig. 13).

DEPTH TO WATER

Depth to water varies with topography, geology, and proximity to a discharge area. Depth to water may be lower where nearby pumping wells create a local cone of depression. A cone of depression is a depression in the potentiometric surface in the shape of an inverted cone; it defines the area of influence of the pumping well. A cone of depression has formed in northwest Warwick Township around public supply wells BK-1316 (Warwick well no. 3) and BK-1196 (Doylestown south well no. 7) (Rowland, 1997). Median water levels in the Lockatong Formation for domestic and nondomestic wells were higher than water levels in wells in the Stockton Formation. Measured depths to water are shown in table 5.

WATER BUDGET

A water budget is an estimate of all water entering and leaving a basin over a specific time interval. Water enters the basin as precipitation and as water imported from sources outside the basin. Water leaves the basin as streamflow, evapotranspiration, and as water exported to locations outside the basin. The budget also must take into account changes in ground-water storage. The general equation that represents this budget is

$$P = SF + \Delta GWS + GWP + ET, \qquad (1)$$

where P is precipitation,
SF is streamflow,
ΔGWS is change in ground-water storage,
GWP is ground-water pumpage exported from basin, and
ET is evapotranspiration.

The basin selected for this study is that of an unnamed tributary to the Little Neshaminy Creek. This basin is in southern Warwick Township and lies almost entirely within the township. The tributary above the streamflow-measurement station near Traymore (USGS site 01464930) drains 4.74 mi^2 in Warwick, Warminster, and Northampton Townships and Ivyland Borough. The basin is underlain by the Stockton Formation.

Precipitation was measured at two sites in the basin in 1994 and 1995. Average annual precipitation for the 2-year period was 48 in. The average annual evapotranspiration and other losses were 32.1 in., or 67 percent of the annual precipitation. Water-level data from wells BK-1020, BK-1040, BK-1087, and DG-24 were used to estimate the change in ground-water storage. Well DG-24 is located in Warminster Township and is only used in the estimate of ground-water storage change in this report; it has not been given a USGS well number. The average annual change in ground-water storage was an increase of 0.1 in., which was 0.2 percent of the average annual precipitation. The water budget is given in table 6.

RECHARGE

Recharge to the ground-water system comes from local precipitation. Precipitation first replenishes soil moisture and then recharges the ground-water system. Recharge from precipitation depends on the amount and duration of precipitation, topography, surface cover, soil conditions, and bedrock characteristics. Recharge generally occurs in topographically high areas; low areas are normally areas of discharge.

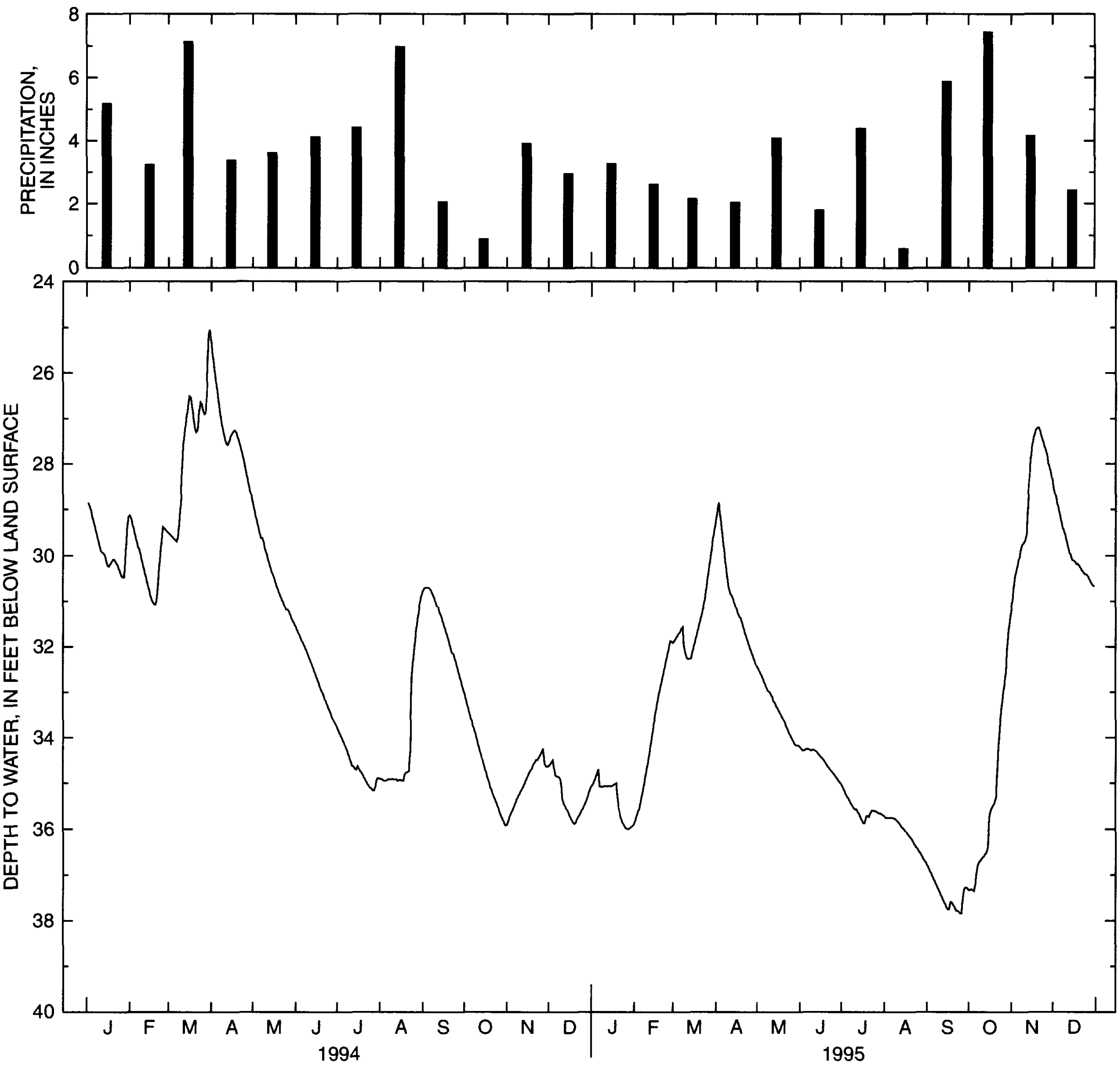


Figure 13. Monthly precipitation at Neshaminy Falls, Bensalem Township, and depth to water in well BK-1020, Warminster Township, Pennsylvania, 1994-95.

Table 5. *Measured or reported depth to water in feet below land surface in Warwick Township, Bucks County, Pennsylvania*

Hydrogeologic unit	Nondomestic wells				Domestic wells			
	Number of wells	Minimum	Median	Maximum	Number of wells	Minimum	Median	Maximum
Stockton Formation	21	2.5	36.9	317	36	Flowing	70.2	199
Lockatong Formation	10	11.5	29.4	85.7	31	3.07	33.6	117

Table 6. *Annual water budget for unnamed tributary to Little Neshaminy Creek, Warwick Township, Bucks County, Pennsylvania*

Year	Precipitation (inches)	Ground-water pumpage (inches)	Streamflow (inches)	Percentage of precipitation as streamflow	Change in ground-water storage (inches)	Percentage of precipitation as change in ground-water storage	Evapotrans-piration and other losses (inches)	Percentage of precipitation as evapotrans-piration
1994	52	0.7	19.9	38	+1.4	2.7	30	58
1995	44	.7	10.4	24	−1.3	3.0	34.2	78
Average	48	.7	15.2	32	+.1	.2	32.1	67

Table 7. *Estimated recharge for unnamed tributary to Little Neshaminy Creek, 1994-95, Warwick Township, Bucks County, Pennsylvania*

Year	Precipitation (inches)	Recharge (inches)	Percentage of precipitation as recharge	Base flow (inches)	Change in ground-water storage (inches)	Estimated ground-water evapotranspiration (inches)
1994	52	10.8	21	7.4	+1.4	2
1995	44	3.8	9	3.1	−1.3	2
Average	48	7.4	15	5.3	+.1	2

Recharge was estimated for the basin of the unnamed tributary to Little Neshaminy Creek for the 1994-95 calendar years (table 7) from the following equation:

$$R = BF + \Delta GWS + GWET, \qquad (2)$$

where R is estimated recharge,
BF is base flow of the stream,
ΔGWS is change in ground-water storage, and
GWET is estimated ground-water evapotranspiration.

Base flow is the minimum sustained flow of a stream and was estimated by use of the HYSEP hydrograph separation and analysis program (Sloto and Crouse, 1996). Change in ground-water storage is from the water budget for the basin shown in table 6. Ground-water evapotranspiration is estimated at 2 in. per year on the basis of ground-water-flow model hydrologic budget simulations (Sloto, 1991).

Precipitation was less in 1995 (44 in.) than in 1994 (52 in.). Estimated recharge in 1995 (3.8 in.) was less than in 1994 (10.8 in.). The average recharge for the basin was 7.4 in. for the 2-year period. This is equal to a recharge of 555 gal/d per acre.

WATER USE

Water for domestic and nondomestic uses in Warwick Township is supplied from both private and public supply wells. Warwick Township Water and Sewer Authority wells currently supply an estimated 5,000 people with an average demand of 0.347 Mgal/d and a maximum demand of 0.641 Mgal/d. By the year 2006, these figures are expected to rise to 8,777 people with an average demand of 0.55 Mgal/d and a maximum demand of 0.73 Mgal/d (Delaware River Basin Commission, 1996).

GROUND-WATER QUALITY

Chemical and mineral substances accumulate in ground water from contact with air, soil, and rock. These substances, and the quantity of each present, determine the quality of ground water. Substances that may affect ground-water quality also may be added through human activity.

PHYSICAL PROPERTIES

The physical properties of ground water include temperature, specific conductance, pH, alkalinity, and dissolved oxygen. These properties may change with storage and are measured when the sample is collected. Data for physical properties are presented in table 8.

Specific conductance is a measure of water's ability to conduct an electrical current and is measured in microsiemens per centimeter at 25°C. Specific conductance is directly related to the total dissolved solids (TDS) in dilute solutions. TDS can be estimated from specific-conductance measurements. The median specific conductance of eight ground-water samples from the Lockatong Formation is 414 µS/cm, and the median specific conductance of eight ground-water samples from the Stockton Formation is 398 µS/cm.

The pH is a measure of hydrogen ions in water. A pH of 7 is considered neutral, lower pH is acidic, and higher pH is basic. The median pH of eight ground-water samples from the Lockatong Formation is 7.0, and the median pH of eight ground-water samples from the Stockton Formation is 6.7.

Alkalinity is the capacity of water to neutralize acid. Alkalinity is produced by dissolved carbonate, bicarbonate, and carbon dioxide and is measured as an equivalent amount of calcium carbonate, in milligrams per liter as $CaCO_3$. The median alkalinity of eight ground-water samples from the Lockatong Formation is 157 mg/L as $CaCO_3$. The median alkalinity of eight ground-water samples from the Stockton Formation is 133 mg/L as $CaCO_3$.

Dissolved oxygen concentrations in water are expressed in milligrams per liter. The concentration of dissolved oxygen in ground water is related to the amount of oxidizable minerals in the surrounding rock; as these minerals, such as pyrite, oxidize, dissolved oxygen in the ground water is depleted. The median dissolved oxygen concentration of eight ground-water samples from the Lockatong Formation is 5.2 mg/L, and the median dissolved oxygen concentration of six ground-water samples from the Stockton Formation is 2.2 mg/L. This trend is opposite that found by Sloto and Schreffler (1994), where the median dissolved oxygen concentration in ground-water samples from the Stockton Forma-

Table 8. *Results of chemical analyses for physical properties in selected wells in Warwick Township, Bucks County, Pennsylvania*

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

U.S. Geological Survey identification number	Date	Hydrogeologic unit	Specific conductance (µS/cm)	pH (standard units)	Temperature (°C)	Oxygen, dissolved (mg/L)	Alkalinity, field (mg/L as $CaCO_3$)
BK-958	07-25-79	Stockton	560	7.1	14.0	--	100
1128	10-23-79	Stockton	280	6.4	14.0	--	58
2732	07-26-95	Stockton	435	6.6	16.5	8.2	142
2742	07-26-95	Lockatong	407	6.7	13.5	5.3	161
2746	07-26-95	Stockton	331	6.1	14.5	.5	160
2751	07-31-95	Lockatong	429	6.8	14.5	5.3	196
2758	09-01-95	Lockatong	570	7.0	15.0	3.8	186
2771	07-31-95	Lockatong	418	6.5	16.5	3.4	145
2778	07-31-95	Stockton	770	6.7	21.5	.5	108
2812	07-19-95	Stockton	354	6.8	13.5	6.2	90
2816	07-19-95	Stockton	381	7.0	15.5	1.1	147
2822	07-27-95	Lockatong	409	7.0	16.5	.3	154
2823	08-01-95	Lockatong	311	7.8	14.0	7.1	113
2824	08-08-95	Lockatong	390	7.2	14.5	5.9	140
2825	08-15-95	Stockton	415	6.6	14.0	3.2	123
2826	09-01-95	Lockatong	436	7.1	13.5	5.1	160

tion was higher than for ground-water samples from the Lockatong Formation. The higher dissolved oxygen concentration in the Lockatong Formation in Warwick Township is possibly caused by a localized lack of oxidizable minerals.

INORGANIC CONSTITUENTS

Common ions analyzed were calcium, potassium, magnesium, sodium, chloride, fluoride, sulfate, and silica. Nutrients analyzed were ammonia, nitrite, nitrate, phosphorus, and orthophosphate. Metals and trace constituents analyzed were iron, manganese, arsenic, and lead.

COMMON IONS

Common ions dissolved from rock and soil comprise most of the dissolved solutes in ground water, although some solutes were originally dissolved in precipitation. Common ions in the ground water in Warwick Township, in order of decreasing concentration, are calcium, sulfate, silica, magnesium, chloride, sodium, nitrate, potassium, and fluoride. Concentrations of each ion are given in table 9. Nitrate is discussed in the Nutrients section.

Maximum contaminant levels (MCL's) and secondary maximum contaminant levels (SMCL's) have been set by the U.S. Environmental Protection Agency (USEPA) for some constituents in drinking water (table 10). MCL's represent concentrations that may cause adverse health effects. SMCL's represent concentrations that may impart objectionable characteristics to water, such as bad taste or odor.

Solutes in ground water are dissolved primarily from rocks and soil, although some originate in precipitation. TDS is a measurement of the total solutes in ground water. The median concentration of TDS in eight ground-water samples from the Stockton Formation was 233.5 mg/L. The median concentration of TDS in eight ground-water samples from the Lockatong Formation was 240 mg/L. One sample exceeded the USEPA SMCL of 500 mg/L for TDS; the sample was from well BK-2778 in the Stockton Formation.

Chloride in ground water may be derived from natural sources or it may come from anthropogenic sources, such as fertilizers, road salt, or septic systems. Of 16 water samples, none exceeded the USEPA SMCL of 250 mg/L for chloride.

Sulfate in ground water comes from minerals such as gypsum, anhydrite, and pyrite. These minerals are common in sedimentary rock. The median sulfate concentration of eight ground-water samples from the Stockton Formation was 30 mg/L. The median sulfate concentration of eight ground-water samples from the Lockatong Formation was 33.5 mg/L. One of 16 samples exceeded the USEPA SMCL of 250 mg/L for sulfate; the sample was from well BK-2778 in the Stockton Formation. Water from this well also had the highest calcium concentration (130 mg/L) and lowest iron concentration (less than 3.0 µg/L); this suggests that gypsum ($CaSO_4 \cdot 2H_2O$) or anhydrite ($CaSO_4$), rather than pyrite (FeS_2), is the source of sulfate. Gypsum is sometimes found interbedded with Triassic-age sedimentary rocks. Water from well BK-2778 also had the highest concentration of TDS (562 mg/L) because of the high concentrations of calcium and sulfate.

NUTRIENTS

Nitrogen and phosphorus are essential nutrients for plant growth. Nitrogen in water is found as nitrate (NO_3), nitrite (NO_2), and ammonia (NH_4); phosphorus is usually found as a form of the orthophosphate ion (P^{5+}). Excessive amounts of nutrients usually indicate ground-water contamination. Sources of contamination include sewer and septic systems, animal waste, and fertilizers. Concentrations of nutrients in water samples collected in Warwick Township are given in table 11.

The prevalent nitrogen species in ground water is nitrate. The median concentration of nitrate in eight ground-water samples from the Stockton Formation is 2.8 mg/L. The median concentration of nitrate in eight water samples from the Lockatong Formation is 2.0 mg/L. Of 16 samples, none exceeded the USEPA MCL of 10 mg/L for nitrate concentration. The median concentrations of nitrite, ammonia, and phosphorus species in water samples from both formations were less than or equal to 0.02 mg/L.

METALS AND OTHER TRACE CONSTITUENTS

Metals, such as iron, manganese, and lead, and other trace constituents, such as arsenic, are normally present in low concentrations in ground water and are usually dissolved from the soil or bedrock, although some may come from human sources or precipitation. Lead in tap water may leach from pipes, joints, or fixtures in

Table 9. *Results of chemical analyses for major ions, trace constituents, and radon in ground water, Warwick Township, Bucks County, Pennsylvania*

[°C, degree Celsius; mg/L, milligram per liter; µg/L, microgram per liter; <, less than; pCi/L, picoCuries per liter; --, no data]

U.S. Geological Survey identification number	Hydrogeologic unit	Date	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)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Solids, residue at 180 °C, dissolved (mg/L)	Arsenic, dissolved (µg/L as As)	Iron, dissolved (µg/L as Fe)	Lead, dissolved (µg/L as Pb)	Manganese, dissolved (µg/L as Mn)	Radon 222, total (pCi/L)
BK-958	Stockton	07-25-79	56	15	24	1.0	44	69	<0.1	23	245	2	<10	38	<10	--
1128	Stockton	10-23-79	27	8.0	11	.8	27	11	.1	25	169	1	10	11	3	--
2732	Stockton	07-26-95	42	19	17	.9	32	21	<.1	16	252	10	<3	<1	<1	2,000
2742	Lockatong	07-26-95	49	17	9.8	1.0	34	5.7	<.1	22	246	<1	4	<1	<1	1,300
2746	Stockton	07-26-95	29	11	26	.4	9.5	9.7	.1	16	190	13	<3	1	5	2,400
2751	Lockatong	07-31-95	40	21	22	1.7	33	8.6	.2	18	254	<1	<3	<1	3	290
2758	Lockatong	09-01-95	59	29	16	1.3	49	23	<.1	16	338	<1	<3	1	<1	2,300
2771	Lockatong	07-31-95	40	22	10	1.0	33	16	<.1	18	234	2	<3	<1	<1	1,600
2778	Stockton	07-31-95	130	15	19	.8	270	11	.1	16	562	9	<3	<1	12	1,200
2812	Stockton	07-19-95	41	10	10	.9	28	15	<.1	21	206	<1	<3	<1	4	2,500
2816	Stockton	07-19-95	46	14	13	1.0	7.5	22	<.1	15	222	<1	<3	<1	2	2,400
2822	Lockatong	07-27-95	37	19	16	1.0	38	9.5	.2	18	228	2	11	<1	14	340
2823	Lockatong	08-01-95	21	20	9.1	1.7	23	13	<.1	17	176	6	<3	<1	<1	1,600
2824	Lockatong	08-08-95	43	18	9.8	1.3	40	8.8	<.1	14	230	<1	<3	<1	<1	2,100
2825	Stockton	08-15-95	51	13	11	1.1	49	15	<.1	21	256	2	4	<1	6	2,200
2826	Lockatong	09-01-95	43	21	13	1.1	32	14	<.1	18	258	6	<3	1	<1	1,300

Table 10. *U.S. Environmental Protection Agency maximum contaminant levels and secondary maximum contaminant levels for selected constituents in drinking water*

[From U.S. Environmental Protection Agency (1996); concentrations in micrograms per liter except as indicated; mg/L, milligrams per liter; --, indicates no set limit]

Constituent	Maximum contaminant level	Secondary maximum contaminant level
Inorganic		
Arsenic	50	--
Chloride (mg/L)	--	250
Fluoride (mg/L)	4	2
Iron	--	300
Lead	[1]15	--
Manganese	--	50
Nitrate as nitrogen (mg/L)	10	--
Nitrite as nitrogen (mg/L)	1	--
Sulfate (mg/L)	--	250
Total dissolved solids (mg/L)	--	500
Organic		
Chloroform	100	--
1,2-Dichloroethane	5	--
1,1-Dichloroethylene	7	--
Trans-1,2-dichloroethylene	100	--
Methylene chloride	5	--
Tetrachloroethylene	5	--
1,1,1-Trichloroethane	200	--
1,1,2-Trichloroethane	5	--
Trichloroethylene	5	--

[1] Action level.

Table 11. *Results of chemical analyses for nutrients, Warwick Township, Bucks County, Pennsylvania*

[mg/L, milligram per liter; <, less than]

U.S. Geological Survey identification number	Hydrogeologic unit	Date	Nitrogen, ammonia, dissolved (mg/L as N)	Nitrogen, nitrite, dissolved (mg/L as N)	Nitrogen, $NO_2 + NO_3$ dissolved (mg/L as N)	Phosphorus, dissolved (mg/L as P)	Phosphorus, ortho, dissolved (mg/L as P)
BK-958	Stockton	07-25-79	0.02	0.01	3.2	0.07	0.02
1128	Stockton	10-23-79	.01	.00	6.6	.09	.09
2732	Stockton	07-26-95	.03	<.01	2.70	<.01	.02
2742	Lockatong	07-26-95	.02	<.01	2.70	<.01	.02
2746	Stockton	07-26-95	.03	<.01	<.05	<.01	<.01
2751	Lockatong	07-31-95	.02	<.01	1.60	<.01	<.01
2758	Lockatong	09-01-95	<.015	<.01	1.80	<.01	<.01
2771	Lockatong	07-31-95	<.015	<.01	2.80	.04	.03
2778	Stockton	07-31-95	<.015	<.01	1.80	<.01	<.01
2812	Stockton	07-19-95	.02	<.01	7.00	.08	.08
2816	Stockton	07-19-95	<.015	<.01	1.70	.01	.02
2822	Lockatong	07-27-95	.04	<.01	.36	<.01	<.01
2823	Lockatong	08-01-95	<.015	<.01	1.70	<.01	.02
2824	Lockatong	08-08-95	<.015	<.01	2.10	<.01	<.01
2825	Stockton	08-15-95	.05	<.01	2.90	.06	.07
2826	Lockatong	09-01-95	<.015	<.01	2.70	.03	.04

plumbing systems. Concentrations of iron, manganese, lead, and arsenic in water samples from 16 wells in Warwick Township are given in table 12.

The USEPA has established MCL's and SMCL's for iron, manganese, and arsenic (table 10). For lead, the USEPA has established an action level of 15 µg/L; this means that corrective action must be taken if the concentration exceeds this level in 10 percent of water samples collected during any monitoring period. The USEPA action level for lead was exceeded in water from 1 well of 16 sampled; the sample was from well BK-958 in the Stockton Formation.

Iron and manganese in ground water may affect taste and cause staining if concentrations are elevated. Of the 16 wells sampled in both formations, none exceeded the USEPA SMCL's of 300 and 50 µg/L set for concentrations of iron and manganese, respectively. None of the 16 water samples exceeded the USEPA MCL of 50 µg/L for arsenic.

VOLATILE ORGANIC COMPOUNDS

Volatile organic compounds (VOC's) originate from human sources. They are used in domestic, commercial, and industrial applications. Many VOC's are suspected or proven carcinogens and pose serious problems for water producers and consumers. VOC's originate from spills, storage tank leakage, lagoons, and disposal sites and are difficult and expensive to treat or remove.

Water samples from five wells (BK-2758, BK-2771, BK-2778, BK-2816, BK-2825) in areas of suspected contamination were analyzed for VOC's. The USEPA has set MCL's for only a few VOC's (table 10). Samples were analyzed for 61 compounds, and 8 compounds were detected (table 12). The most commonly detected compound was methyl tert butyl ether (MTBE) (four of five wells). The USEPA has set MCL's for four of the eight compounds detected. One of five samples exceeded the USEPA MCL of 5 µg/L for trichloroethylene (TCE). The highest concentration of total VOC's for a single well was 47.2 µg/L; the highest concentration for a single compound was 41 µg/L for TCE. The concentrations of most compounds detected, however, was less than 2.0 µg/L.

MTBE is a low-cost oxygenate that is added to gasoline to increase its octane level and reduce carbon monoxide and ozone in exhaust emissions. MTBE is released to the air from industrial sources, fueling operations, and vehicles; it is released to the ground from fueling operations and spills. MTBE is soluble in water; it is picked up in the air and soil by precipitation and carried to ground water. In 1993, MTBE ranked second among organic chemicals produced in the United States; it was the second most frequently detected VOC in water from urban wells (Squillace and others, 1995). MTBE is not yet regulated, but the USEPA draft drinking water lifetime health advisory should fall within the range of 20-200 µg/L; this is the maximum concentration of MTBE in drinking water that is not expected to cause adverse effects over a lifetime of exposure. Detectable levels of MTBE were found in four of the five wells sampled in Warwick Township; the highest concentration detected was 8.1 µg/L in well BK-2758.

RADON

Radon is a naturally occurring, chemically inert gas found in the atmosphere or dissolved in ground water. It is a product of the radioactive decay of radium-226 in rocks. Radium-226 (half-life 1,620 years) is a daughter product of the radioactive decay of uranium-238, which has a half-life of 4.5×10^9 years. The uranium-238 decay series products account for most of the radioactivity in ground water. Radon-222 (half-life 3.8 days) is the most common radon isotope. It is a colorless, odorless, water-soluble gas that decays by alpha-particle emission. Radon-222 activity is measured in picoCuries per liter.

Although radon-222 is a daughter product in the uranium-238 decay series, its activity in water is determined by geochemical processes rather than abundance of the parent isotopes. Senior and Vogel (1995) found that elevated radium activity in ground water is associated with low pH. This may account for the median activity of radon-222 in ground water from the Stockton Formation exceeding the median activity of radon-222 in ground water from the Lockatong Formation, even though some black siltstone beds in the Lockatong may contain relatively high concentrations of uranium (Sloto and Schreffler, 1994). The median radon-222 ground-water activity in the Stockton Formation for six wells was 2,300 pCi/L, and the median radon-222 ground-water activity in the Lockatong Formation for eight wells was 1,450 pCi/L.

Table 12. *Results of chemical analyses for volatile organic compounds, Warwick Township, Bucks County, Pennsylvania*

[All values are in micrograms per liter; USGS, U.S. Geological Survey; <, less than]

USGS identification number	Date	Benzene	Bromo-benzene	Bromo-chloro-methane	Bromo-form	n-Butyl-benzene	Carbon tetra-chloride	Chloro-benzene	Chloro-ethane	2-Chloro-ethyl-vinyl-ether	Chloro-form
BK-2758	09-01-95	<0.2	<.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<1.0	<0.2
2771	07-31-95	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<1.0	<.2
2778	07-31-95	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<1.0	<.2
2816	07-19-95	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<1.0	<.2
2825	08-15-95	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<1.0	<.2

USGS identification number	Date	o-Chloro toluene	o-Di-chloro-benzene	1,2-Di-chloro-propane	1,2,3-Tri-chloro-propane	Dichloro-bromo-methane	Dibromo-chloro-propane	Dibromo-chloro-methane	1,2-Di-bromo-ethane	Dibromo-methane	1,3-Di-chloro-benzene
BK-2758	09-01-95	<0.2	<0.2	<0.2	<0.2	<0.2	<1.0	<0.2	<0.2	<0.2	<0.2
2771	07-31-95	<.2	<.2	<.2	<.2	<.2	<1.0	<.2	<.2	<.2	<.2
2778	07-31-95	<.2	<.2	<.2	<.2	<.2	<1.0	<.2	<.2	<.2	<.2
2816	07-19-95	<.2	<.2	<.2	<.2	<.2	<1.0	<.2	<.2	<.2	<.2
2825	08-15-95	<.2	<.2	<.2	<.2	<.2	<1.0	<.2	<.2	<.2	<.2

USGS identification number	Date	1,4-Di-chloro-benzene	1,1-Di-chloro-ethane	1,2-Di-chloro-ethane	1,1-Di-chloro-ethylene	cis-1,2-Dichloro-ethene	1,2-trans-Dichloro-ethylene	1,3-Di-chloro-propane	2,2-Di-chloro-propane	1,1-Di-chloro-propene	cis-1,3-Dichloro-propene
BK-2758	09-01-95	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
2771	07-31-95	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
2778	07-31-95	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
2816	07-19-95	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
2825	08-15-95	<.2	.8	<.2	.8	1.2	<.2	<.2	<.2	<.2	<.2

USGS identification number	Date	trans-1,3-Dichloro-propene	Dichloro-difluoro-methane	1,2,4-Tri-methyl-benzene	1,3,5-Tri-methyl-benzene	Ethyl-benzene	Freon-113	Methyl-bromide	Hexa chloro-butadiene	Iso-propyl-benzene	p-Chloro-toluene
BK-2758	09-01-95	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
2771	07-31-95	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
2778	07-31-95	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
2816	07-19-95	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
2825	08-15-95	<.2	<.2	<.2	<.2	<.2	.300	<.2	<.2	<.2	<.2

USGS identification number	Date	p-Iso-propyl-toluene	Methyl-ene chloride	Methyl-chloride	Methyl tert butyl ether	Naphtha-lene	n-Propyl-benzene	Sec-butyl-benzene	Styrene	Tert-butyl-benzene	Toluene	1,1,1,2-Tetra-chloro-ethane
BK-2758	09-01-95	<0.2	<0.2	<0.2	8.1	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
2771	07-31-95	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
2778	07-31-95	<.2	.2	<.2	.3	<.2	<.2	<.2	<.2	<.2	<.2	<.2
2816	07-19-95	<.2	<.2	<.2	.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
2825	08-15-95	<.2	<.2	<.2	1.9	<.2	<.2	<.2	<.2	<.2	<.2	<.2

USGS identification number	Date	1,1,2,2-Tetra-chloro-ethane	Tetra-chloro-ethylene	1,2,3-Trichloro-benzene	1,2,4-Trichloro benzene	1,1,1-Tricloro-ethane	1,1,2-Trichloro-ethane	Trichloro-ethylene	Trichloro-fluoro-methane	Vinyl chloride	Xylene
BK-2758	09-01-95	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
2771	07-31-95	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
2778	07-31-95	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
2816	07-19-95	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
2825	08-15-95	<.2	<.2	<.2	<.2	1.2	<.2	41.0	<.2	<.2	<.2

SUMMARY

Warwick Township encompasses 11.14 mi^2 in south-central Bucks County. Virtually all of the township is underlain by the Triassic-age sedimentary rocks of the Stockton and Lockatong Formations, which consist primarily of shale and sandstone. These rocks have little primary porosity, and ground water moves through an interconnected network of secondary openings—joints, fractures, and bedding-plane separations. The ground-water system consists of a series of permeable, high-transmissivity beds that form aquifers separated by less permeable, low-transmissivity beds that form confining or semiconfining units. This leaky, multiaquifer system may have a different hydraulic head in each water-bearing zone. Most wells penetrate multiple water-bearing zones, and hydraulic heads in these wells are a composite; this may cause water levels to be different in nearby wells with different depths. Ground water in the weathered zone is unconfined; ground water below the weathered zone is confined or semiconfined.

On the basis of the median specific capacity of domestic and nondomestic wells, the Stockton Formation is the more productive of the two hydrogeologic units. The Stockton Formation also has higher median domestic and nondomestic well yields (19 gal/min and 125 gal/min, respectively) than the Lockatong Formation (15 gal/min and 32.5 gal/min, respectively).

Water levels fluctuate in response to recharge-to and to discharge-from the ground-water system. Recharge is from precipitation and discharge is to pumped wells, streams, and evapotranspiration. Water levels usually rise in late fall, winter, and early spring when recharge is highest and evapotranspiration is lowest; water levels generally decline in late spring, summer, and early fall when evapotranspiration is highest and recharge is lowest. The median depth to water for domestic and nondomestic wells in the Stockton Formation (70.2 ft and 36.9 ft, respectively) was greater than for the Lockatong Formation (33.6 ft and 29.4 ft, respectively).

A water budget was calculated for the unnamed tributary to Little Neshaminy Creek at Traymore for 1994-95. The average annual precipitation for the period was 48 in. Average annual evapotranspiration and other losses were 33.5 in., average annual streamflow was 15.2 in., and the average annual change in ground-water storage was an increase of 0.1 in. The estimated recharge for the basin was 10.8 in. in 1994 and 3.8 in. in 1995. The average recharge for the basin was 7.4 in. (555 gal/d per acre) for the 2-year period.

The specific conductance of water from wells in the Stockton Formation (398 µS/cm) and Lockatong Formation (414 µS/cm) was similar. The median pH of water from wells in the Stockton Formation (6.7) is slightly acidic; the median pH of water from wells in the Lockatong Formation (7.0) is neutral. Median alkalinity of water in the Stockton Formation (133 mg/L as $CaCO_3$) was similar to that in the Lockatong Formation (157 mg/L as $CaCO_3$). The median concentration of dissolved oxygen in water from wells in the Stockton Formation (2.2 mg/L) was lower than in water from wells in the Lockatong Formation (5.2 mg/L).

Common ions found in the ground water of Warwick Township, in order of decreasing abundance, include calcium, sulfate, chloride, magnesium, silica, sodium, nitrate, potassium, and fluoride. One of 16 samples exceeded the USEPA SMCL for sulfate, and 1 of 16 samples exceeded the USEPA action level for lead. These two wells were in the Stockton Formation. The median concentrations of TDS in the Stockton and Lockatong Formations were similar (233.5 mg/L and 240 mg/L, respectively). The USEPA SMCL for TDS was exceeded in 1 of 16 samples; the well was in the Stockton Formation.

The prevalent nitrogen species in ground water is the nitrate ion. The median concentration of nitrate in ground water in the Stockton Formation was 2.8 mg/L; the median concentration of nitrate in ground water in the Lockatong Formation was 2.0 mg/L. Concentrations of nitrite were 0.01 mg/L as N or less for all samples. No samples exceeded the USEPA MCL for nitrate or nitrite. The median concentrations of ammonia and phosphorus species for both formations were less than or equal to 0.02 mg/L.

Water samples from five wells were analyzed for VOC's. VOC's were detected in four of the five wells. One sample exceeded the USEPA MCL for TCE. The most commonly detected compound was MTBE (four of five wells). The highest concentration for a single compound was 41 µg/L (TCE).

Water samples from 14 wells were analyzed for dissolved radon-222 activity. The median radon-222 activity was higher in water from wells in the Stockton Formation (2,300 pCi/L) than in water from wells in the Lockatong Formation (1,450 pCi/L).

REFERENCES CITED

Bascom, Florence, Wherry, E.T., Stose, G.W., and Jonas, A.I., 1931, Geology and mineral resources of the Quakertown-Doylestown district, Pennsylvania and New Jersey: U.S. Geological Survey Bulletin 828, 62 p.

Bucks County Planning Commission, 1984, 1980-2000 Population Projections, 11 p.

Delaware River Basin Commission, 1996, Docket no. D-94-72 CP, Ground Water Protected Area, Warwick Township Water & Sewer Authority, Ground Water Withdrawal, Warwick Township, Bucks County, Pennsylvania, p. 5.

Keys, W.S., 1990, Borehole geophysics applied to ground-water investigation: U.S. Geological Survey Techniques of Water-Resources Investigations, book 2, chap. E2, 150 p.

Lyttle, P.T., and Epstein, J.B., 1987, Geologic map of the Newark 1° × 2° quadrangle, New Jersey, Pennsylvania, and New York: U.S. Geological Survey Miscellaneous Investigations Series I-1715, 2 pls., scale 1:250,000.

Olsen, P.E., 1980, Triassic and Jurassic formations of the Newark basin *in* Manspeizer, Warren, ed., Field studies of New Jersey geology and guide to field trips: New York State Geological Association, 52nd Annual Meeting, 1980, Rutgers University, Newark, N.J., p. 8.

Owenby, J.R., and Ezell, D.S., 1992, Monthly station normals of temperature, precipitation, and heating and cooling degree days, 1961-1990, Pennsylvania: National Oceanographic and Atmospheric Administration Climatography of the United States No. 81, 25 p.

Paulachok, G.N., and Wood, C.R., 1988, Water resources of Oley Township, Berks County, Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 87-4065, 59 p.

Rima, D.R., Meisler, Harold, and Longwill, Stanley, 1962, Geology and hydrology of the Stockton Formation in southeastern Pennsylvania: Pennsylvania Geologic Survey, 4th ser., Water Resources Report 114, 111 p.

Rowland, C.J., 1997, Altitude and configuration of the potentiometric surface in Warwick Township, Bucks County, Pennsylvania, September 1994 through May 1995: U.S. Geological Survey Open-File Report 97-554, scale 1:24,000.

Senior, L.A., and Vogel, K.L., 1995, Radium and radon in ground water in the Chickies Quartzite, southeastern Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 92-4088, 145 p.

Schreffler, C.L., McManus, B.C., Rowland, C.J., and Sloto, R.A., 1994, Hydrologic data for northern Bucks County, Pennsylvania: U.S. Geological Survey Open-File Report 94-381, 89 p.

Sloto, R.A., 1991, Geohydrology and simulation of ground-water flow in the carbonate rocks of the Valley Creek Basin, eastern Chester County, Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 89-4169, 60 p.

Sloto, R.A., and Crouse, M.Y., 1996, HYSEP—A computer program for streamflow hydrograph separation and analysis: U.S. Geological Survey Water-Resources Investigations Report 96-4040, 46 p.

Sloto, R.A., and Davis, D.K., 1983, Effects of urbanization on the water resources of Warminster Township, Bucks County, Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 82-4020, 72 p.

Sloto, R.A., Macchiaroli, Paola, and Conger, R.W., 1995, Geohydrology and vertical distribution of volatile organic compounds in ground water, Fischer and Porter Superfund site, Warminster, Bucks County, Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 95-4220, 137 p.

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

Sloto, R.A., and Schreffler, C.L., 1994, Hydrogeology and ground-water quality of northern Bucks County, Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 94-4109, 85 p.

Squillace, P.J., Pope, D.A., and Price, C.V., 1995, Occurrence of the gasoline additive MTBE in shallow ground water in urban and agricultural areas: U.S. Geological Survey Fact Sheet FS-114-95, 4 p.

Turner-Peterson, C.E., and Smoot, J.P., 1985, New thoughts on facies relationships in the Triassic Stockton and Lockatong Formations, Pennsylvania and New Jersey: U.S. Geological Survey Circular 946, p. 10-17.

U.S. Environmental Protection Agency, 1996, Drinking water regulations, U.S. Code of Federal Regulations, Title 40, Part 141.62, and Part 143.30; revised February, 1996: Washington, U.S. Environmental Protection Agency Office of Water, 15 p.

Van Houten, F.B., 1962, Cyclic sedimentation, Upper Triassic Lockatong Formation, central New Jersey and adjacent Pennsylvania: Kansas Geological Survey Bulletin 169, p. 497-531.

Willard, D.B., Freedman, Jacob, McLaughlin, D.B., Peltier, L.C., and Gault H.R., 1959, Geology and mineral resources of Bucks County, Pennsylvania: Pennsylvania Geological Survey, 4th ser., Bulletin C9, 243 p.

Table 13. *Records of wells in Warwick Township, Bucks County, Pennsylvania*

USGS: U.S. Geological Survey.

Latitude: Latitude in degrees, minutes, and seconds (DDMMSS).

Longitude: Longitude in degrees, minutes, and seconds (DDMMSS).

Driller license number: -241, John Wiley; -408, Wiley and Buhler; 0111, Bucks County Artesian Well Drilling; 0121, Allen H. Dorn; 0130, F.E. Buehler and Son; 0188, C.S. Garber and Sons, Inc.; 0228, Samuel Y. Moyer; 0260, Carson Brothers; 0330, W. Rollin Raab and son; 0331, Joseph J. Guenthuer; 0399, John O'Donnell and son; 0512, Miller Pump Service, Inc.; 0514, F.L. Bollinger and Sons; 0560, Johnson and Gross; 0982, Mayers Well Drilling.

Primary use of site: C, standby emergency supply; O, observation well; U, unused; W, withdrawal; Z, destroyed.

Primary use of water: C, commercial; H, domestic; I, irrigation; N, industrial; P, public supply; U, unused.

Elevation of land surface is estimated from topographic maps. Datum is sea level.

Topographic setting: F, flat; H, hilltop; S, hillside; V, valley; W, upland draw.

Hydrogeologic-unit codes: 231SCKN, Stockton Formation; 231LCKG, Lockatong Formation.

Water level is in feet below land surface. F, flowing.

Other abbreviations: --, no data.

Table 13. *Record of wells in Warwick Township, Bucks County, Pennsylvania—Continued*

USGS well number	Location		Owner	Driller license number	Date drilled	Primary		Elevation of land surface (feet)	Topo-graphic setting
	Latitude (DDMMSS)	Longitude (DDDMMSS)				Use of site	Use of water		
BK-345	401433	0750412	Maple Farm Pork Products	--	01-01-20	U	U	320	S
346	401500	0750501	Warwick School	--	01-01-19	W	P	350	S
347	401500	0750459	Warwick School	-241	01-01-27	U	U	350	V
348	401459	0750520	Ludwig Fetzer Green	0399	--	W	N	350	V
349	401343	0750541	Hartsville Hotel	--	--	W	H	260	S
714	401512	0750511	--	0130	11-00-56	W	H	320	V
715	401513	0750513	Bradley, Charles	0130	11-00-56	W	H	318	V
828	401508	0750504	Luddy, Edmund	0330	00-00-48	W	H	325	S
958	401340	0750517	Warminster Twp Mun Auth	0188	01-01-55	W	P	200	V
961	401542	0750647	Warwick Twp Wat & Sewer	--	01-01-79	O	U	380	S
967	401540	0750653	Warwick Twp Wat & Sewer	--	01-01-79	W	P	390	S
999	401351	0750558	Walther, S.	--	--	W	H	200	S
1026	401454	0750628	Warwick Twp Wat & Sewer	--	01-01-79	O	U	355	S
1029	401450	0750633	Warwick Twp Wat & Sewer	--	01-01-79	W	P	350	S
1040	401336	0750522	Warminster Twp Mun Auth	0330	06-19-78	W	P	210	V
1042	401326	0750515	Zimmerman, Harry	--	--	W	H	245	S
1127	401408	0750428	Alderfer	--	--	W	H	195	V
1128	401356	0750407	Cornell, Alvin	--	--	W	H	205	S
1133	401405	0750600	Neshaminy-Warwick Pres	0330	01-01-74	W	H	205	S
1196	401600	0750700	Doylestown Twp Mun Auth	--	--	W	P	260	W
1241	401456	0750436	Warwick Twp Wat & Sewer	--	07-01-81	W	P	340	S
1242	401500	0750443	Warwick Twp Wat & Sewer	--	--	W	P	345	S
1243	401503	0750426	Warwick Twp Wat & Sewer	--	--	W	P	310	W
1296	401454	0750607	Warwick Twp Wat & Sewer	0330	11-04-87	W	P	332	V
1310	401600	0750513	Bucks Co Country Club	0330	06-18-67	W	I	255	W
1316	401556	0750640	Warwick Twp Wat & Sewer	0330	02-27-86	W	P	340	S
1845	401403	0750505	Warminster Twp Mun Auth	0330	00-00-91	U	P	185	V
2473	401636	0750449	Gephardt, Melvin	0130	06-11-92	W	H	235	S
2478	401648	0750514	Gerth, Charles	--	--	W	H	290	S
2697	401430	0750424	Young, Mike	0330	08-12-96	W	H	280	S
2698	401317	0750431	Warwick Twp Wat & Sewer	0330	--	O	U	210	F
2699	401501	0750426	Warwick Twp Wat & Sewer	0330	07-00-81	O	U	315	W
2711	401519	0750642	Rushton, Steve	0130	08-10-90	W	H	352	S
2713	401410	0750555	Edgar, Frank	0330	05-27-83	W	H	222	S
2714	401338	0750412	Havis Shields Equipment	0330	10-00-88	W	N	195	V
2715	401441	0750558	Ponente, Mike	0330	10-29-92	W	H	363	S
2716	401352	0750359	Russell, Ed	0512	00-00-73	W	H	212	S
2717	401510	0750341	K & D Growers	0188	05-00-93	W	1	281	S
2718	401439	0750423	Gotshall, Bruce	0330	11-00-92	W	H	360	H

Table 13. *Record of wells in Warwick Township, Bucks County, Pennsylvania—Continued*

Hydro-geologic unit	Depth of well (feet)	Casing		Depth to water bearing zone(s) (feet)	Water level (feet)	Date water level measured	Measured yield			USGS well number
		Depth (feet)	Diameter (inches)				Discharge (gal/min)	Specific capacity [(gal/min)/ft]	Pumping period (hours)	
231SCKN	185	--	6	--	--	--	--	--	--	BK-345
231LCKG	165	--	6	--	--	--	2.00	--	--	346
231LCKG	400	--	8	--	12.7	12-01-52	--	--	--	347
231LCKG	150	10	6	--	--	--	60.0	--	--	348
231SCKN	30.0	--	36	--	--	--	--	--	--	349
231SCKN	65	26	6	--	43.9	11-00-56	9	--	--	714
231SCKN	60	26	6	--	43.9	11-00-56	15	--	--	715
231LCKG	40	--	6	--	4.86	05-24-61	10.3	1.5	1	828
231SCKN	107	22.6	12	--	--	--	230	--	--	958
231SCKN	300	--	--	--	81.9	07-27-81	--	--	--	961
231SCKN	400	60	10	--	95.0	11-01-81	75.0/40.0	--	48.0/49.0	967
231SCKN	125	--	--	--	17.9	07-06-78	--	--	--	999
231SCKN	300	--	--	--	52.0	06-29-81	--	--	--	1026
231SCKN	400	60	10	--	56.7	06-29-81	250	2.25	27.0	1029
231SCKN	400	60	12	102/150/200/218/240/315	25.8	09-06-78	480	4.60	48.0	1040
231SCKN	--	--	--	--	--	--	--	--	--	1042
231SCKN	45.0	--	--	--	--	--	--	--	--	1127
231SCKN	--	--	--	--	--	--	--	--	--	1128
231SCKN	--	--	--	--	--	--	--	--	--	1133
231SCKN	500	10	62	--	72	01-01-86	304	5.7	48	1196
231SCKN	605	60	10	--	56.0	09-02-86	125	.60	52	1241
231SCKN	605	120	10	--	80	03-18-86	100/150	.55/.65	52/48	1242
231SCKN	510	--	--	--	2.5	01-07-86	125	.60	64	1243
231SCKN	560	62	10	65/115/205/305	70.5	11-23-87	125	2.63	48	1296
231SCKN	300	54	6	110/165/210	4	06-18-67	50	.78	--	1310
231SCKN	506	74	10	85/157/182/254/282/315/332/415	82.2	03-04-86	295	4.9	49	1316
231SCKN	421	--	10	--	3.02	12-06-91	120	--	--	1845
231LCKG	560	43	6	280/500	55.6	12-03-92	6	.01	1.5	2473
231LCKG	--	--	--	--	10.3	12-04-92	--	--	--	2478
231SCKN	405	60	6	191	107.4	08-14-96	12	--	.75	2697
231SCKN	222.5	60	10	--	5.5	08-23-96	--	--	--	2698
231SCKN	427	20	6	--	317	08-26-96	70	.7	4	2699
231SCKN	460	40	6	180/310/445	103	09-13-94	10	.02	.5	2711
231SCKN	150	42	6	--	28.7	09-13-94	100	5.00	4	2713
231SCKN	130	60	6	70/80/95/115	18.2	09-13-94	35	--	.50	2714
231SCKN	330	64	6	115/170/230/310	78.3	09-13-94	20	--	4.25	2715
231SCKN	90	--	6	--	22.9	09-14-94	--	--	--	2716
231LCKG	577	42	6.25	207/482/541/568	85.7	09-15-94	35	.07	.5	2717
231SCKN	330	60	6	190/215/265	130	09-15-94	14	--	4	2718

Table 13. *Record of wells in Warwick Township, Bucks County, Pennsylvania—Continued*

USGS well number	Location		Owner	Driller license number	Date drilled	Primary		Elevation of land surface (feet)	Topo-graphic setting
	Latitude (DDMMSS)	Longitude (DDDMMSS)				Use of site	Use of water		
BK-2719	401440	0750437	Costello, Joe	0330	12-31-91	W	H	355	S
2720	401336	0750418	Kosma Tool & Die, Inc.	0330	07-00-87	W	N	225	S
2721	401322	0750426	Whytoseck, Eugene	0331	02-21-73	W	H	224	S
2722	401417	0750331	Lindsey Estate, Mary	0330	08-00-90	W	H	182	F
2723	401303	0750432	Molenaar, Jerry	0130	08-18-91	W	I	241	F
2724	401302	0750433	Molenaar, Jerry	--	--	W	H	240	S
2725	401618	0750604	Kane, Joe	0330	10-25-88	W	H	275	S
2726	401512	0750651	Pease, Arthur	0130	12-13-84	W	H	352	S
2727	401450	0750453	Ginsburg, Dr. Robert	0111	10-15-92	W	H	365	H
2728	401458	0750454	McGraft, Joe	0130	03-03-92	W	H	353	S
2729	401439	0750423	Gotshall, Bruce	0560	00-00-64	U	U	360	H
2730	401257	0750417	Hunsinger, J./Jackson, M.E.	0514	12-00-88	W	H	243	S
2731	401532	0750659	Barowski, Joe	0330	04-00-90	W	H	406	S
2732	401523	0750652	Morrison, Thomas	0330	07-18-88	W	H	373	S
2733	401446	0750504	Reller, Richard	0330	11-10-92	W	H	355	S
2734	401556	0750619	Alden, Helen	0330	08-18-88	W	H	364	S
2735	401624	0750550	DeGroot, Phyllis	0130	--	W	H	228	S
2736	401625	0750549	DeGroot, Phyllis	0130	09-20-90	W	H	215	V
2737	401418	0750625	Fronkin, Don	--	00-00-44	W	H	301	S
2738	401428	0750603	Giame, Joe	0260	01-02-84	W	H	370	H
2739	401408	0750621	Locklyn Hall	--	--	W	C	247	S
2740	401435	0750458	Sproat, Bob	--	00-00-69	W	H	351	S
2741	401540	0750420	Haug, Ken	0514	11-00-92	W	H	210	V
2742	401613	0750526	Pursell, F./Vogel, C.	--	--	W	H	281	F
2743	401603	0750437	Salladay, D	--	00-00-53	W	H	230	S
2744	401549	0750452	Samios, Mary	--	00-00-88	W	H	324	S
2745	401450	0750425	Lawrence, Ed	0111	09-00-85	W	H	345	S
2746	401438	0750716	Droll, Tom	0130	08-29-81	W	H	357	S
2747	401357	0750549	Hallman, Joe	--	--	W	H	190	V
2748	401353	0750553	Beck, Rob	--	--	W	H	197	S
2749	401515	0750522	Exxon USA	0982	06-00-88	W	C	308	S
2750	401610	0750443	Zaks, Ida	--	--	W	H	209	S
2751	401554	0750433	Ewer, Eleanor	--	00-00-50	W	H	265	S
2752	401558	0750513	Bucks Co. Country Club	0228	--	W	C	262	S
2753	401559	0750514	Bucks Co. Country Club	0228	--	W	I	256	S
2754	401628	0750518	Turczyn, Tom	--	00-00-43	W	H	201	S
2755	401453	0750708	Stewart, Jim	0130	09-00-89	W	H	373	S
2756	401523	0750630	Regenhard, Ann	0130	02-28-85	W	H	350	S
2757	401526	0750635	Lewis, Mike	0130	01-11-85	U	I	362	S
2758	401526	0750515	McLaughlan, Martha	--	--	W	H	303	S

Table 13. Record of wells in Warwick Township, Bucks County, Pennsylvania—Continued

Hydro-geologic unit	Depth of well (feet)	Casing		Depth to water bearing zone(s) (feet)	Water level (feet)	Date water level measured	Measured yield			USGS well number
		Depth (feet)	Diameter (inches)				Discharge (gal/min)	Specific capacity [(gal/min)/ft]	Pumping period (hours)	
231SCKN	370	79	6	130/280/345	131	09-15-94	20	--	4.5	BK-2719
231SCKN	170	60	6	40/110/160	32.0	09-15-94	25	0.63	.50	2720
231SCKN	125	32	6	40/65/100	25.1	09-15-94	30	.86	2	2721
231SCKN	130	60	6	95/115/120	27.7	09-15-94	18	--	.5	2722
231SCKN	220	40	6	65/100/ 160/180	18.0	09-16-94	80	.40	.50	2723
231SCKN	--	--	--	--	24.2	09-16-94	--	--	--	2724
231SCKN	190	60	6	80/110/ 140/155	53.1	09-16-94	15.0	--	.50	2725
231SCKN	360	40	6	120/230/350	93.8	09-16-94	10	.03	1.0	2726
231LCKG	430	42	6	175/420	73.4	09-16-94	10	--	--	2727
231LCKG	500	40	6	180/270/480	102	09-16-94	12	.03	.50	2728
231SCKN	126	--	6	--	124	09-15-94	--	--	--	2729
231SCKN	100	42	6	60/90	15.4	09-21-94	100	--	--	2730
231SCKN	310	60	6	110/135/205	71.8	09-21-94	12	--	.50	2731
231SCKN	410	60	6	35/108/145	114	09-21-94	6.0	--	.50	2732
231LCKG	410	60	6	140/235/300	117	09-21-94	30	--	4.0	2733
231SCKN	450	60	6	130/380/440	199	09-26-94	10	.04	4.0	2734
231LCKG	--	--	6	--	33.6	09-27-94	--	--	--	2735
231LCKG	300	40	6	120/210/280	16.6	09-27-94	15	.06	.5	2736
231SCKN	140	--	--	--	77.8	09-27-94	--	--	--	2737
231SCKN	235	40	6	--	125	09-27-94	25	--	--	2738
231SCKN	--	--	--	--	36.4	09-27-94	--	--	--	2739
231SCKN	156	--	6	--	134	09-27-94	40	--	--	2740
231LCKG	535	80	6	225/520	3.07	09-27-94	15	--	--	2741
231LCKG	--	--	--	--	24.5	09-28-94	--	--	--	2742
231LCKG	325	--	--	--	11.7	09-28-94	--	--	--	2743
231LCKG	--	--	6	--	26.5	09-28-94	--	--	--	2744
231LCKG	145	42	6	95/115	82.6	09-28-94	15	.16	2.0	2745
231SCKN	400	41	6	100/200/ 360/380	183	09-29-94	25	.10	2.0	2746
231SCKN	--	--	--	--	--	09-29-94	--	--	--	2747
231SCKN	--	--	--	--	6.22	09-29-94	--	--	--	2748
231LCKG	420	85	6	120/320/ 370/410	16.5	09-29-94	30	.31	5.25	2749
231LCKG	--	--	--	--	16.5	09-29-94	--	--	--	2750
231LCKG	204	20	6	--	70.3	09-29-94	--	--	--	2751
231LCKG	--	--	--	--	28.4	09-30-94	--	--	--	2752
231LCKG	--	--	--	--	12.0	09-30-94	--	--	--	2753
231LCKG	--	--	--	--	17.9	09-30-94	--	--	--	2754
231SCKN	--	40	--	--	116	09-30-94	--	--	--	2755
231SCKN	420	40	6	150/240/390	69.5	09-30-94	12	.03	.50	2756
231SCKN	280	40	6	140/180/ 240/270	117	09-30-94	30	.14	.50	2757
231LCKG	--	--	--	--	41.2	10-07-94	--	--	--	2758

Table 13. Record of wells in Warwick Township, Bucks County, Pennsylvania—Continued

USGS well number	Location Latitude (DDMMSS)	Longitude (DDDMMSS)	Owner	Driller license number	Date drilled	Primary Use of site	Use of water	Elevation of land surface (feet)	Topo-graphic setting
BK-2771	401453	0750409	McCarty, Pat	0330	09-00-86	W	H	340	S
2772	401456	0750349	Reiders, Michael	--	--	U	H	326	S
2773	401456	0750349	Davis, V./Reiders, M.	0330	12-31-91	W	H	326	S
2774	401508	0750514	Thomas, Robert	0121	07-24-87	W	H	326	S
2775	401437	0750549	James, Thomas	--	--	W	H	382	H
2776	401428	0750536	Van Pelt, Robert	--	--	W	H	310	S
2777	401404	0750515	Serrill, Andy	0330	--	W	H	179	V
2778	401428	0750340	Gemmil, Kenneth	0330	00-00-84	C	--	167	V
2779	401441	0750338	Gemmil, Kenneth	0330	09-21-76	W	H	333	S
2780	401502	0750506	St. Cyril Of Jerusalem Ch.	--	--	W	--	341	S
2781	401401	0750537	Peluso, Marianne	--	--	W	H	191	V
2782	401457	0750313	Hullman, Lisa	--	00-00-86	W	H	318	S
2783	401643	0750529	Berlinger, Bernard	0130	08-07-89	W	H	286	S
2784	401644	0750533	Berlinger, Bernard	0121	00-00-79	W	H	280	S
2785	401642	0750530	Berlinger, Bernard	--	--	U	H	272	S
2786	401327	0750514	The New Church	0330	--	W	--	245	S
2812	401357	0750423	Colladay, C./Van Ingen, W.	--	--	W	H	195	S
2813	401430	0750534	Ailes, Bill	0330	08-00-93	W	H	318	S
2815	401521	0750224	Brasko, Alexander	--	--	W	H	216	S
2816	401419	0750539	Schabener, Barbara	0111	12-17-71	W	H	245	S
2817	401542	0750608	Klein, Diane	--	--	W	H	336	S
2818	401507	0750235	Conyne, Bertha	--	--	W	H	282	S
2819	401456	0750521	Fetzer, Carl	--	00-00-28	W	I	342	S
2820	401517	0750336	Marley	0330	11-00-94	W	H	270	S
2821	401454	0750434	Paul, Frank	0130	11-00-92	W	H	338	S
2822	401521	0750224	--	--	--	W	H	216	S
2823	401620	0750550	Albert, Mary	-408	00-00-20	W	H	266	S
2824	401531	0750356	Lake, Gregory	--	--	W	H	290	S
2825	401316	0750419	Warwick Twin Rinks	0330	00-00-95	W	--	209	V
2826	401457	0750601	Meyer, John	--	00-00-52	W	H	327	S
2843	401359	0750417	Van Ingen, William	--	--	W	H	174	V
2861	401318	0750432	Warwick Twp Wat & Sewer	0330	00-00-88	U	P	210	F
2862	401611	0750533	Camp Neumann	--	--	U	I	283	S
2864	401624	0750504	Creek Wood Estates	0330	--	Z	N	210	S
2868	401504	0750556	Meyer, John	0330	--	W	--	315	V

Table 13. Record of wells in Warwick Township, Bucks County, Pennsylvania—Continued

Hydro-geologic unit	Depth of well (feet)	Casing		Depth to water bearing zone(s) (feet)	Water level (feet)	Date water level measured	Measured yield			USGS well number
		Depth (feet)	Diameter (inches)				Discharge (gal/min)	Specific capacity [(gal/min)/ft]	Pumping period (hours)	
231LCKG	330	40	6	110/245/300	78.2	10-07-94	15	0.30	2.0	BK-2771
231LCKG	--	--	--	--	65.9	10-26-94	--	--	--	2772
231LCKG	410	63	6	145/320/370	43.8	10-26-94	12	--	4	2773
231LCKG	200	40	6	160	16.5	10-26-94	20	--	.25	2774
231SCKN	--	--	--	--	68.5	01-27-95	--	--	--	2775
231SCKN	--	--	--	--	70.9	01-27-95	--	--	--	2776
231SCKN	85	--	6	--	4.34	01-27-95	--	--	--	2777
231SCKN	--	--	8	--	9.07	03-01-95	--	--	--	2778
231SCKN	--	--	8	--	103	03-01-95	--	--	--	2779
231LCKG	--	--	--	--	30.4	03-01-95	--	--	--	2780
231SCKN	--	--	--	--	15.3	03-01-95	--	--	--	2781
231LCKG	--	--	--	--	38.8	03-01-95	--	--	--	2782
231LCKG	280	40	6	90/150/260	26.2	03-15-95	15	.07	.50	2783
231LCKG	240	--	6	--	27.4	03-15-95	--	--	--	2784
231LCKG	23	--	--	--	7.07	03-15-95	--	--	--	2785
231SCKN	--	--	6	--	37.4	03-15-95	--	--	--	2786
231SCKN	--	--	--	--	35.6	03-17-95	--	--	--	2812
231SCKN	330	63	6	--	102	03-30-95	15	--	--	2813
231LCKG	15.5	--	--	--	9.94	03-30-95	--	--	--	2815
231SCKN	145	32	6	112/124/ 135/145	43.9	05-10-95	30	1.50	--	2816
231LCKG	--	--	--	--	98.6	05-11-95	--	--	--	2817
231LCKG	--	--	12	--	5.76	05-11-95	--	--	--	2818
231LCKG	--	--	6	--	36.3	05-11-95	--	--	--	2819
231LCKG	--	--	--	--	46.0	05-11-95	--	--	--	2820
231LCKG	--	--	6	--	70.9	05-11-95	--	--	--	2821
231LCKG	--	--	--	--	--	--	--	--	--	2822
231LCKG	--	--	--	--	105	08-01-95	--	--	--	2823
231LCKG	75	--	--	--	--	--	--	--	--	2824
231SCKN	--	--	--	--	--	--	--	--	--	2825
231LCKG	--	--	--	--	--	--	--	--	--	2826
231SCKN	--	--	--	--	1.50	02-04-94	--	--	--	2843
231SCKN	158.4	84	10		6.4	08-29-96	388		48	2861
231LCKG	305	19	8	--	57.3	08-30-96	--	--		2862
231LCKG	265	--	8	--	11.5	09-03-96	--	--		2864
231LCKG	--	--	10.5	--	60.9	09-30-94	--	--	--	2868