HYDROGEOLOGY AND GROUND-WATER QUALITY OF NORTHERN BUCKS COUNTY, PENNSYLVANIA

by Ronald A. Sloto and Curtis L. Schreffler

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Multiply	by	To obtain
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer
	Volume	
gallon (gal)	3.785	liter
	Flow	
gallon per minute (gal/min)	0.06308	liter per second
gallon per day (gal/d)	.003785	cubic meters per day
million gallon per year (Mgal/yr)	1.38152	cubic meter per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer
	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

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)

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ABSTRACT

The 187-square mile study area is in the Triassic-Jurassic Newark Basin. Most of the area is underlain by sedimentary rocks of Upper Triassic age (74 percent) and intrusive diabase of Jurassic age (12 percent) and includes two southwest-northeast trending valleys underlain by carbonate and crystalline rock.

Ground water in the sedimentary rocks of Triassic age moves through a network of interconnecting secondary openings—fractures, bedding planes, and joints. The ground-water system consists of beds with a relatively high transmissivity separated by beds with a relatively low transmissivity that form a leaky, multiaquifer system. Ground water is unconfined in the shallower part of the aquifer and confined or semiconfined in the deeper part of the aquifer. Most deep wells are open to several water-bearing zones and are multiaquifer wells.

The frequency of occurrence of water-bearing zones decreases with depth. Sixty-five percent of water-bearing zones for all hydrogeologic units are within 200 feet of land surface, and 85 percent are within 300 feet of land surface. On the basis of the median specific capacity of nondomestic wells, carbonate rocks, the Brunswick Group, and the Stockton Formation are the most productive hydrogeologic units. Carbonate rocks and the Stockton Formation have the highest median nondomestic well yields (156 and 120 gallons per minute, respectively) among the hydrogeologic units. Thirty-four percent of domestic wells drilled in diabase, 30 percent in the Lockatong Formation, and 21 percent in carbonate rock yield less than 5 gallons per minute.

Average water budgets for the Cooks, Tinicum, Paunnacussing, and Mill Creek Basins weighted by drainage area were calculated for 1991-92. Average annual precipitation was 41.7 in. (inches); average annual evapotranspiration (ET) and other losses were 26.2 in. or 63 percent of precipitation; average annual streamflow was 15.9 in., or 38 percent of the average precipitation; and the average annual change in ground-water storage was a decrease of 0.3 in., or less than 1 percent of the average annual precipitation. Average estimated recharge for 1991-92 weighted by drainage area was 10.1 in. [0.485 (Mgal/d)/mi^2 (million gallons per day per square mile)]; this is equal to a recharge rate of 758 gallons per day per acre.

Water budgets for the Tohickon Creek Basin were calculated for 1968-91 (prior to regulation of the stream by Lake Nockamixon). The average annual precipitation was 47.2 in.; average annual ET and other losses were 24.3 in., or 51 percent of the average annual precipitation; and annual streamflow was 22.6 in., or 48 percent of the average annual precipitation.

Streamflow hydrographs for 1991-92 for Cooks, Tinicum, Paunnacussing, and Mill Creeks were separated into base-flow and surface-runoff components. Average annual ground-water discharge to streams weighted by drainage area was 8.4 in. [0.403 (Mgal/d)/mi^2], which was 20 percent of the average annual precipitation and 53 percent of the average annual streamflow. Average annual surface runoff weighted by drainage area was 7.4 in., which was 18 percent of the average annual precipitation and 47 percent of the average annual streamflow. Annual base flow for 1936-71 for Tohickon Creek ranged from 2.5 in. [0.12 (Mgal/d)/mi^2] in 1965 to 8.4 in. [0.40 (Mgal/d)/mi^2] in 1945. The median base flow was 5.3 in. [0.25 (Mgal/d)/mi^2].

Water from wells in the crystalline rocks has the lowest median pH (5.8), the lowest median specific conductance (139 microsiemens per centimeter), the lowest median alkalinity [16 mg/L (milligrams per liter) as $CaCO_3$], and the highest dissolved oxygen concentration (9.0 mg/L) of the hydrogeologic units. Water from wells in carbonate rocks has the highest median pH (7.8) and the highest median alkalinity (195 mg/L as $CaCO_3$) of the hydrogeologic units. Water from wells in the Lockatong Formation has the highest median specific conductance (428 microsiemens per centimeter) and the lowest dissolved oxygen concentration (0.8 mg/L) of the hydrogeologic units. Water from wells in crystalline rocks contains the lowest concentrations of total dissolved solids (TDS) of the hydrogeologic units. Water from the Lockatong Formation contains the highest concentration of TDS of the hydrogeologic units. Water from only 1 of 83 wells sampled exceeded the U.S. Environmental Protection Agency (USEPA) secondary maximum contaminant level (SMCL) for TDS; the well is in the Lockatong Formation. Five of 86 samples (6 percent) and 6 of 75 samples (8 percent) exceed the USEPA SMCL for iron and manganese, respectively. Nitrate is the most prevalent nitrogen species in ground water. The median nitrate concentration for all hydrogeologic units is 2.3 mg/L. Of 71 water samples from wells, no concentrations of nitrate exceed the USEPA maximum contaminant level. The median dissolved radon-222 activity was highest for water samples from wells in crystalline rock [3,600 pCi/L (picocuries per liter)] and lowest for water samples from wells in the Lockatong Formation (340 pCi/L) and diabase (350 pCi/L). Water samples for analysis for volatile organic compounds (VOC's) were collected from 34 wells in areas where the potential existed for the presence of VOC's in ground water. VOC's were detected in 23 percent of the 34 wells sampled. The most commonly detected compound was trichloroethylene (13 percent of sampled wells).

INTRODUCTION

Bucks County has one of the fastest growing populations in the Commonwealth of Pennsylvania. The population of the nine municipalities in the study area increased 92 percent between 1960 and 1990. Between 1980 and 1990, the population of Solebury Township increased 24.3 percent, and the population of Plumstead Township increased 22 percent.

The rolling landscape of northern Bucks County provides a desirable setting for development. Many areas, which were formerly agricultural, are rapidly being urbanized. Between 1970 and 1980, the 2 years for which land-use data are available (Bucks County Planning Commission, 1983a, 1983b), residential development in the nine municipalities in the study area increased by 7,264 acres or 35 percent. During the same period, land used for agriculture decreased by 4,855 acres or 8 percent.

The residents of northern Bucks County depend on ground water as a source of water supply. As growth continues and population increases, the demand for ground water also increases. In response to a need for information about the availability and quality of ground water in northern Bucks County, the U.S. Geological Survey (USGS), in cooperation with New Hope Borough and Bridgeton, Buckingham, Nockamixon, Plumstead, Solebury, Springfield, Tinicum, and Wrightstown Townships conducted the study described in this report.

Purpose and Scope

This report provides basic information on the geology and the quantity and quality of ground water in northern Bucks County, Pa. The study area includes New Hope Borough and Bridgeton, Buckingham, Nockamixon, Plumstead, Solebury, Springfield, Tinicum, and Wrightstown Townships and parts of the surrounding areas.

Data analysis is based on hydrologic data from 1,357 wells and chemical analyses of water from 120 wells. This report describes the hydrogeologic system and water-bearing capabilities of the hydrogeologic units, presents water budgets for selected basins, describes the relation between ground water and surface water, and presents statistical summaries of water-quality data.

This report incorporates recent geologic mapping and nomenclature changes. The report provides a description of geologic units and incorporates all relevant geologic literature to 1992. The bibliography includes all relevant references on the geology and hydrology of northern Bucks County.

Location and Physiography

The study area (fig. 1) is a 187-mi^2 area in northern Bucks County. The study area is chiefly underlain by sedimentary rocks of Upper Triassic age and intrusive diabase of the Triassic Lowlands Section of the Piedmont Physiographic Province. Two northeast trending valleys, the Durham and Buckingham Valleys, are underlain by carbonate and crystalline rock. Most of the area underlain by sedimentary rocks of Triassic age is flat to rolling. Diabase forms prominent, wooded hills, rising up to 826 ft above sea level. The extreme northern part of the area lies in the Reading Prong and Great Valley Sections of the New England Physiographic Province (Berg and others, 1989). The rocks of Middle Proterozoic age of the Reading Prong form a steep hillside at the Bucks-Northampton County border that rises to 880 ft above sea level.

The Delaware River forms the eastern boundary of the study area. The flood plain of the Delaware River is bordered by steep hillsides. In Nockamixon and Bridgeton Townships, cliffs with a relief of 250 to 280 ft rise nearly vertical.

All streams draining the study area are tributaries to the Delaware River. Major streams draining to the Delaware River are Cooks Creek, Gallows Run, Tinicum Creek, Tohickon Creek, Geddes Run, Paunnacussing Creek, Aquetong Creek, and Pidcock Creek. Most of Buckingham and Wrightstown Townships are drained by tributaries to Neshaminy Creek, which is a tributary to the Delaware River.

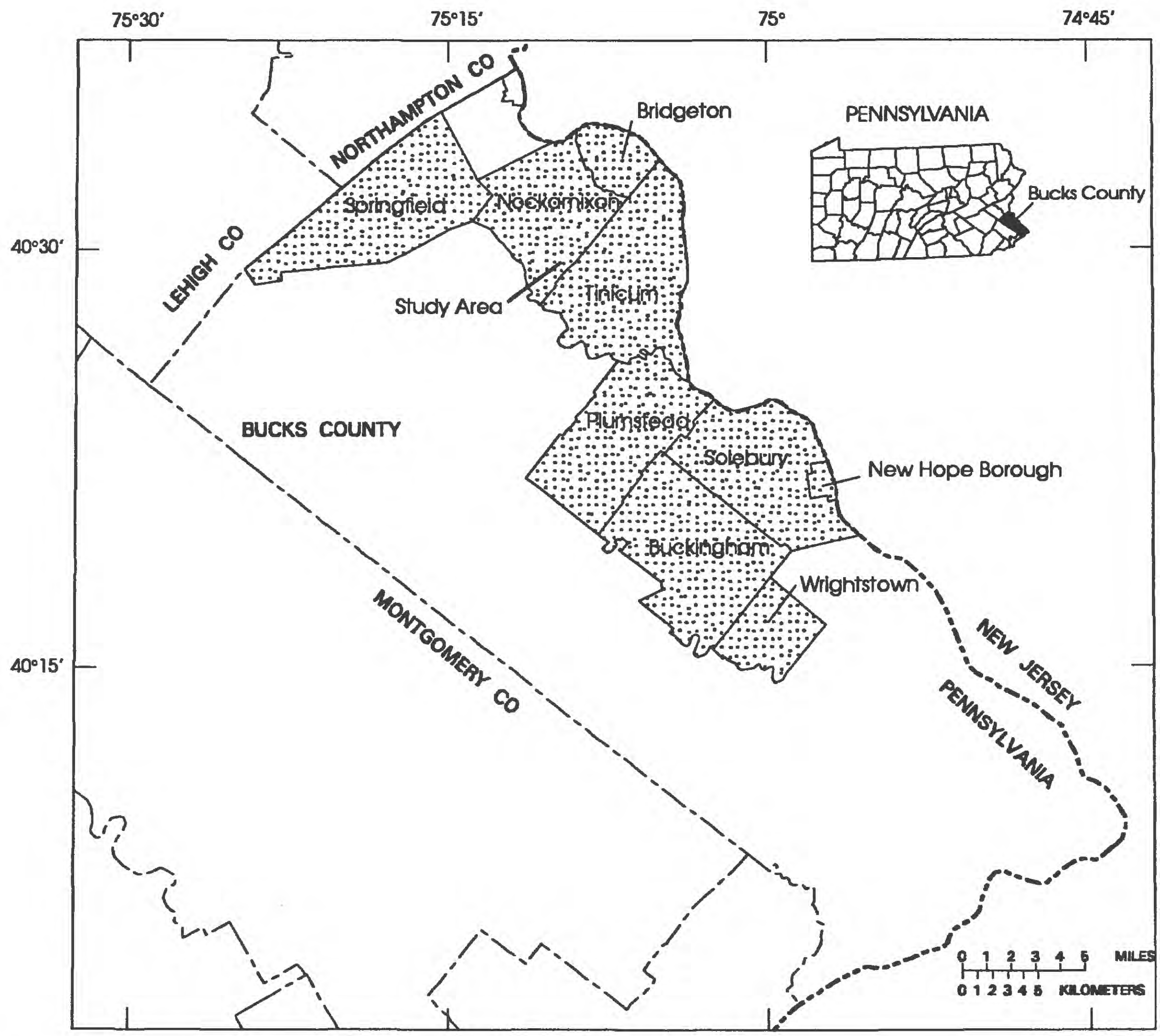

Figure 1. Location of northern Bucks County study area.

Climate

Northern Bucks County has a humid, modified continental climate characterized by warm summers and moderately cold winters. The normal (1961-90) mean annual temperature at Lambertville, N.J., is 53.3°F (Owenby and Ezell, 1992a). The normal (1961-90) mean temperature for January, the coldest month, is 29.6°F, and the normal mean temperature for July, the warmest month, is 75.4°F. The normal (1961-90) mean annual temperature at Neshaminy Falls, Pa., which is just south of the study area, is 51.7°F (Owenby and Ezell, 1992b). The normal (1961-90) mean temperature for January, the coldest month, is 28.3°F, and the normal mean temperature for July, the warmest month, is 73.8°F.

The normal (1961-90) annual precipitation at Lambertville, N.J., is 45.43 in. The normal (1961-90) annual precipitation at Neshaminy Falls, Pa., is 47.47 in. Precipitation is about evenly distributed throughout the year, with slightly more occurring during July and August because of localized thunderstorms. Figure 2 shows annual precipitation at Lambertville, N.J., from 1970 to 1992 and normal (1961-90) annual precipitation.

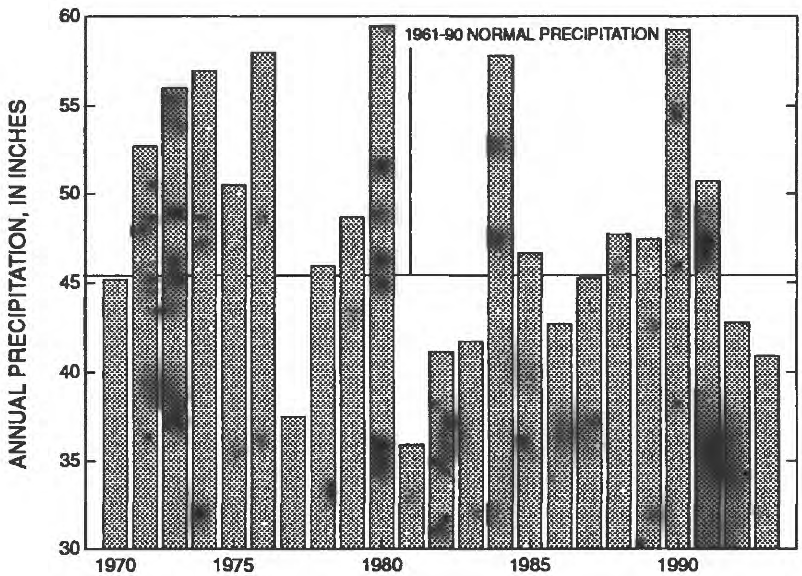

Figure 2. 1970-92 annual precipitation and 1961-90 normal precipitation at Lambertville, New Jersey.

Well-Numbering System

The well-numbering system used in this report consists of a county abbreviation prefix followed by a sequentially-assigned number. The prefix BK denotes a Bucks County well. Locations of selected wells are shown on plate 1; locations of other wells are given by Schreffler and others (1994).

Borehole Geophysical Logging

Caliper, natural-gamma, single-point-resistance (electric), fluid-resistivity, and fluid-temperature logs were run in 46 boreholes (table 1). Locations of the logged wells are shown on plate 1. Borehole geophysical logs provide information on physical properties of the formation penetrated by the borehole, the fluid in the borehole, and well construction. The application of borehole geophysical methods to water-resources investigations is discussed by Keyes (1990). Borehole-flow measurements were made in boreholes if the fluid logs indicated that borehole flow was occurring. A borehole television survey was run in selected wells.

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

Single-point-resistance logs record the electrical resistance between the borehole and an electrical ground at land surface. In general, resistance increases with grain size and decreases with borehole diameter, density of water-bearing fractures, and increasing dissolved-solids concentration of borehole fluid. A fluid-filled borehole is required for single-point-resistance logs, and they are run only for the saturated part of the formation below the casing. Single-point-resistance logs are used to correlate lithostratigraphy and may help to identify the location of water-bearing zones.

***Table 1.** Wells in which geophysical logs were run in northern Bucks County*

U.S. Geological Survey identification number	Owner and identification number	Township	Hydrogeologic unit	Depth logged (feet)
BK-920	Bucks County Department of Natural Resources 3	Solebury	Brunswick Group	516
BK-922	Bucks County Department of Natural Resources 5	Solebury	Brunswick Group	331
BK-1211	Newtown Artesian Water Company 21	Newtown	Lockatong Formation	662
BK-1303	W. Steinhauser 1	Plumstead	Stockton Formation?	610
BK-1304	W. Steinhauser 2	Plumstead	Stockton Formation	601
BK-1343	Buckingham Springs 3	Buckingham	Brunswick Group	347
BK-1344	Buckingham Springs 4	Buckingham	Brunswick Group	405
BK-1345	Buckingham Springs 5	Buckingham	Brunswick Group	405
BK-1346	C and M Builders, Inc. A	Plumstead	Lockatong Formation	563
BK-1347	C and M Builders, Inc. B	Plumstead	Lockatong Formation	427
BK-1483	Country Greene Estates 1	Plumstead	Lockatong Formation	413
BK-1484	Country Greene Estates 2	Plumstead	Lockatong Formation	288
BK-1493	Bucks County Crushed Stone Company, Inc.	Nockamixon	Brunswick Group, lower beds	249
BK-1498	S. Farbotnik	Nockamixon	Diabase	260
BK-1554	J. Dolinski	Nockamixon	Diabase	600
BK-1556	Revere Chemical Company	Nockamixon	Brunswick Group, lower beds	393
BK-1744	Plumstead Christian School	Plumstead	Lockatong Formation	518
BK-1838	DeLuca 3	Solebury	Stockton Formation and carbonate rock	465
BK-1839	DeLuca 1	Solebury	Limeport Formation	215
BK-1840	DeLuca 2	Solebury	Limeport Formation	548
BK-1841	DeLuca 2A	Solebury	Limeport Formation	117
BK-1842	DeLuca 4	Solebury	Limeport Formation	547
BK-1846	Durham Ridge 1	Plumstead	Stockton Formation	632
BK-1847	Durham Ridge 2	Plumstead	Stockton Formation	509
BK-1848	North Branch Farm 1	Plumstead	Lockatong Formation	548
BK-1849	North Branch Farm 2	Plumstead	Lockatong Formation	637
BK-1850	North Branch Farm 3	Plumstead	Lockatong Formation	471
BK-2007	G. Taber	Tinicum	Brunswick Group	108
BK-2087	Miller and Son Paving, Inc. OBS-5	Plumstead	Lockatong Formation	195
BK-2088	Miller and Son Paving, Inc. OBS-4	Plumstead	Lockatong Formation	196
BK-2090	Miller and Son Paving, Inc. OBS-2	Plumstead	Lockatong Formation	195
BK-2091	Miller and Son Paving, Inc. OBS-1	Plumstead	Lockatong Formation	295
BK-2092	Miller and Son Paving, Inc. W-1	Plumstead	Lockatong Formation	196
BK-2093	Miller and Son Paving, Inc. W-2	Plumstead	Lockatong Formation	196
BK-2094	Miller and Son Paving, Inc. W-3	Plumstead	Lockatong Formation	495
BK-2095	Miller and Son Paving, Inc. P-2	Plumstead	Lockatong Formation	118
BK-2201	W. Brokaw	Bridgeton	Brunswick Group, hornfels	283
BK-2202	Bridgeton Township	Bridgeton	Diabase	161
BK-2203	U.S. Geological Survey Deer Park 1	Solebury	Brunswick Group and diabase	713
BK-2205	P. Stoop W-1	Solebury	Brunswick Group	221
BK-2206	P. Stoop W-2	Solebury	Brunswick Group	221
BK-2207	P. Stoop W-3	Solebury	Brunswick Group	200
BK-2347	J. Shaak	Bridgeton	Diabase	760
BK-2479	New Hope Crushed Stone	Solebury	Limeport Formation	270
BK-2480	D. Ely	Solebury	Stockton Formation and carbonate rock	185
BK-2481	Newtown Artesian Water Company 29	Newtown	Lockatong Formation	334

Natural-gamma logs, also called gamma-ray logs, record the natural gamma radiation emitted from rocks penetrated by the borehole. Gamma radiation can be measured through casing, but the gamma response is dampened. Uranium-238, thorium-232, and the progeny of their decay series and potassium-40 are the most common emitters of natural-gamma radiation. These radioactive elements may be concentrated in clay by adsorption and ion exchange, and, therefore, fine-grained sedimentary rocks (siltstone, mudstone, and shale) usually emit more gamma radiation than do quartz sand rocks (sandstone).

Fluid-resistivity logs measure the electrical resistance of borehole fluid. Resistivity is the reciprocal of fluid conductivity, and fluid-resistivity logs reflect changes in the dissolved-solids concentration of the borehole fluid. Fluid-resistivity logs are used to identify water-producing and water-receiving zones and to determine intervals of vertical borehole flow. Water-producing and water-receiving zones usually are identified by sharp resistivity changes, and intervals of borehole flow are identified by a low resistivity gradient between water-producing and water-receiving zones.

Fluid-temperature logs provide a continuous record of the temperature of the borehole fluid. Fluid-temperature logs are used to identify water-producing and water-receiving zones and to determine intervals of vertical borehole flow. Intervals of vertical borehole flow are identified by little or no temperature gradient. Temperature logs from wells with no borehole flow generally show a fluid-temperature decrease with depth in the upper part of the borehole and a fluid-temperature increase with depth as a function of the geothermal gradient in the lower part of the borehole.

The direction and rate of borehole-fluid movement was determined by injecting a slug of high-conductance fluid at a specific depth in the borehole and monitoring the slug movement with the fluid-resistivity tool. This is called the "brine-tracing" method of flow measurement. The lower limit of flow measurement is about 0.5 gal/min in a 6-in. diameter borehole.

Borehole television surveys were conducted by lowering a waterproof video camera with a very wide angle lens down the borehole and recording the results on videotape. Selected features were photographed from a video monitor to produce the photographs in this report.

Previous Investigations

Hall (1934) briefly discussed the water-bearing characteristics of the principal geological formations of southeastern Pennsylvania. Greenman (1955) described the ground-water resources of Bucks County. The geology and hydrology of the Stockton Formation in southeastern Pennsylvania was described by Rima and others (1962). Data collected for this study was published by Schreffler and others (1994).

As part of this study, the potentiometric surface was mapped in Springfield Township by Schreffler (1993a); in Bridgeton, Nockamixon, and Tinicum Townships by McManus and Rowland (1993); in Plumstead Township by Schreffler (1993b); in New Hope Borough and Solebury Township by Schreffler (1993c); and in Buckingham and Wrightstown Townships by McManus and others (1994).

The geology of much of northern Bucks County was mapped by Bascom and others (1931). The geology of all of Bucks County is included on the geologic map of Willard and others (1959); this map also was included in Greenman (1955). The geology of the Frenchtown and Riegelsville quadrangles was remapped by Drake and others (1961) and Drake and others (1967), respectively. Northern Bucks County is included on the geologic map of Lyttle and Epstein (1987). Numerous papers have been written on the geology of northern Bucks County; the most important papers are listed in the bibliography of this report.

Acknowledgments

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The authors thank the following volunteer observers who provided daily precipitation data essential for developing the basin water budgets: David and Carol Barnhart, Steve Farbotnik, Richard French, Martha Harhigh, Edwin Harrington, Pearl Holm, Gilbert and Rebecca Kerlin, Kathy Leaver, Allen Miller, Lois Oleska, Jeff and Carol Rawes, Charles Reichner, Richard Reihman, and Bruce Wallace.

Hydrologic data essential for this study and access to wells were provided by the Bucks County Planning Commission; Delaware River Basin Commission; Del Val Soil Environmental Consultants, Inc.; International Hydrogeologists, Inc.; the Pennsylvania Department of Environmental Resources; and the U.S. Environmental Protection Agency. David Brown, Phil Getty, Joseph Miketta, and Shams Siddiqui were especially helpful.

GEOLOGY

The geologic units of northern Bucks County include crystalline rocks of Precambrian age of the Reading Prong and crystalline rocks of Lower Paleozoic age of the Great Valley along the northern border of the study area, sedimentary rocks of Upper Triassic age and intrusive rocks of lower Jurassic age of the Newark Basin, and crystalline rocks of Lower Paleozoic age of the Buckingham Valley (fig. 3). Table 2 compares the stratigraphic nomenclature of Lyttle and Epstein (1987) used in this report with that of Willard and others (1959), which was used in previous reports.

Precambrian Crystalline Rocks

Crystalline rocks of Precambrian age of the Reading Prong are present north of the Triassic border fault. The rocks of the Reading Prong are allochthonous and represent an overlapping stack of thrust sheets that have been thrust over the Paleozoic Rocks of the Great Valley to the north. The rocks have undergone at least one high-grade and two low-grade metamorphism events and are metamorphosed to amphibolite to granulite facies. In this report, the geologic units of the Reading Prong are grouped as undifferentiated granitic and hornblende gneiss. These rocks are of Middle Proterozoic age and include rocks of the Byram Intrusive Suite (alaskite and hornblende granite), metasedimentary layered rocks (pyroxene gneiss), rocks of the Losee Metamorphic Suite (albite-oligoclase granite and oligoclase-quartz gneiss), and rocks of uncertain origin (amphibolite and amphibolite migmitite) (Lyttle and Epstein, 1987). They were mapped and described by Drake and others (1967). The following descriptions were taken from Lyttle and Epstein (1987).

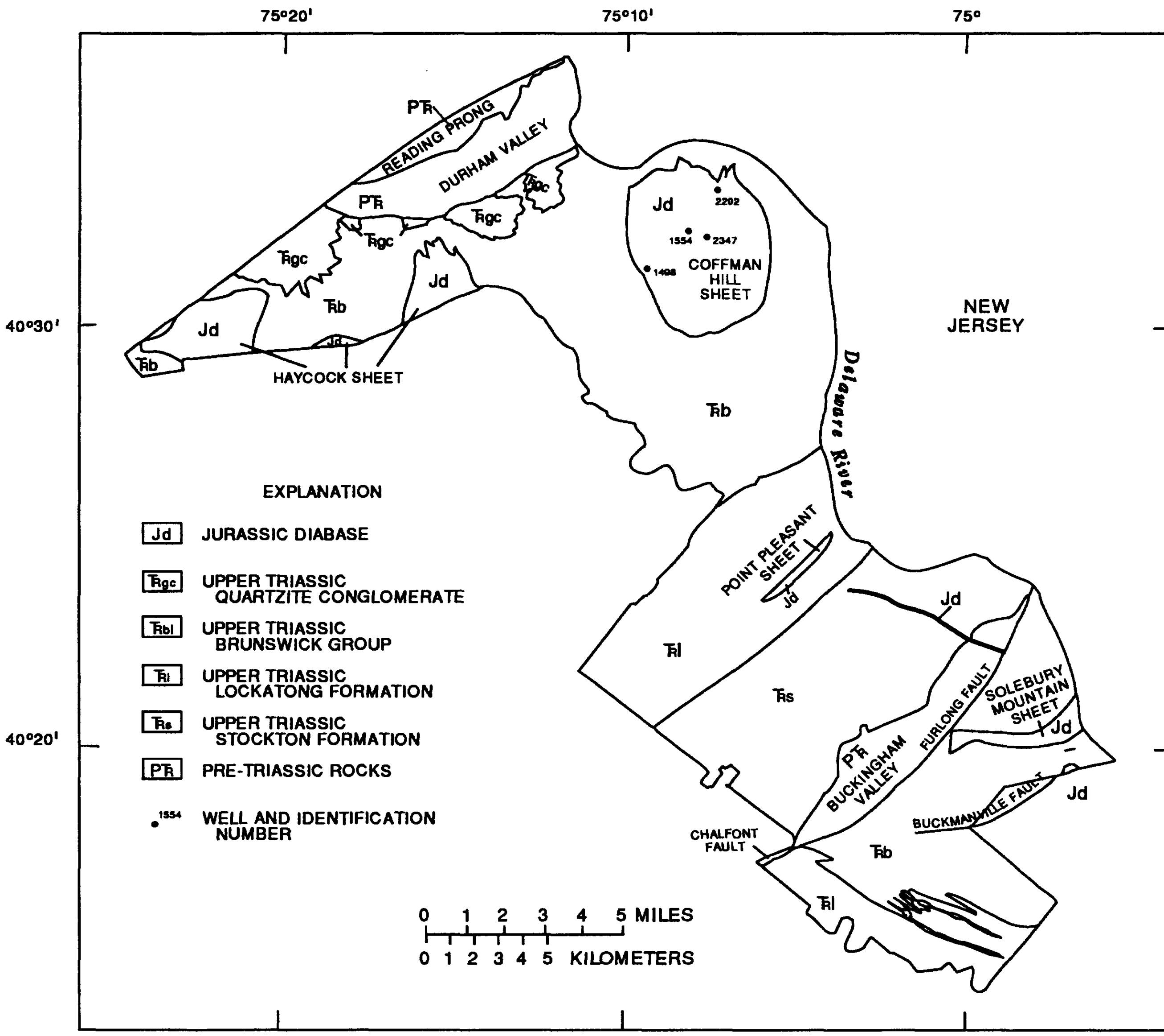
Rocks of the Byram Intrusive Suite include alaskite and hornblende granite. Alaskite is a light pink to light gray, medium- to coarse-grained, foliated alaskite and gneissoid alaskite composed largely of microperthite, quartz, and oligoclase. Hornblende granite is a pink to light gray, medium- to coarse-grained, gneissoid granite, foliated granite, and sparse granite gneiss composed principally of microperthite, quartz, oligoclase, hornblende, and (or) biotite.

Pyroxene gneiss is a layered metasedimentary sequence consisting of greenish-gray to light grayish-green, medium-grained, well-layered to nearly massive, granoblastic gneiss composed principally of diopsidic pyroxene and plagioclase.

Rocks of the Losee Metamorphic Suite include albite-oligoclase granite and oligoclase-quartz gneiss. Albite-oligoclase granite is a medium- to coarse-grained, light green to dull white, gneissoid granite composed principally of albite, oligoclase, and quartz. It includes local layers of amphibolite. Oligoclase-quartz gneiss is a light greenish-gray to grayish-green, medium-fine- to medium-coarse-grained, poorly foliated, granoblastic gneiss and minor granofels composed principally of oligoclase and quartz.

Amphibolite is light to dark gray to nearly black, fine- to medium-grained rock composed principally of hornblende and andesine. Much of the rock is probably metavolcanic, and some may be metasedimentary. Amphibolite migmitite is a mixed rock composed of irregular knots, lenses, veins, and layers of microperthite alaskite in amphibolite. In some areas, it is a mixture of albite-oligoclase granite and amphibolite. Both types of mixed rocks are intruded by gneiss.

On Buckingham Mountain south of Buckingham Valley, a small area of quartz diorite is mapped (Lyttle and Epstein, 1987). The quartz diorite is a light to dark gray, medium- to coarse-grained rock composed principally of andesine or oligoclase, quartz, and hypersthene. This unit was mapped as gabbro by Bascom and others (1931) and was not included on the geologic map of Willard and others (1959).



Geology modified from Willard and others (1959).

Figure 3. Generalized geologic map of northern Bucks County.

Table 2. *Stratigraphic column for northern Bucks County*

Age	Geologic unit	
	This report (Lyttle and Epstein, 1987)	Willard and others (1959)
Quaternary	Alluvium and glacial outwash	Pre-Wisconsin (Pleistocene), Wisconsin (Pleistocene), and Recent unconsolidated deposits
Early Jurassic	Diabase	Diabase
Late Triassic	Quartzite conglomerate	Brunswick quartzite fanglomerate
	Limestone conglomerate	Brunswick limestone fanglomerate
	Brunswick Group	Brunswick Formation
	Brunswick Group, lower beds	Lockatong Formation
	Lockatong Formation	Lockatong Formation
	Lockatong Formation, lower beds	Brunswick Formation
	Stockton Formation	Stockton Formation
Ordovician	Rickenbach Dolomite	Beekmantown (?) Limestone
Ordovician and Cambrian	Allentown Dolomite	Undifferentiated Conococheague (Allentown) Limestone and Tomstown Dolomite (Leithsville Limestone)
Cambrian	Limeport Formation[1]	Conococheague (Limeport) Limestone
	Leithsville Formation	Elbrook (?) Limestone in Buckingham Valley; Undifferentiated Allentown and Leithsville Limestones in Durham Valley
	Hardyston Quartzite	Hardyston and Chickies Quartzite
Cambrian (?)	Undifferentiated Taconic-like rocks of the Furlong Klippe in Buckingham Valley	Cocalico Phyllite
Precambrian	Quartz dolerite	
	Granitic gneiss and hornblende gneiss, undifferentiated	Byram granite gneiss and Pochuck hornblende gneiss

[1] From Repetski and Drake (1991).

Cambrian and Ordovician Rocks

Rocks of Cambrian and Ordovician age are exposed in the Durham and Buckingham Valleys. These rocks include the Hardyston Quartzite, Leithsville Formation, and Allentown Dolomite in Durham Valley and undifferentiated rocks of the Furlong Klippe, Hardyston Quartzite, Leithsville Formation, Limeport Formation, and Rickenbach Dolomite in Buckingham Valley. These rocks are shallow-water marine deposits. Following their deposition and prior to deposition of the Newark Basin sediments, they were intensely folded and faulted and subjected to multiple deformations. In the northern part of the study area, carbonate rocks and quartzite of the Lehigh Valley sedimentary sequence underlie the Durham Valley north of the Triassic border fault (fig. 3). In the southern part of the study area, rocks of Cambrian and Ordovician age underlie the Buckingham Valley (fig. 3). These rocks, which underlie the Triassic sediments of the Newark Basin, have been brought to the surface by the Furlong fault (fig. 4). Ratcliffe and Burton (1988) determined by surface observation and coring that the Furlong fault zone southeast of Buckingham Valley dips 47° to 50° to the southeast and displaces basement rock approximately 1.2 mi vertically.

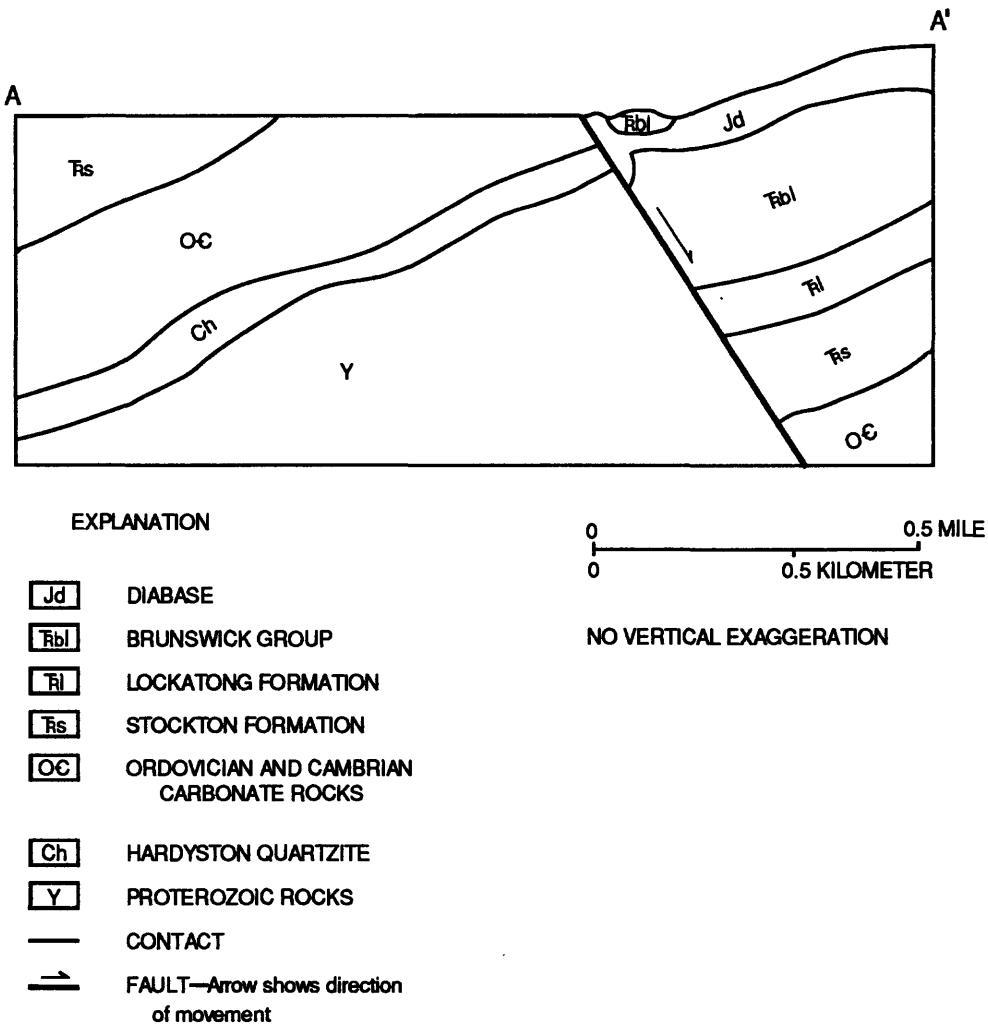


Figure 4. Geologic cross-section of the Furlong fault, northern Bucks County. (Modified from Ratcliffe and Burton, 1988, fig 1.)
Line section of A-A' shown on plate 1.

Rocks of the Furlong Klippe

Rocks of the Furlong Klippe, which are possibly of Cambrian age, are exposed on the crest of an anticline at the southwestern end of the Buckingham Valley. These rocks were called Cocalico Phyllite by Bascom and others (1931, p. 23) because of their similarity to the Cocalico Phyllite in Lancaster County. They are considered to be a Klippe by Lyttle and Epstein (1987). A klippe is a block of generally older rocks separated from the underlying younger rocks by a fault. A klippe may be an erosional remnant of an overthrust sheet or it may have moved into place by gravity sliding. However, these rocks may be a fenster (an erosional break in strata) rather than a klippe (John Adams, Temple University, written commun., 1994).

The rocks of the Furlong Klippe are fissile to slaty, black, blue, purplish and gray phyllite. Their minimum thickness is approximately 200 ft. Bascom and others (1931, p. 23) estimated their maximum thickness at less than 500 ft. No contacts with surrounding units are exposed. To the east, they are in fault contact with the Leithsville and Limeport Formations. To the north, they are unconformably overlain by the Stockton Formation. Since these rocks resemble Taconic allochthon rocks, it is possible that they have been thrust over the rocks of the Buckingham Valley (Lyttle and Epstein, 1987).

Hardyston Quartzite

The Hardyston Quartzite of Lower Cambrian age is the oldest unit in the Lehigh Valley sequence. In the Durham Valley, the Hardyston consists of a gray, brown-weathering quartzite, quartz pebble conglomerate, arkosic sandstone, silty shale, and yellowish-brown, iron-stained jasper. It is less than 100 ft thick (Drake and others, 1967).

Bascom and others (1931, p. 17-19) called this unit Hardyston Quartzite in the Buckingham Valley; however, Willard and others (1959, p. 40) called this unit Chickies Quartzite. In the Buckingham Valley, the Hardyston Quartzite is a thick-bedded, vitreous, white quartzite. The upper part is less vitreous and coarser grained than the lower part and contains a layer of closely packed, clean, white quartz pebbles at the top. The basal bed of the Hardyston is a bluish-purple, crumbly, coarse arkosic sandstone, conglomerate, and quartzite containing fragments of red feldspar and round quartz pebbles 1 in. or less in diameter (Bascom and others, 1931, p. 18). The basal bed is 25 ft thick. Willard and others (1959, p. 40) calculated that the Hardyston Quartzite is 900 ft thick in the Buckingham Valley.

Leithsville Formation

The Leithsville Formation is Lower to Middle Cambrian in age. The Leithsville Formation in the Durham Valley was called the Tomstown Dolomite by Willard and others (1959, p. 28). In the Durham Valley, the Leithsville is a dark gray, buff-weathering dolomite and sericitic, limey clay- and silt-shale that is phyllitic in places. The Leithsville is cyclically bedded, with shaley beds giving way to platy beds, which in turn pass into massive beds. Massive-bedded rock is much more abundant in the lower half of the formation than in the upper half. The Leithsville is estimated to be 1,000 ft thick; however, no reliable measurements are available (Drake and others, 1967).

The Leithsville Formation in the Buckingham Valley was called the Elbrook Limestone by Bascom and others (1931, p. 20-21) because of its similarity to the Elbrook Limestone in Franklin County. Willard and others (1959, p. 41) used "Elbrook (?) (Leithsville) Limestone" for this unit. In the Buckingham Valley, the Leithsville consists of shaley, fine-grained, finely laminated, light blue and light gray dolomite and thick-bedded, fine-grained, dove-colored marble (Bascom and others, 1931, p. 41). Ripple marks, mud cracks, and local black chert layers are common. Bascom and others (1931, p. 41) estimated that the Leithsville is 400-600 ft thick in the Buckingham Valley; however, the upper and lower contacts of the formation are not exposed.

Limeport Formation

The Limeport Formation of Upper Cambrian age (Repetski and Drake, 1991) crops out in Buckingham Valley. This formation was called the Conococheague Limestone by Bascom and others (1931, p. 21-22) and "Conococheague (Limeport) Limestone" by Willard and others (1959, p. 43). Lyttle and Epstein (1987) called this formation the Allentown Dolomite. On the basis of conodont identifications for two sites in Buckingham Valley, Repetski and Drake (1991) determined that it was the Limeport Formation. The Limeport Formation is a massive, dense, blue and light-blue dolomite with thin, wavy, argillaceous partings and black cherty layers up to 1.5 in. thick. The formation consists of cyclic light and dark beds. Some beds may contain algal stromatolites, oolites, flat-pebble conglomerate, black chert, and small black phosphate nodules. The Limeport Formation is conformably overlain by the Rickenbach Dolomite. Willard and others (1959, p. 47) estimated that the Limeport is 400-500 ft thick.

Allentown Dolomite

The Allentown Dolomite of Upper Cambrian to Lower Ordovician age crops out in the Durham Valley. The Allentown is a very fine- to medium-grained, light medium gray to light olive gray to dark medium gray, cyclically bedded dolomite characterized by alternating light and dark weathering bands, abundant stromatolites, oolite beds, and scattered beds and lenses of orthoquartzite. It is about 1,700 ft thick (Drake and others, 1967).

Rickenbach Dolomite

The Rickenbach Dolomite of the Beekmantown Group is Lower Ordovician in age. Bascom and others (1931, p. 22-23) called this unit the Beekmantown Limestone. It is exposed only on the northwestern side of Buckingham Valley. The Rickenbach is a massive, fine-grained, light to dark blue or blue gray dolomite. Locally, it may be siliceous, flinty, laminated, or shaley. The Rickenbach is unconformably overlain by the Stockton Formation. Bascom and others (1931, p. 23) estimated that the Rickenbach is 1,000 ft thick.

Mesozoic Rocks

The sedimentary rocks of the Newark Supergroup underlie most of northern Bucks County. These rocks of Triassic-Jurassic age of the Newark Basin are 16,000 to 20,000 ft thick. The Newark Basin is approximately 140 mi long and 32 mi wide and is the largest of the 13 major exposed Triassic-Jurassic rift basins that stretch from Nova Scotia to South Carolina. The principal formations of the Newark Basin are the Stockton Formation, Lockatong Formation, and Brunswick Group.

Sedimentation in the Newark Basin was the result of infilling of a rift basin formed during the initial stages of continental breakup (Turner-Peterson and Smoot, 1985, p. 10). The sediment was deposited on folded and deeply eroded rocks of Precambrian and Paleozoic age. The predominant depositional environment of the Stockton Formation is fluvial-deltaic, the Lockatong is lacustrine, and the Brunswick Group is fluvial-lacustrine.

The Newark Basin filled with sediments mainly derived from crystalline rocks southeast and northwest of the basin over a period of 45 million years. The formations in the basin are a large-scale time-transgressive facies whose distribution is in response to the tectonic asymmetry of the basin (Turner-Peterson, 1980; Turner-Peterson and Smoot, 1985). Tectonic activity and climatic changes during basin infilling accompanied by fluctuations in sediment input caused migration of facies belts and boundaries. These external controls were probably the most significant factors in determining the relative proportions of fluvial and lacustrine depositional environments.

The Newark Basin is a half graben bordered on its northwestern margin by a fault system (Schlische, 1992, p. 1,262). The northern border fault system strikes NE. Newark Basin rocks dip 5° to 20° NW. toward the northern border fault system. Younger strata generally dip at a more shallow angle than older strata. On the basis of seismic data and drill cores, Ratcliffe and others (1986) determined that near Riegelsville, the fault dips 25° to 30° SE. and that the faulting was the reactivation of Paleozoic imbricate thrust faults in the basement rocks. Faulting continued contemporaneously with basin filling; the down-faulted basin floor provided a continually deepening sink for sediment. Strata of all ages thicken toward the northern border fault system. Structural development of the Newark Basin is described by Schlische (1992, p. 1,262).

Following deposition, the sediments were intruded by diabase, faulted, uplifted, and eroded. In the early Jurassic, the sediments were intruded by diabase, which locally metamorphosed the adjacent rocks to a hornfels. Post-depositional faulting near the center of the basin broke the sediments into three fault blocks. Some of these faults may have been active during deposition. The major interbasin faults in the study area are the Furlong, Chalfont, and Buckmanville faults (fig. 3). The Furlong fault is on the southeastern side of the Buckingham Valley. The fault brings rocks of Paleozoic age to the surface in the center of the Newark Basin. The downthrow is on the southeastern side, and the displacement is about 6,300 ft vertically (Ratcliffe and Burton, 1988). The Chalfont fault joins the Furlong fault at the southwestern end of the Furlong fault. Downthrow is on the south side, and the displacement where the two faults join is estimated to be 6,500 ft (Willard and others, 1959, p. 129). The Buckmanville fault is the continuation of the Flemington fault from New Jersey into Pennsylvania. Downthrow is on the south side, and maximum displacement at the Delaware River is estimated to be less than 4,000 ft (Willard and others, 1959, p. 132-133). Smaller faults are described by McLaughlin (1942) and Willard and others (1959, p. 134-141). Beds on the northwestern side of fault blocks tend to be folded into a series of anticlines and synclines with their long axes perpendicular to the long axes of fault blocks; beds on the southeastern side of the same fault blocks tend not to be folded. Structures in the Triassic rocks are described by Willard and others (1959, p. 126-141).

Stockton Formation

The Stockton Formation of Upper Triassic age is the oldest of the Newark Basin sediments and forms the basal unit. The Stockton rests unconformably on rocks of Paleozoic and Precambrian age. Sedimentation in the Newark Basin began with an influx of arkosic detritus from uplifted crystalline rocks to the south not far from the present day southern basin margin (Glaeser, 1966). The Stockton Formation includes alluvial fans, fluvial and lacustrine sandstones, and fluvial and near-shore lacustrine mudstones and siltstones (Turner-Peterson and Smoot, 1985). Near the southern margin, the Stockton contains laterally coalescing alluvial fans deposited by well-established streams. Thick, poorly defined upward fining cycles possibly were deposited by large, perennial, meandering rivers.

The Stockton Formation dips about 10° NW. Rima and others (1962, p. 9) estimate that the Stockton is 6,000 ft thick in the center of the basin at the Bucks-Montgomery County border. The Stockton thins in all directions from the center of the basin. McLaughlin (1945) and Johnson and McLaughlin (1957) subdivided the Stockton into members on the basis of mapping of exposures along the Delaware River. Those subdivisions are not used in this report.

Stockton lithology is diverse, and the rocks differ widely in bedding, texture, and color. The rocks of the Stockton are characterized by their high arkose content. The Stockton Formation includes interbedded sandstone, arkose, arkosic sandstone, arkosic conglomerate, siltstone, and shale. Conglomerates are much more abundant in the lower half of the formation than in the upper half, and fine-grained sandstones are more abundant in the upper half of the formation than in the lower half. Arkose is abundant everywhere in the formation, except for the uppermost few hundred feet. The rocks contain channels, ripple marks, mudcracks, crossbeds, lenses, pinch-and-swell structures, and minor burrows. Rapid lithologic changes are characteristic of the Stockton Formation. Single beds may grade along strike from fine grained to coarse grained in a few yards (Willard and others, 1959, p. 65).

The coarser sediments consist of light to medium gray and light yellowish-gray to pale reddish-brown, thin- to thick-bedded, fine- to coarse-grained sandstone, arkose, and arkosic conglomerate with pebbles of quartzite, feldspar, shale, limestone, and metamorphic rock locally more than 3 in. long. The grayish-red to reddish-brown, thin- to thick-bedded, very fine- to medium-grained, arkosic sandstone generally is fining upward with abrupt lateral lithic changes (Lyttle and Epstein, 1987).

Some conglomerate units are extensive enough to be mapped separately (Willard and others, 1959). The units are gray and buff, thick-bedded to crudely bedded, arkosic conglomerate and arkose with subangular to rounded pebbles of quartz, quartzite, limestone, and underlying basement rocks as much as 3 in. long in a red, arkosic, sandy to silty shale matrix. Conglomerate units average about 320 ft thick (Lyttle and Epstein, 1987).

The siltstone and shale are grayish-red to moderate reddish-brown, and light to medium gray and are bioturbated by roots and burrows. Purplish siltstone present near the middle and top of the formation usually is densely penetrated by roots, but rarely penetrated by burrows. A few thin beds of well-bedded, gray and gray-green, fossiliferous siltstone and dark, greenish or gray to black shale are present locally in the upper part of the Stockton. Siltstones and shales are fairly weak, slightly sandy, and usually micaceous. Ripple marks and mudcracks are common.

Some black siltstone beds in the Stockton Formation may contain anomalously high concentrations of uranium that correlate with high total organic carbon and sulfur content. Uranium was precipitated at or near the sediment-water interface during deposition of lake-bottom sediments in a reducing environment (Turner-Peterson and others, 1985). Turner-Peterson and others (1985, p. 120) reported a shaley, black mudstone containing lacustrine fossils in the Stockton Formation near the Delaware River that contained 0.29 percent uranium oxide, which is considered to be ore grade.

The Stockton Formation grades into the Lockatong Formation. Olson (1980a, p. 8) places the Stockton-Lockatong boundary at the base of the lowest continuous black siltstone bed. The Stockton also laterally interfingers with the Lockatong.

Lockatong Formation

The Lockatong Formation of Upper Triassic age is 90 mi long, 25 mi wide, and 3,500 ft thick. Lockatong sediments, chiefly from the southeast, were deposited in a large, shallow, thermally stratified, alkaline lake. The Lockatong predominantly consists of laminated to thick-bedded, gray and black siltstone and shale. Climate variations were a major control on lacustrine deposits, producing small-scale detrital and chemical-lacustrine cycles, which were first recognized by Van Houten (1962). The detrital cycles average 17.1 ft thick and consist of laminated, medium dark gray to black, calcareous, pyritic siltstone and shale in the lower part of the cycle overlain by platy to massive, disrupted (mudcracked and burrowed), dark gray, calcareous siltstone, ripple-bedded siltstone, and fine-grained sandstone. The chemical-lacustrine cycles average 10.5 ft thick and consist of platy, medium dark gray to black, dolomitic siltstone and marlstone with shrinkage cracks and lenses of pyritic limestone in the lower part overlain by massive, gray or red, analcime- and carbonate-rich, disrupted siltstone.

Van Houten cycles were apparently produced by the rise and fall of a very large lake that corresponded to periodic climate changes controlled by variations in the earth's orbit (Van Houten, 1962; Olsen, 1984, 1986). Chemical cycles accumulated when the lake was low and had no outlet; chemical constituents from a deeply weathered source area were concentrated and precipitated in the lake. Detrital cycles accumulated when the lake level was high during wetter periods that maintained a through-flowing drainage, which carried most of the soluble material to the ocean (Van Houten, 1964). Each Van Houten cycle consists of three divisions interpreted by Olsen (1980b, p. 352) as lake transgression (division 1), high stand (division 2), and regression plus low stand (division 3) facies. Features, such as mudcracks, burrows, and root disruptions indicate that lake levels were substantially reduced during drier periods, and, in some instances, the lake may have been completely dry. Smoot and Olsen (1985) interpret such features as representing a playa floor.

Some black siltstone beds in the Lockatong Formation may contain anomalously high concentrations of uranium. Turner-Peterson and others (1985) correlate uraniferous zones with division 2 Van Houten cycles, which are characterized by a high organic carbon content (Olsen, 1984). Division 2 sediments may contain as much as 20 percent total organic carbon (Olsen, 1985, p. 61).

Shales and siltstones surrounding diabase have been thermally metamorphosed to a purplish-red, light gray, and dark gray, indurated, brittle, and fine-grained hornfels in a zone averaging about 2,000 ft wide (Lyttle and Epstein, 1987). Hematite in the shale has been reduced to magnetite, giving it a dark color.

The lower beds of the Lockatong Formation (Lyttle and Epstein, 1987) in Plumstead and Wrightstown Townships are mapped as a separate unit (pl. 1); they contain interbedded, reddish-brown, sandy siltstone units about 10 to 270 ft thick. These lower beds previously were mapped as thin beds of the Brunswick Group that interfingered with the Lockatong (Willard and others, 1959).

The Lockatong interfingers laterally with and grades upward into the lower part of the Brunswick Group. The lower contact of the Lockatong with the Stockton Formation is gradational, and the Lockatong laterally interfingers with the Stockton. The thickness of the Lockatong at the Delaware River is about 3,900 ft (Willard and others, 1959, p. 85).

Brunswick Group

Rocks of the lower part of the Brunswick Group of Mesozoic age are exposed in the northern part of the study area. These rocks are the Brunswick Formation of Bascom and others (1931) and Willard and others (1959). Olsen (1980c) elevated the Brunswick Formation to the Brunswick Group and subdivided it into seven units in New Jersey. In Pennsylvania, Lyttle and Epstein (1987) divided the Brunswick Group into three parts—the lower part, the Jacksonwald Basalt (not present in the study area), and the upper part (not present in the study area). The lower part of the Brunswick Group in the study area is equivalent to the Passaic Formation of Olsen (1980c) in New Jersey. Part of the Brunswick Group in Pennsylvania has been subdivided into members by McLaughlin (1933), Johnson and McLaughlin (1957), and Drake and others (1961). Those subdivisions are not used in this report.

The lower part of the Brunswick Group is predominantly homogeneous, soft, red to reddish-brown and gray to greenish-gray mudstones and clay- and mud-shales that crumble easily into hackly fragments. The bedding is irregular and wavy. Some beds are micaceous. Interbedded silt-shales and siltstones are fairly well sorted. Fine-grained sandstone and conglomerate are present in the upper part of the formation near the northern border. Mudcracks, ripple marks, crossbeds, and burrows are common in all of the beds (Drake and others, 1967).

The Brunswick contains detrital cycles of medium to dark gray and olive to greenish-gray, thin-bedded and evenly bedded shale and siltstone, similar to the underlying Lockatong Formation (Lyttle and Epstein, 1987). The cyclic units are not as continuous as those in the Lockatong Formation. Higher in the formation, the gray beds are softer and are largely mud- and silt-shale and siltstone.

Shales and siltstones surrounding diabase have been thermally metamorphosed to a purplish-red, light gray, and dark gray, indurated, brittle, fine-grained hornfels in a zone averaging about 2,000 ft wide. The transition across this zone from a soft, red shale to a dark, tough hornfels is gradual. The hornfels closely resembles the Lockatong Formation.

West and southwest of the Coffman Hill diabase sheet, thin beds previously mapped as the Lockatong Formation (Willard and others, 1959) interbedded with the Brunswick Group are now considered the lower beds of the Brunswick Group (Lyttle and Epstein, 1987). The lower contact of the Brunswick Group with the Lockatong Formation is gradational over about 1,640 ft (Lyttle and Epstein, 1987). The lower contact of the Brunswick is either conformable and gradational to older rocks of the Newark Supergroup or is unconformable on basement rocks. The Brunswick also interfingers laterally with the Lockatong Formation. The boundary between the Brunswick and the Lockatong generally is placed where the thickness of red beds is dominant over the thickness of gray and black beds, both horizontally and vertically. Drake and others (1967) estimated that the Brunswick in northern Bucks County is about 3,420 ft thick.

Limestone Conglomerate

Two areas of limestone conglomerate have been mapped at the northern border of the Newark Basin in Springfield Township (pl. 1). These rocks were considered a limestone fanglomerate facies of the Brunswick Formation by Willard and others (1959, p. 95-96), but they are not considered part of the Brunswick Group by Lyttle and Epstein (1987) or in this report. The limestone conglomerate consists of subangular, medium to dark medium gray limestone and dolomite clasts as much as 3.3 ft in diameter (derived from limestone and dolomite of Cambrian and Ordovician age in the immediate area) and rare gneiss pebbles and cobbles in a matrix of red, partly arkosic sandstone and siltstone. The conglomerate generally becomes finer grained toward the south (Lyttle and Epstein, 1987).

Quartzite Conglomerate

Three areas of quartzite conglomerate have been mapped along the northern border of the Newark Basin in Springfield and Nockamixon Townships (pl. 1). These rocks were considered a quartzite fanglomerate facies of the Brunswick Formation by Willard and others (1959, p. 95) and Drake and others (1967), but they are not considered part of the Brunswick Group by Lyttle and Epstein (1987) or in this report. The quartzite conglomerate consists of rounded pebbles, cobbles, and boulders, as much as 1 ft long, of white, light-gray, and reddish quartzite, and lesser calcareous sandstone in a matrix of red, partly arkosic siltstone. The source of the clasts is rocks of Silurian age to the north. The conglomerate generally becomes finer grained toward the south and grades into the Brunswick Group. The quartzite conglomerate is about 1,000 ft thick (Willard and others, 1959, p, 95).

Diabase

Several diabase intrusions of early Jurassic age are exposed in northern Bucks County. The diabase is a dark-gray to black, fine- to coarse-grained, crystalline rock composed largely of calcic plagioclase and augite. Near the chilled margins, the diabase is very fine- to fine-grained. Diabase intruded under high temperature and low pressure into rocks of pre-Jurassic age. The diabase has been exposed by weathering of the softer intruded rocks. Diabase sheets in northern Bucks County generally form prominent hills and are discordant sheets with oval or ring-like outcrop patterns (Hotz, 1952; Froelich and Gottfried, 1985). Diabase dikes also are present.

Diabase sheets exposed in northern Bucks County include the Coffman Hill sheet, the Haycock sheet, and the Point Pleasant sheet (fig. 3). The Coffman Hill sheet is about 3.8 mi wide and 5 mi long in Bridgeton, Tinicum, and Nockamixon Townships.

The thickness of the Coffman Hill diabase sheet was measured at four places (fig. 3) by use of natural-gamma borehole geophysical logs. Diabase contains few gamma-emitting minerals and is characterized by low natural-gamma emissions. The underlying hornfels contains gamma-emitting minerals and is characterized by much higher natural-gamma emissions than the diabase. The natural-gamma log for well BK-1554 shows that the contact between the diabase and the underlying hornfels is at 300 ft below land surface. The contact between diabase and hornfels is difficult to locate from drill cuttings. Driller's logs are not reliable indicators of the thickness of the diabase; the driller's log for well BK-1554, for example, placed the contact 118 ft lower than the actual contact. Thickness of the diabase determined by natural-gamma logs was 81 ft (well BK-2202) near the eastern edge, 300 ft (well BK-1554) and 568 ft (well BK-2347) near the center, and 114 ft (well BK-1498) at the western edge of the Coffman Hill sheet.

Alluvium and Glacial Outwash

Deposits of alluvium and glacial outwash are present adjacent to the Delaware River. These unconsolidated deposits are not differentiated in this report. The alluvium consists of deposits of clay, silt, sand, and gravel along streams. The glacial outwash deposits consist of stratified sand and gravel of glacial-fluvio origin, probably of Wisconsin age; they may include remnants of glacial deposits older than Wisconsin (Drake and others, 1967). The deposits thin from 205 ft thick (well BK-981 in Riegelsville Borough) in the north to 34 ft thick at Washington's Crossing in the south.

HYDROLOGY

All hydrogeologic units in northern Bucks County are considered to be aquifers. The terms hydrogeologic unit and aquifer are used interchangeably in this report. The hydrogeologic units are sometimes referred to as "bedrock aquifers." Nearly all wells have casing set into the upper few feet of unweathered rock and are completed as open-hole wells. A less-permeable overlying hydrogeologic unit or bed within a hydrogeologic unit may be considered locally as a confining unit. Diabase sheets act as confining units for the underlying sedimentary rocks.

Relation of Geology to Ground-Water Flow

The hydrogeologic units of northern Bucks County are combined into five general groups on the basis of similarity in ground-water-flow systems: (1) unconsolidated sediments, (2) diabase, (3) Triassic sedimentary rocks (sandstone, shale, and conglomerate), (4) carbonate rocks (limestone and dolomite), and (5) crystalline and metamorphosed sedimentary rocks (quartzite, phyllite, schist, and gneiss). Characteristics of the ground-water-flow system, as well as aquifer hydraulic properties, are related to geology. Flow systems of each group differ from each other.

Unconsolidated Sediments

Unconsolidated sediments, averaging about 35 ft thick (Drake and others, 1961), are located adjacent to the Delaware River. Only 3 percent of the study area is underlain by unconsolidated sediments. Most wells drilled into the sediments along the Delaware River case off the sediments and derive water from the underlying bedrock aquifers. Only a few wells tap the unconsolidated sediments. Unconsolidated deposits have primary porosity, and ground water moves through the pore spaces between the grains. Because of the high porosity and permeability of these sediments, especially the coarser-grained sediments, high well yields are possible. However, the porous nature of the sediments also makes them highly susceptible to ground-water contamination.

Ground water in the unconsolidated sediments is under unconfined conditions. In unconfined or water-table conditions, the water table is a free surface in contact with the atmosphere through pore spaces in the unsaturated zone. The water table, which is the upper surface of the saturation zone, rises and falls in response to recharge and discharge from the aquifer. Because of the high porosity of the unconsolidated sediments and their close proximity to the Delaware River, they are in direct hydraulic contact with the river. Pumping water from these sediments could readily cause streamflow to enter the aquifer.

Diabase

Diabase sheets form prominent hills that cap underlying sedimentary rock. Twelve percent of the study area is underlain by diabase. Diabase is massive and weathers to large, spheroidal boulders. Diabase boulders weather to a buff-colored, granular sand. The sand, in turn, breaks down into a sticky, red, montmorillonite-type swelling clay. The land is unsuitable for agriculture and is largely wooded. The depth of weathering, on the basis of the median casing length of 65 wells drilled in diabase, is about 30 ft. Diabase has no primary porosity, and the depth of fracturing rarely exceeds 100 to 150 ft. Therefore, all ground-water flow is through fractures, and nearly all ground-water storage is in the upper weathered zone. Where the weathered zone is absent, little ground-water storage is available.

Water-bearing and ground-water flow characteristics of diabase are similar to that of crystalline rocks, but diabase is not as fractured and does not have the thick weathered zone frequently associated with crystalline rocks. The reasons for this are (1) diabase is younger than the crystalline rocks and has not been subjected to the intense folding and faulting that produced the fracturing of the crystalline rocks; (2) diabase sheets are more resistant to weathering and stand topographically higher than the more easily eroded adjacent rocks, thus undergoing less weathering by circulating ground water; and (3) surface runoff is greater from diabase ridges than the surrounding rocks, probably because of the clay-rich soil, and there is less chance for recharge (Kasabach, 1966, p. 36).

Many wells drilled into diabase penetrate underlying hydrogeologic units, and these wells may derive some or all of their water from the underlying units. The potentiometric surface map of McManus and Rowland (1993) shows the potentiometric surface in the Coffman Hill diabase sheet (labeled as the upper aquifer system) and in the underlying sedimentary rocks (labeled as the lower aquifer system). Shallow wells completed in diabase derive water only from diabase. Deeper wells, which yield little or no water from diabase, penetrate the underlying sedimentary rocks. Away from the edge of the diabase sheets, little or no hydraulic connection exists between the diabase and the underlying sedimentary rocks.

Borehole geophysical logs were run in four wells in diabase on the Coffman Hill sheet (fig. 3). All four wells penetrate and derive water from the underlying formations. A borehole television survey run in well BK-1498 showed a small quantity of water entering the well from fractures in the diabase at 45 ft below land surface (just below the casing) and trickling down the borehole to the water-level surface at 124.6 ft below land surface in the underlying Brunswick Group.

Figure 5 shows the caliper and natural-gamma logs from well BK-2202. The natural-gamma log shows the contact between the diabase and the underlying Brunswick Group at 81 ft below land surface. The water level in the well, 104 ft below land surface, is in the Brunswick Group. Well BK-2202 obtains water from a fracture at 126 ft below land surface in the Brunswick Group.

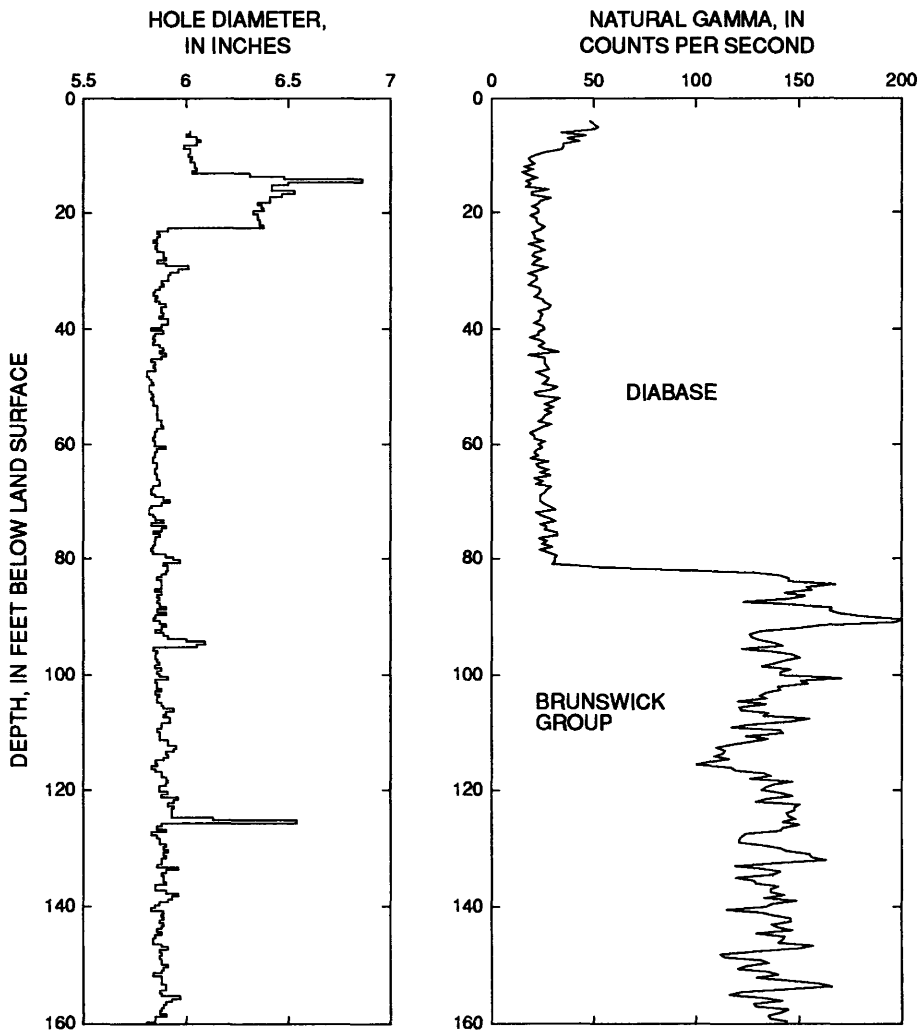


Figure 5. Caliper and natural-gamma logs of well BK-2202, Bridgetown Township, northern Bucks County.

Triassic Sedimentary Rocks

Sedimentary rocks of Triassic age crop out over 74 percent of northern Bucks County. The principal formations are the Brunswick Group, the Lockatong Formation, and the Stockton Formation.

In the Triassic sedimentary rocks, ground water in the weathered zone moves through intergranular openings that have formed as a result of weathering. In some places, permeability of the weathered zone may be poor because of a high percentage of clay derived from weathering of siltstone and mudstone. Ground water in the unweathered zone moves through a network of interconnecting secondary openings—fractures, bedding planes, and joints. Beds within a formation are hydraulically connected by vertical joints that cross each other at various angles throughout the beds. Some water-bearing openings may be slightly enlarged by circulating ground water that has decomposed and disintegrated mineral constituents in the walls of fractures. Primary porosity that may have originally existed has been almost eliminated by compaction and cementation. Some water may move through intergranular openings in the rock below the weathered zone where the cement has been removed and the permeability has increased, but this generally is restricted to a few sandstone and conglomerate beds.

The ground-water system can be visualized as a series of sedimentary beds with a relatively high transmissivity separated by beds with a relatively low transmissivity. The beds, a few inches to a few feet thick, act as a series of alternating aquifers and confining or semiconfining units that form a leaky, multiaquifer system. Each bed generally has different hydraulic properties, and permeability commonly differs from one bed to another. Soft shale beds deform without breaking under stress and, as a result, have lower permeability than the harder sandstone beds, which tend to develop fractures and joints and are more permeable. Thick, hard, competent sandstone beds develop fewer joints than thin sandstone beds (Wood, 1980, p. 16) and bedding planes are widely spaced; therefore, they are less permeable.

Ground water is unconfined in the shallower part of the aquifer and confined or semiconfined in the deeper part of the aquifer. Under confined conditions, ground water is confined under pressure greater than atmospheric by less permeable beds or hydrogeologic units and is not free to rise and fall. Differences in vertical hydraulic conductivity within and among hydrogeologic units create confining conditions. The water level in a well constructed in a confined aquifer rises above the top of the aquifer. The imaginary surface to which water will rise in wells tightly cased in a confined aquifer is the potentiometric surface. If the potentiometric surface is above the land surface, the well will flow.

Most deep wells are open to several water-bearing zones and are multiaquifer wells. Some wells may be open to more than one hydrogeologic unit. Each water-bearing zone usually has a different hydraulic head. The hydraulic head in a deep well is the composite of the heads in the several water-bearing zones penetrated. This can cause water levels in some wells to be different than water levels in adjacent wells of different depths. If the composite head is below the uppermost water-bearing zone or zones, water from these zones will drain into the well and cascade down the borehole to the water surface.

Where differences in hydraulic head exist between water-bearing zones, water in the well bore flows under nonpumping conditions in the direction of decreasing head. Flow from an upper zone of higher head to a lower zone of lower head can result in a cone of depression forming around the well under nonpumping conditions and can locally lower water levels.

The ground-water-flow system in Triassic sedimentary rocks is highly anisotropic with the predominant flow direction in the direction of strike (Vecchioli and others, 1969, p. 154). The network of interconnected water-bearing openings is more or less continuous along strike, but the continuity of individual beds downdip is limited because fractures are closed by compression or absent with depth. Because of anisotropy, wells aligned parallel to strike generally show more interference than wells aligned perpendicular to strike. Drawdown in wells aligned along strike may be many times greater than in wells aligned in other directions (Vecchioli and others, 1969, p. 157). Wells drilled to the same depth along strike generally penetrate the same water-bearing beds, whereas wells drilled to the same depth several hundred feet downdip of each other rarely intersect the same water-bearing beds (fig. 6). Therefore, the potential for well interference caused by pumping is greater in wells along strike than in wells in the direction of dip. In the anisotropic Triassic formations, cones of depression are usually elliptical, with the long axis aligned parallel to strike.

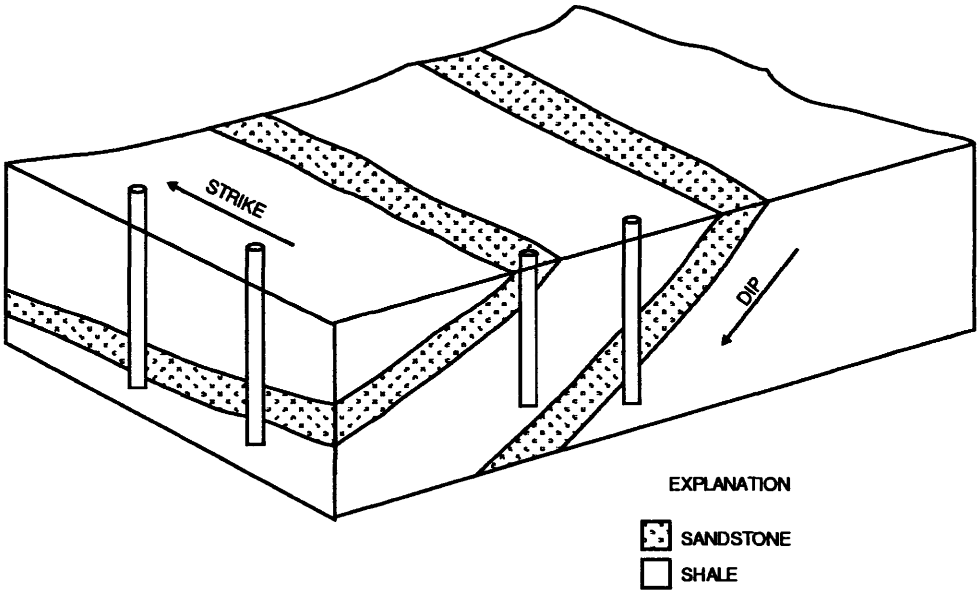


Figure 6. Wells tapping sedimentary rocks of Triassic age. (Modified from Biesecker and others, 1986.)

In the anisotropic systems of the Newark Basin, ground-water flow is not necessarily perpendicular to lines of equal hydraulic head, but may be skewed in the direction of strike (Lewis, 1992, p. 96). Because the beds dip and because fractures are absent or closed at depths greater than a few hundred feet, ground water flows preferentially along strike, even in places where the cross-strike hydraulic gradient is substantial.

Ground-water flow in the Triassic sedimentary rocks has local and regional components. Shallow ground water discharges locally to nearby streams. Deeper, regional ground-water flow is toward points of regional ground-water discharge, such as the Delaware River. Ground-water divides may be different for each zone of ground-water flow, and may not coincide with surface-water divides. Ground-water-flow directions may be different for each zone. For example, the potentiometric surface map of McManus and Rowland (1993) shows that in the area northeast of Bucksville in Nockamixon Township, ground water in the shallow part of the aquifer system flows S. 60° E., assuming flow is perpendicular to equipotential lines. At the same point in the deeper part of the aquifer system, ground water flows S. 35° W., assuming flow is perpendicular to equipotential lines.

Brunswick Group

Rocks of the Brunswick Group underlie 39 percent of the study area. The Brunswick is highly fractured and has many closely spaced joints, which accounts for the relatively high well yields from a shale and siltstone formation. Bedding plane openings may extend to 300 ft below land surface (Kasabach, 1966, p. 33). However, the upper part of the weathered zone, although more fractured than the lower part, may be less permeable than the lower part because the fractures may be clogged with clay derived from weathered shale and siltstone.

Borehole geophysical logs were run in 13 wells at 7 sites in the Brunswick Group; 2 of the wells are completed in the lower beds, and 1 well is completed in hornfels. A borehole television survey was run in well BK-1343. Borehole-flow measurements were made in seven wells at six sites; measurable borehole flow was observed in only three wells. In well BK-2205, upward flow of 3.9 and 2.6 gal/min was measured at 140 and 190 ft below land surface, respectively (fig. 7). Water enters the well through water-producing fractures at 205 and 167 ft below land surface and flows upward to a water-receiving fracture at 94 ft below land surface where it exits the well. Measurable borehole flow was not observed in two nearby wells of the same depth (BK-2206 and BK-2207) at the same site.

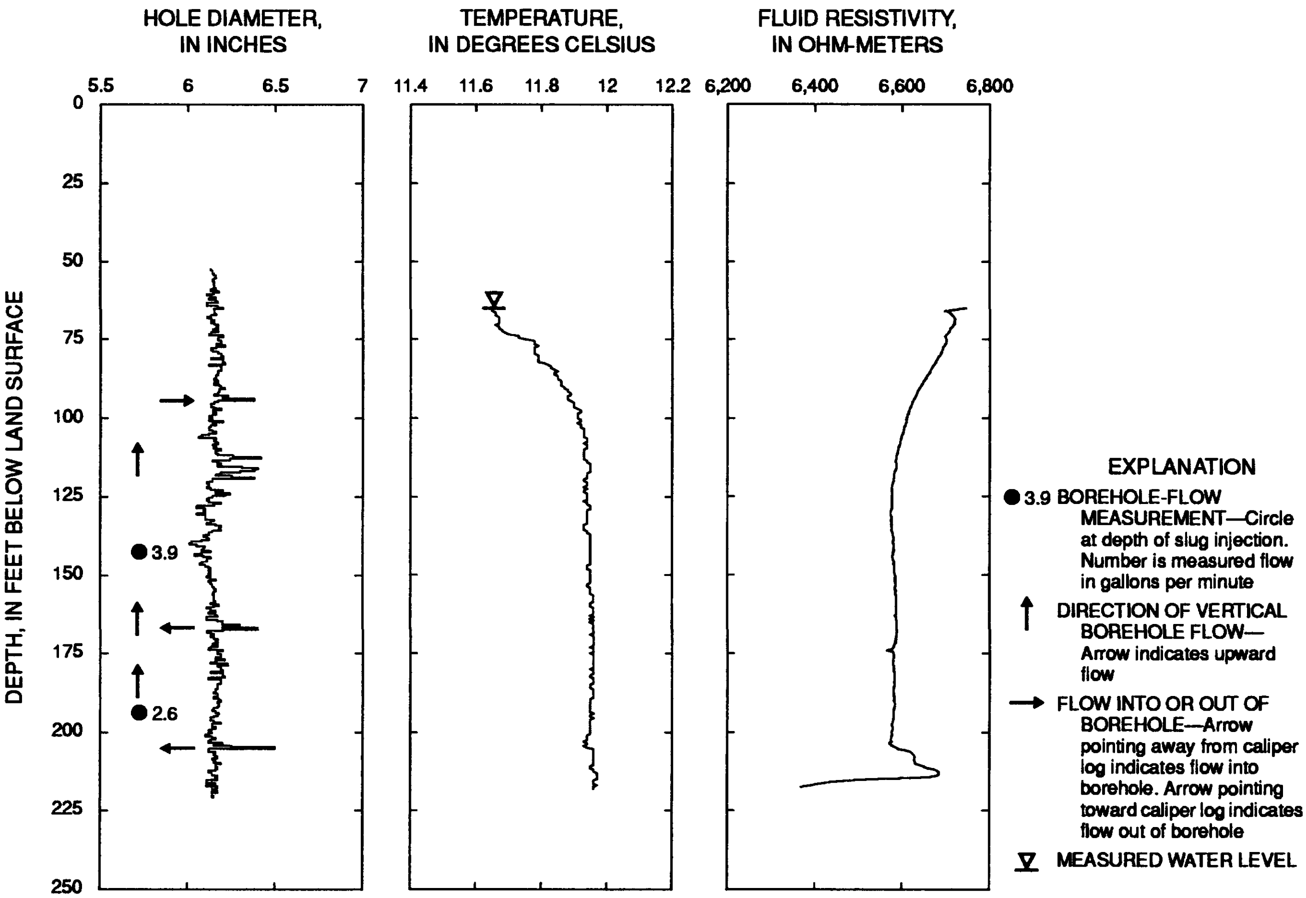


Figure 7. Caliper, fluid-temperature, and fluid-resistivity logs of well BK-2205, Solebury Township, northern Bucks County.

Downward borehole flow was measured in two wells in the lower beds of the Brunswick Group. Wells BK-1493 and BK-1556, which are located 0.6 mi apart along strike, penetrate the same beds. The beds penetrated from 28 to 222 ft below land surface by well BK-1556 are the same beds penetrated from 55 to 249 ft below land surface by well BK-1493. In the lower beds of the Brunswick Group, individual beds may be laterally continuous for some distance. Natural-gamma borehole geophysical logs can be used to correlate lithology. On the basis of the natural-gamma logs, the correlation between beds penetrated by wells BK-1493 and BK-1556, labeled bed "A" and bed "B" is shown on figure 8. The geophysical logs also show that fractures, water-producing zones, and water-receiving zones are not found in the same beds penetrated by both wells. Water enters well BK-1493 through a water-producing fracture at 141.5 ft below land surface and flows downward at 1 gal/min to a water-receiving fracture at 196-203 ft below land surface where it exits the well (fig. 8). Water enters well BK-1556 through a water-producing fracture at 66 ft below land surface, which is above the water surface in the well. The water cascades down the well bore to the water surface at 101 ft below land surface and then flows downward at 0.7 gal/min to a water-receiving fracture at 314 ft below land surface where it exits the well (fig. 8).

The borehole television survey of well BK-1343 showed that most of the fractures intersected by the well above 60 ft below land surface are horizontal (openings along the plane of bedding within a lithologic unit or between lithologic units), and most of the fractures intersected by the well below 60 ft below land surface (fig. 9) are vertical or steeply dipping (joints within a lithologic unit). The major water-bearing zone (25 gal/min) penetrated by well BK-1343 is the intersection of two vertical fractures at 137-138 ft below land surface (fig. 9).

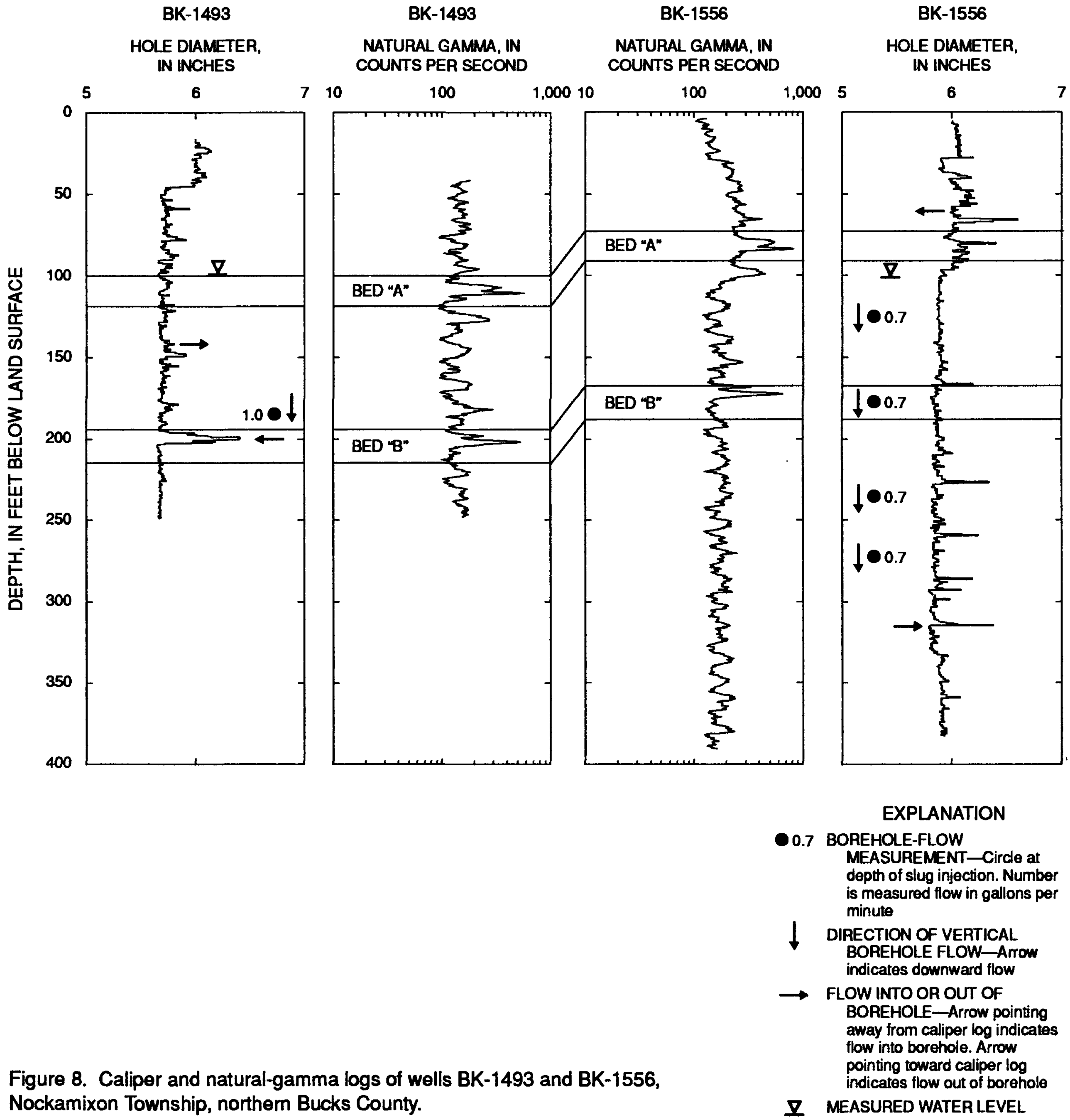
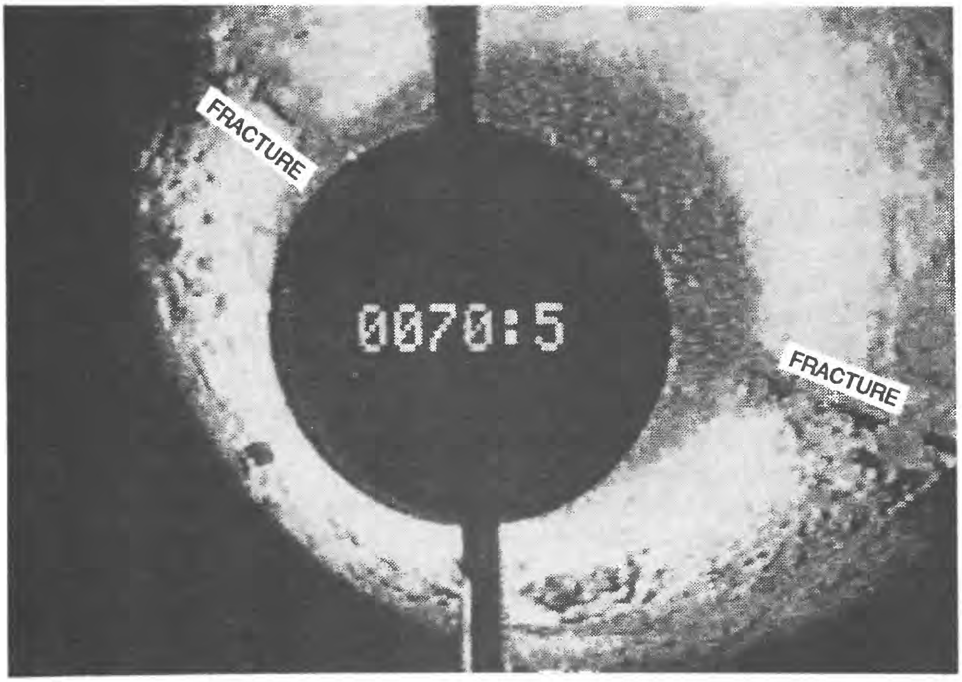


Figure 8. Caliper and natural-gamma logs of wells BK-1493 and BK-1556, Nockamixon Township, northern Bucks County.

Lockatong Formation

Rocks of the Lockatong Formation underlie 17 percent of the study area. The Lockatong Formation has no primary porosity or permeability. All ground water moves through fractures and joints that generally are widely spaced, relatively tight, and poorly interconnected, which accounts for the relatively low well yields in the Lockatong. The Lockatong weathers to a dense, clayey soil that plugs fractures and joints in the weathered zone and commonly causes ground water to be confined. Plugging of openings by clay impedes recharge; to a lesser extent, recharge also is impeded by the generally higher elevations of the Lockatong Formation.



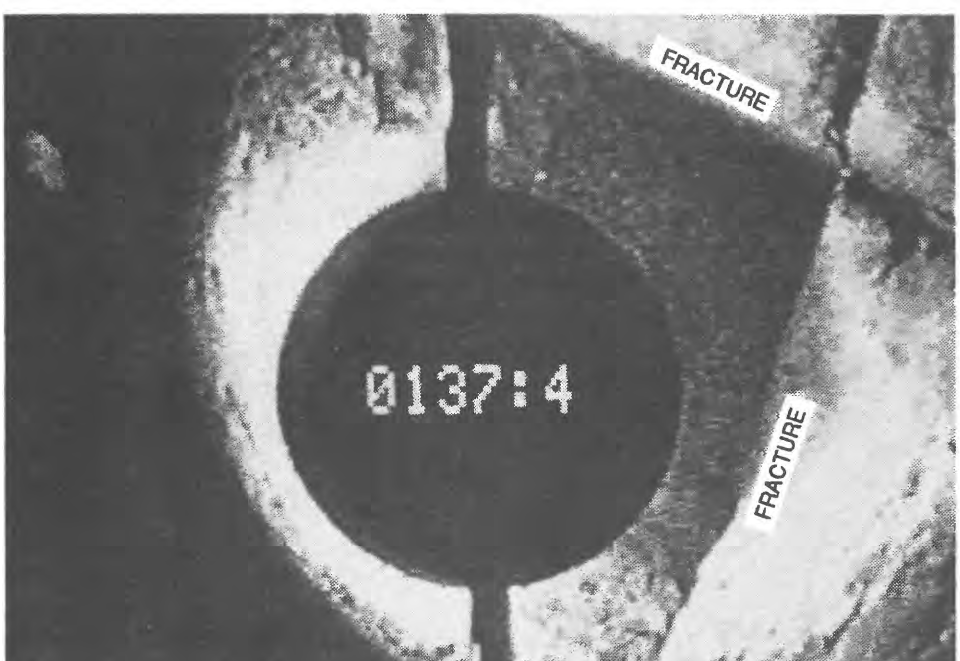


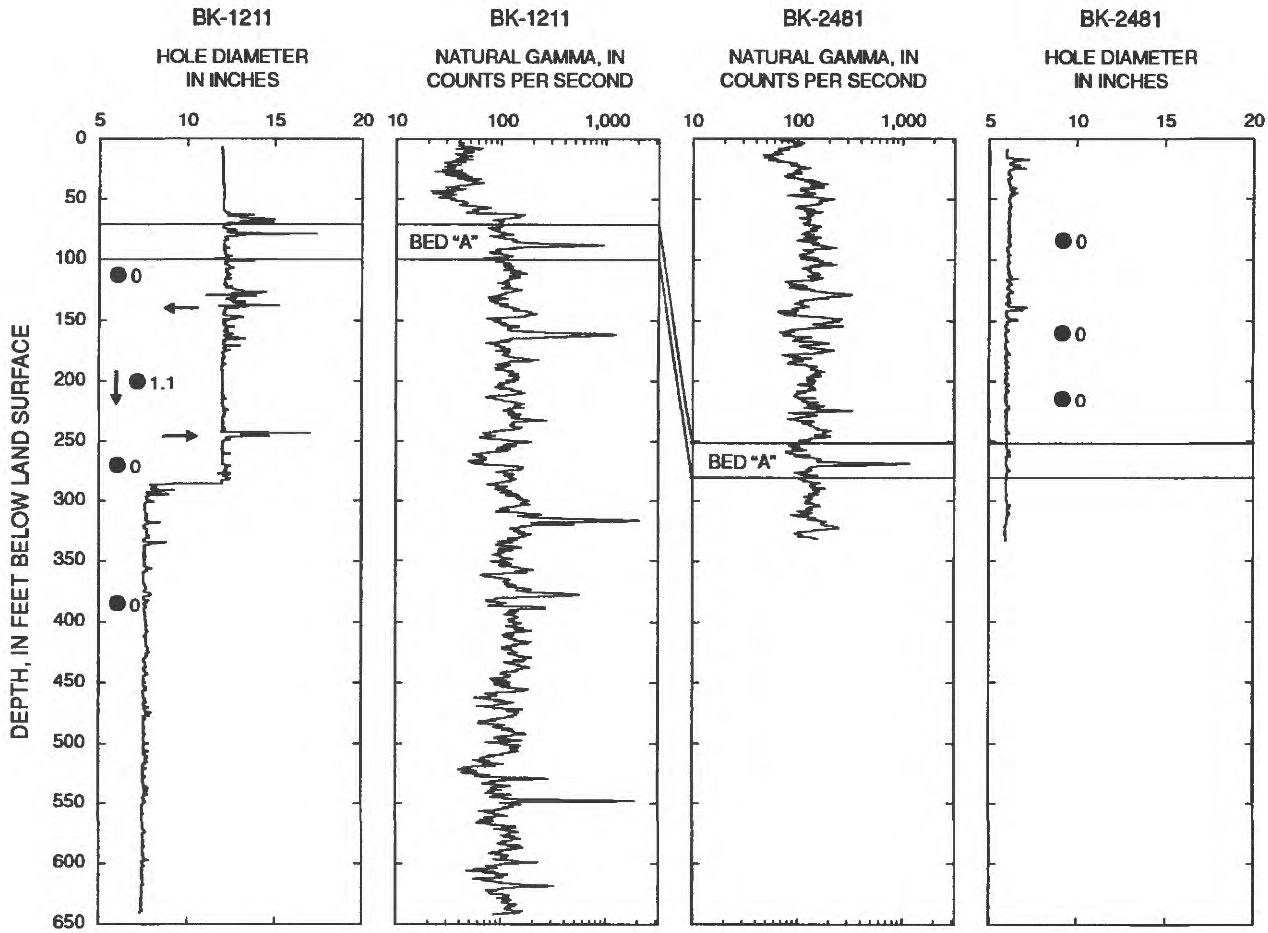
Figure 9. Borehole television survey showing fractures penetrated by well BK-1343, Buckingham Township, northern Bucks County. Numbers are depth below land surface, in feet.

Borehole geophysical logs were run in 18 wells at 6 sites in the Lockatong Formation. Well BK-1303 is in an area mapped as the Stockton Formation, but the natural-gamma log indicates that most of the borehole penetrates the Lockatong Formation. Eight of the logged wells were flowing. Borehole television surveys were run in wells BK-1211, BK-1347, and BK-2481. Borehole-flow measurements were made in seven nonflowing wells and six flowing wells. In the seven nonflowing wells, measurable borehole flow was observed in two wells (BK-1211 and BK-1483).

The same beds may not be fractured in adjacent wells. Well BK-1211 is an unused public-supply well, and well BK-2481 is an observation well drilled approximately 300 ft downdip of well BK-1211. The caliper log from well BK-1211 shows that it is drilled into highly fractured beds that are not fractured where they are penetrated by well BK-2481 (fig. 10). The peak at 88.5 ft below land surface on the natural-gamma log of well BK-1211 (fig. 10) can be correlated with the peak at 269.5 ft below land surface on the natural-gamma log of well BK-2481; these are labeled as bed "A" on figure 10. Assuming a local dip of 14° (Willard and others, 1959) and an estimated 7-ft difference in land-surface elevation, these peaks should be offset 82 ft, rather than the 185 ft shown by the natural-gamma logs. BK-1211 probably is drilled into an unmapped fault that offsets the beds between the two wells by 103 ft. The highly fractured beds penetrated by well BK-1211 from 62 ft (bottom of casing) to 149 ft below land surface are the same unfractured beds penetrated by well BK-2481 from 247 to 334 ft below land surface. Well BK-1211 yields 1,000 gal/min and has the highest reported yield of any well drilled in the Lockatong Formation. The yield of well BK-2481 is reported to be very low. Water enters well BK-1211 through a water-producing fracture at 138 ft and flows downward at 1.1 gal/min to a water-receiving fracture at 243 ft where it exits the well. No borehole flow was measurable in well BK-2481 at 80, 160, and 220 ft below land surface.

In the Lockatong Formation, beds may be continuous for great distances; individual beds have been traced for as far as 38 mi (Turner-Peterson and others, 1985, p. 120). Natural-gamma borehole geophysical logs can be used to correlate lithology in the Lockatong Formation. Figure 11 shows the natural-gamma logs from two wells (BK-2094 and BK-1850) located approximately 1 mi apart along strike. The lithology penetrated by both wells can be correlated on the basis of the natural-gamma logs.

The borehole television survey of well BK-1211, which was run to 285 ft below land surface, showed that most of the openings intersected and all of the largest openings were vertical or steeply dipping fractures. The borehole television survey of well BK-2481 also showed that most of the fractures intersected by the well were vertical or steeply dipping fractures. The borehole television survey of well BK-1347 showed that the well penetrated more major horizontal fractures, such as the one shown in figure 12, than vertical or steeply dipping fractures. The major water-bearing zone (68 gal/min) penetrated by the well at 260 ft below land surface is a horizontal fracture.



EXPLANATION

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

↓ DIRECTION OF VERTICAL BOREHOLE FLOW—Arrow indicates upward flow

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

Figure 10. Caliper and natural-gamma logs of wells BK-1211 and BK-2481, Newtown Township, Bucks County.

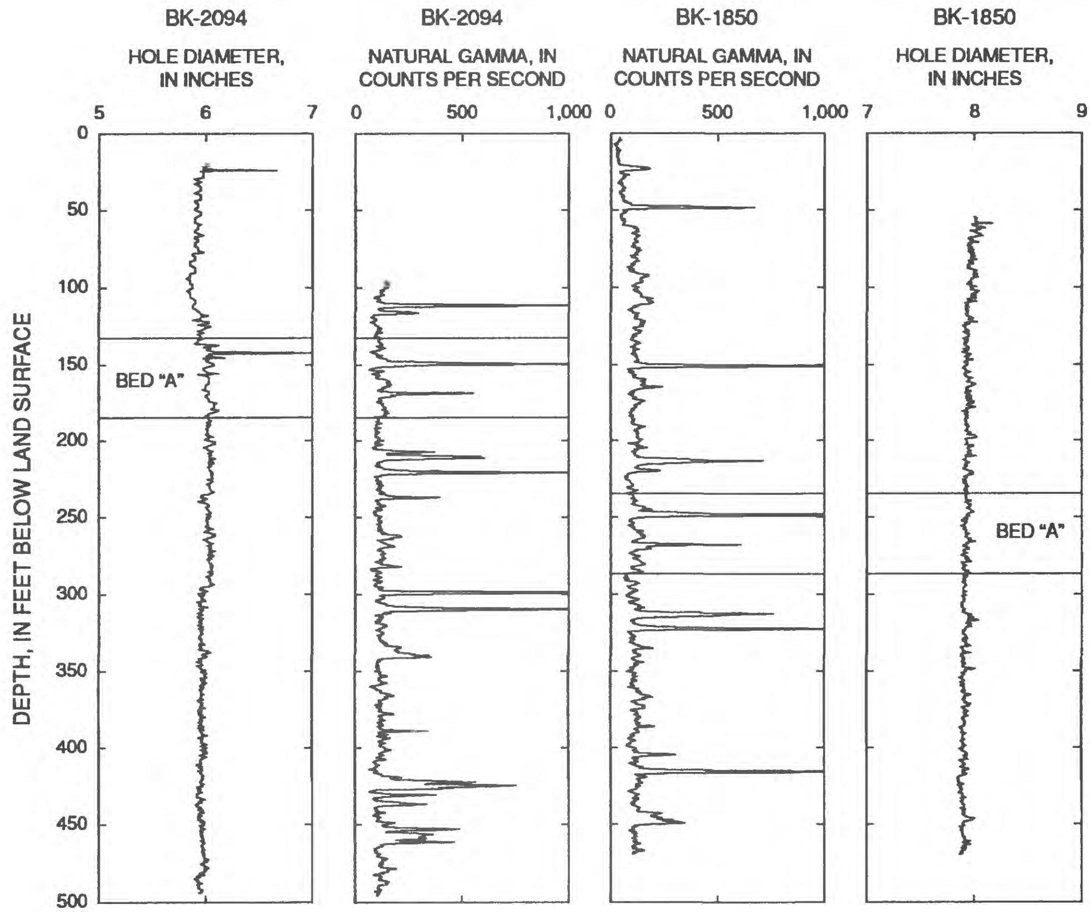


Figure 11. Caliper and natural-gamma logs of wells BK-2094 and BK-1850, Plumstead Township, *northern Bucks County.*

Stockton Formation

The Stockton Formation underlies 15 percent of the study area. In the Stockton, the beds are lens-shaped, overlapping, and discontinuous in all directions along the plane of bedding. The arkosic sandstones and conglomerates of the lower part of the Stockton are poorly cemented and easily fractured, resulting in high transmissivity and high well yields.

Borehole geophysical logs were run in six wells at four sites in the Stockton Formation. Borehole television surveys were run in wells BK-1838 and BK-1847. Well BK-1838 is drilled in the Stockton north of Buckingham Valley and penetrates the underlying carbonate rock. Borehole-flow measurements were made in four wells. Measurable borehole flow was detected in wells BK-1304 and BK-1847. In well BK-1304, downward flow of 2 gal/min was measured at 200 ft below land surface; water enters the well through a water-producing fracture at 120 ft below land surface and flows downward to a water-receiving fracture at 238.5 ft below land surface where it exits the well.

In well BK-1847, downward flows of 4.6, 2.5, and 2.4 gal/min were measured at 150, 300, and 370 ft below land surface, respectively. Water enters the well through a water-producing fracture at 136 ft below land surface and flows downward to water-receiving fractures at 266-269 ft and 503 ft below land surface where it exits the well (fig. 13). The borehole television survey of well BK-1847 showed that the water-producing zone at 136 ft below land surface is a large, horizontal fracture. The water-receiving zones at 266-269 ft and 503 ft below land surface are vertical fractures. The borehole television survey also showed particles falling down the well bore were swirled around by water flowing into the well at 136 ft below

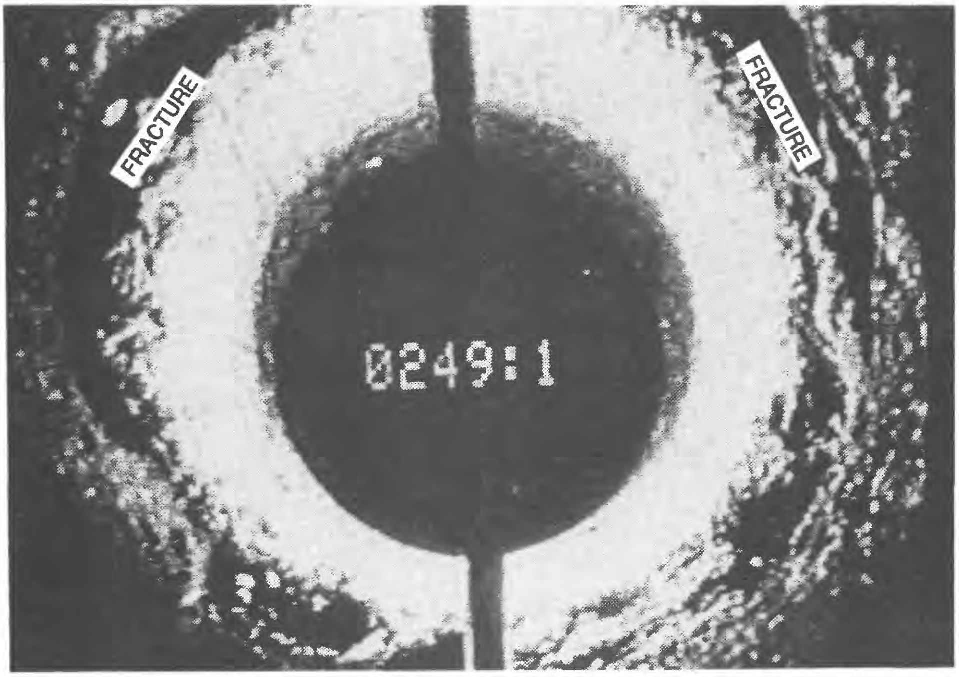


Figure 12. Borehole television survey showing fracture penetrated by well BK-1347, Plumstead Township, northern Bucks County. Number is depth below land surface, in feet.

land surface. Figure 14 shows the water-producing fracture at 136 ft below land surface and the water-receiving fracture at 503 ft below land surface. The fluid-temperature log (fig. 13) shows the low temperature gradient (0.11°C or 0.20°F per 100 ft) associated with zones of borehole flow; the normal geothermal gradient is approximately 0.54°C or 0.97°F per 100 ft (calculated from the fluid-temperature log from a 2,148-ft deep borehole in southern Bucks County).

Some wells in the Stockton Formation north of Buckingham Valley may penetrate the underlying carbonate-rock formations. For example, well BK-1838 penetrates 242 ft of the Stockton Formation, 8 ft of residual clay and paleosol, and 211 ft of carbonate rock. The borehole geophysical logs (fig. 15) indicate that the bottom of the Stockton Formation is at 242 ft below land surface. The natural-gamma log shows a peak at 242-250 ft below land surface that corresponds to the residual clay and paleosol at the top of the carbonate rock. The single-point-resistance log shows a low in resistivity corresponding to the residual clay and paleosol and a higher and more variable resistivity in the carbonate rock than in the Stockton Formation. The borehole television survey of well BK-1838 showed large clasts in the borehole walls in the Stockton Formation, indicating that the lithology is predominantly conglomerate, which generally is the basal lithology of the Stockton. The conglomerate is unfractured and yields no water to the well. The survey confirmed the contact between the Stockton and the residual clay and paleosol at 242 ft below land surface and the contact between the residual clay and paleosol and the carbonate rock at 250 ft below land surface. The paleosol is lithified and is not a conduit for ground-water flow.

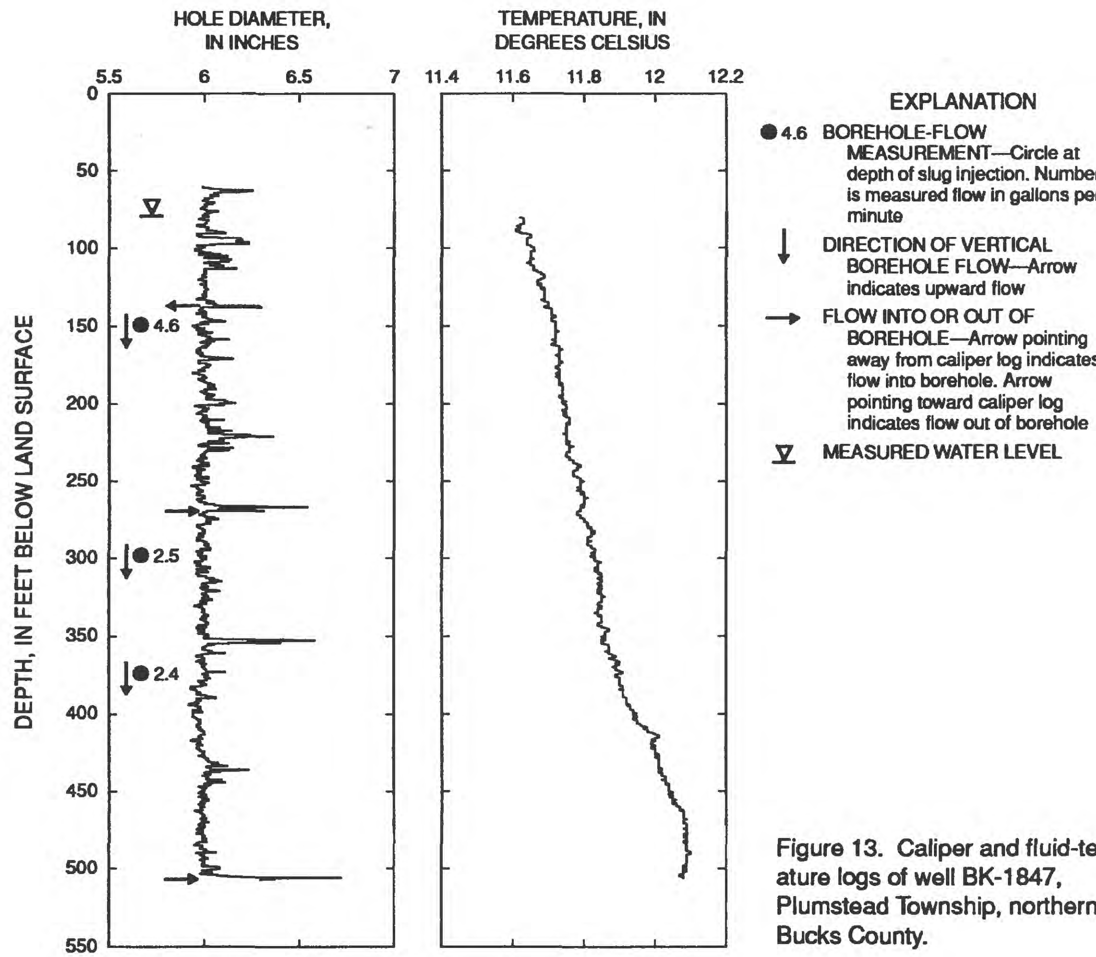


Figure 13. Caliper and fluid-temperature logs of well BK-1847, Plumstead Township, northern Bucks County.

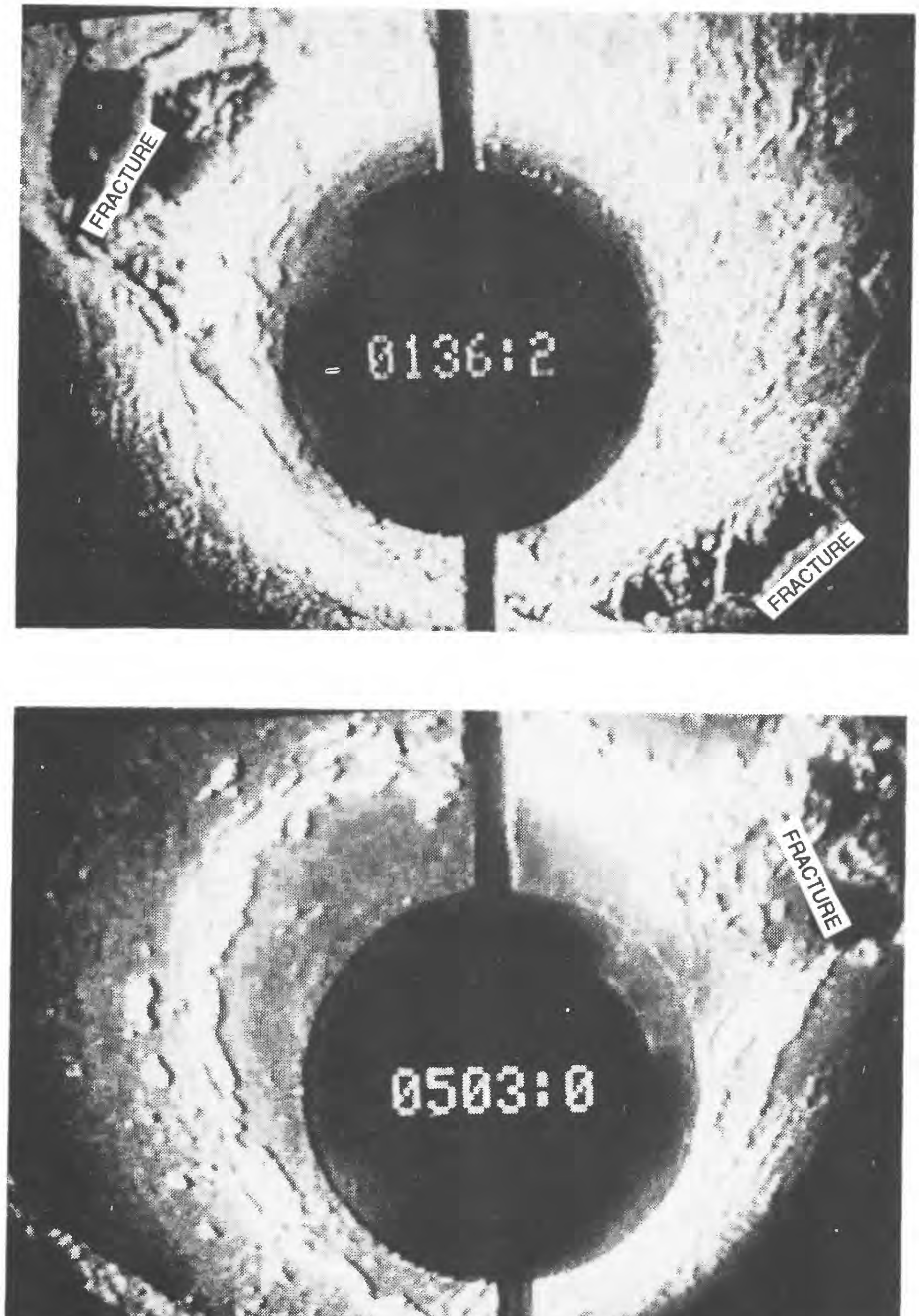


Figure 14. Borehole television survey showing water-producing and water-receiving fractures penetrated by well BK-1847, Plumstead Township, northern Bucks County. Numbers are depth below land surface, in feet. Water-producing zone is 135.2 feet below land surface. Water-receiving zone is 503 feet below land surface.

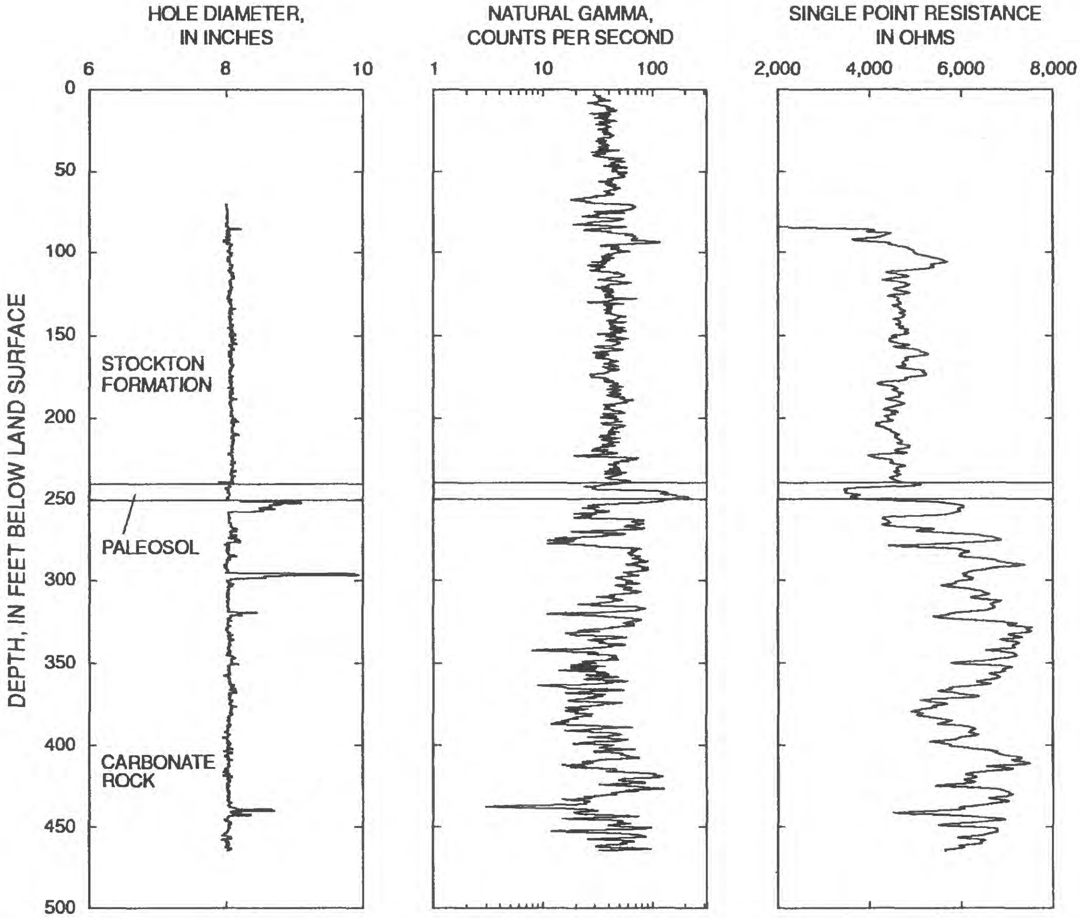


Figure 15. Caliper, natural-gamma, and single-point resistance logs of well BK-1838, Solebury Township, northern Bucks County.

Carbonate Rocks

Four percent of the study area is underlain by carbonate rocks, which crop out in parts of Buckingham and Durham Valleys. The principal formations are the Rickenbach Dolomite, Limeport Formation, Allentown Dolomite, and Leithsville Formation. Most ground water in carbonate rock flows through a network of secondary openings—fractures, joints, and bedding planes—enlarged by solution. Some openings enlarged by solution are several feet wide; however, most are only a fraction of an inch wide, but they are capable of transmitting large quantities of water. The vertical distribution of solution openings is irregular and unpredictable. Adjacent wells may tap different systems of openings in the bedrock.

Permeability of carbonate rock is predominately the result of solution-enlarged fractures. Where solution has been active, permeability may be high; elsewhere, the same unit may be nearly impermeable. Solution is the principle weathering agent of carbonate rocks, which are soluble in acidic water. Solution generally is most active above and within the zone of water-table fluctuation where water movement is relatively rapid and recharge water is acidic. Below the zone of water-table fluctuation, water movement is slower, and acidic recharge water is neutralized. Clay and unconsolidated material sometimes move downward from the surface, plugging openings. This plugging results in decreased well yields and turbid ground-water discharge from some wells.

Borehole geophysical logs were run in five wells at two sites in the Limeport Formation. Borehole television surveys were run in wells BK-1839 and BK-1840 in the Limeport Formation and in well BK-1838, which penetrates carbonate rock at 250 ft below land surface. Borehole-flow measurements were made in wells BK-1838, BK-1840, and BK-2479; no measurable borehole flow was observed.

Figure 16 shows the caliper logs of wells BK-1839 and BK-1840, which are drilled approximately 900 ft apart in the Limeport Formation in Buckingham Valley. Well BK-1839 is drilled into highly fractured rock where the fractures have been enlarged by solution (fig. 17) and yields 178 gal/min. The borehole television survey of well BK-1839 showed that all fractures intersected by the well are vertical fractures. Well BK-1840 is drilled into relatively unfractured rock and is reported to have a very low yield; the major water-bearing fracture was a horizontal fracture encountered at 343.5 ft below land surface (fig. 16).

The borehole television survey of well BK-1838 showed that most of the openings in the carbonate rock are vertical or steeply dipping fractures. Major water-bearing fractures at 294-299, 320, 419, and 439-443 ft below land surface are all vertical or steeply dipping fractures (fig. 18).

Although the ground-water system is generally under unconfined conditions in carbonate rock, confined ground water may be present locally. Confined conditions were observed in well BK-1840; the continuous water level recorded in well BK-1840 shows the effect of earth tides, which is the result of confined conditions. Confining conditions in well BK-1840 are the result of the relatively unfractured rock above the deep major water-bearing fracture (figs. 16) at 343.5 ft below land surface.

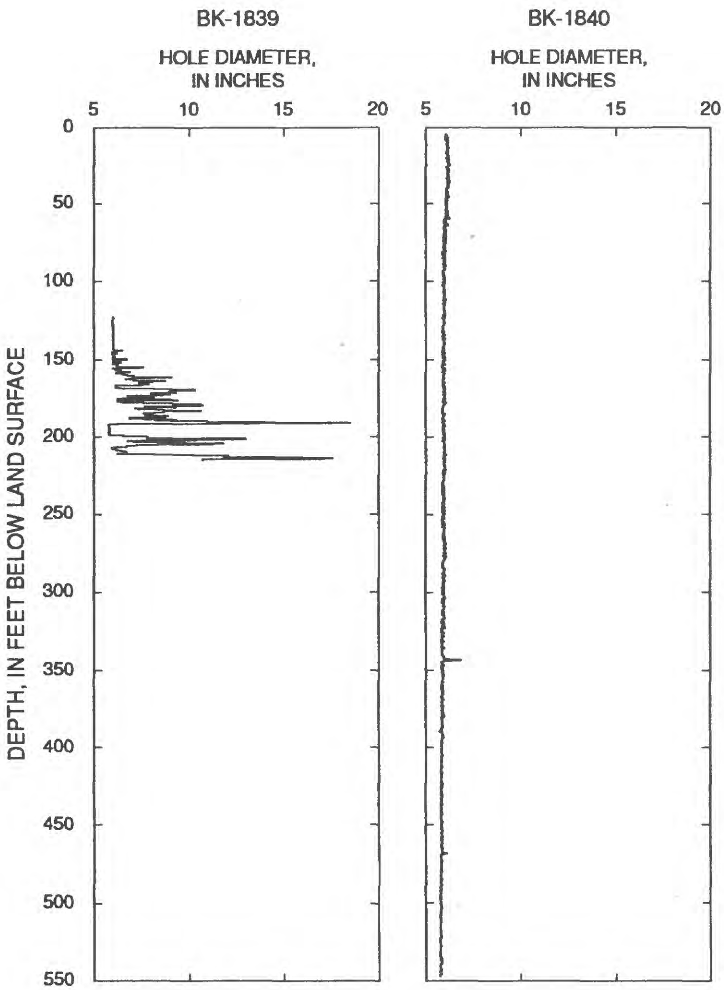


Figure 16. Caliper logs of wells BK-1839 and BK-1840, Solebury Township, northern Bucks County.

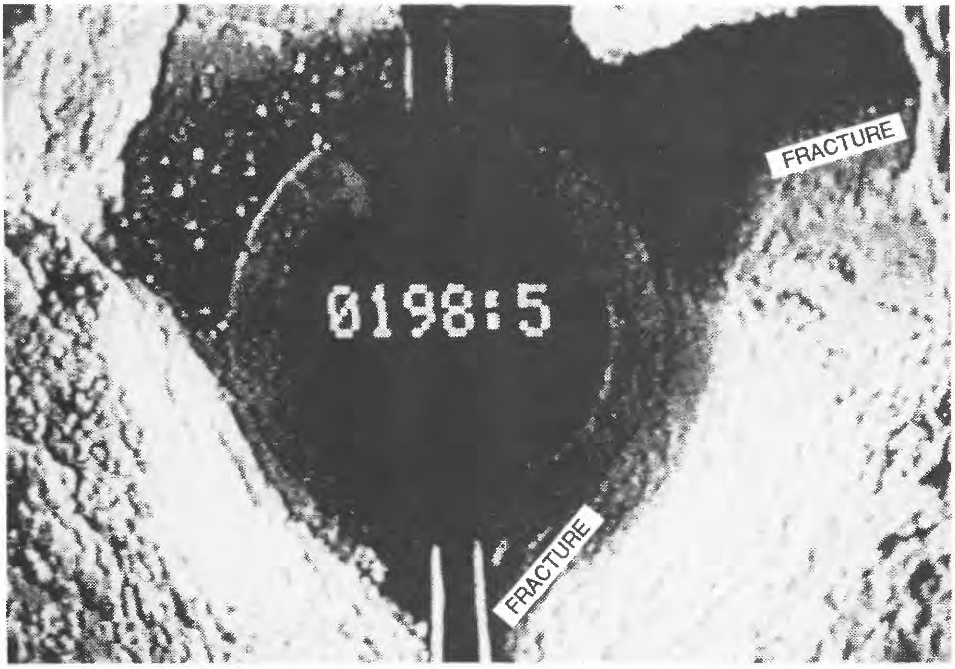


Figure 17. Borehole television survey showing fracture penetrated by well BK-1839, Solebury Township, northern Bucks County. Number is depth below land surface, in feet.

Figure 18. Borehole television survey showing fracture penetrated by well BK-1838, Solebury Township, northern Bucks County. Number is depth below land surface, in feet.

Crystalline Rocks

Seven percent of the study area is underlain by crystalline rocks. Crystalline rocks are found in Buckingham and Durham Valleys and in the Reading Prong to the north of Durham Valley. The crystalline rocks in the northern part of the study area are Hardyston Quartzite in Durham Valley and granitic and hornblende gneisses in the Reading Prong. The crystalline rocks of Buckingham Valley are Hardyston Quartzite, phyllite of the Furlong Klippe, and quartz diorite.

In crystalline rocks, ground water moves through intergranular openings in the weathered zone (saprolite) and through a network of interconnecting secondary openings—fractures and joints—in the underlying unweathered rock. The permeability of fractured crystalline rock depends on the number of fractures, the size of the fracture openings, and the degree of interconnection of the fractures. A considerable quantity of water may be stored in the weathered zone where it is thick.

The ground-water-flow system in crystalline rock is local with streams acting as drains. Flow paths are short, and ground water flows from areas of higher elevation to adjacent streams. Ground-water and surface-water divides usually coincide. The hydrologic system generally is under unconfined (water-table) conditions; the water-table surface is a subdued replica of the land surface. In areas where the fractures are far apart and poorly interconnected, a true water table may be absent and each system of fractures may have its own water level. Semiconfined ground water may occur locally.

Aquifer and Well-Construction Characteristics

Aquifer and well-construction characteristics are briefly discussed in the following sections. Because of the many hydrogeologic units in northern Bucks County, data for each hydrogeologic unit or rock type are given in tables in each section. The unit that a well penetrates is considered to be the unit at the surface shown on the geologic map (pl. 1). For statistical analysis and description, the geologic units mapped in northern Bucks County have been grouped into nine hydrogeologic units or rock types: diabase, quartzite conglomerate, Brunswick Group (red beds, lower beds, and hornfels), Lockatong Formation, Stockton Formation, carbonate rocks (Rickenbach Dolomite, Limeport Formation, Allentown Dolomite, and Leithsville Formation), and crystalline rocks (Hardyston Quartzite, phyllite, and gneiss). The unconsolidated sediments along the Delaware River and the limestone conglomerate were not used in statistical analyses because too few data were available.

One-way analysis-of-variance tests were made to determine if statistically significant differences in specific capacity and well yield exist among hydrogeologic units or rock types. Nonparametric (distribution free) statistical tests were used because the data are not normally distributed. Specific-capacity data for the Lockatong Formation, for example, spans three orders of magnitude. The Kruskal-Wallis test, a nonparametric one-way analysis of variance that uses rank-transformed data, was used to test for statistically significant differences among groups at the 95-percent confidence level. The null hypothesis tested by the Kruskal-Wallis test is that all groups come from the same population or from populations with equal medians. For ranked data, the median and the mean are equal. If the null hypothesis is rejected, the alternative hypothesis is that at least one group is from a different population or has an unequal median. The Kruskal-Wallis test, however, does not indicate which group or groups are different.

If the null hypothesis of the Kruskal-Wallis test was rejected (p-value less than or equal to 0.05), indicating that at least one group was significantly different, further testing by a multiple comparison test (MCT) was performed to identify the hydrogeologic units or rock types with significantly different medians. Because sample size is unequal, Tukey's W studentized range test, honestly significant difference procedure (Steel and Torrie, 1960, p. 109-110), was the MCT used on rank-transformed data to make multiple comparisons and test for significant differences at the 95-percent confidence level.

One-way analysis-of-variance tests were made to determine if statistically significant differences in hydraulic characteristics exist among the different units of the Brunswick Group—red siltstone and shale beds, lower beds, and hornfels. The test results indicated no statistically significant differences in hydraulic characteristics in the units of the Brunswick Group, except for depth to water. Therefore, the hydraulic and well-construction data were combined and reported as the Brunswick Group. Hydraulic and well-construction data for the Lockatong Formation used in statistical testing included Lockatong shale or siltstone, lower beds, and hornfels. Hydraulic and well-construction data for the Stockton Formation used in statistical testing included Stockton sandstone, shale, or siltstone and the Stockton conglomerate.

Water-Bearing Zones

Primary (intergranular) porosity below the weathered zone, except in a very few Triassic sedimentary beds, is virtually nonexistent in the consolidated rocks of northern Bucks County. Ground water flows through a network of interconnected secondary openings that comprise the water-bearing zones that provide water to wells. The number and size of the water-bearing openings determines the secondary porosity of the rock; the number, size, and degree of interconnection of the openings determines the secondary permeability. The larger and more numerous the openings, the greater the yield of a well. Where a formation is extensively fractured, permeability may be high; elsewhere, the same unit may be nearly impermeable.

The distribution of 560 water-bearing zones reported by drillers in 217 wells was analyzed (table 3). This represents 49,552 ft of uncased borehole; well depths range to 800 ft. The data are summarized by selected hydrogeologic unit and by all units combined. The data are expressed in units of water-bearing zones per 100 ft of uncased borehole. The frequency of occurrence of water-bearing zones generally decreases with depth (fig. 19). Sixty-five percent of water-bearing zones for all hydrogeologic units are within 200 ft of land surface, and 85 percent are within 300 ft of land surface. Figure 19 shows that 90 percent of water-bearing zones are encountered above 300 ft below land surface in wells drilled in the Stockton Formation and the Brunswick Group, above 350 ft below land surface in wells drilled in the Lockatong Formation, and above 450 ft below land surface in wells drilled into diabase.

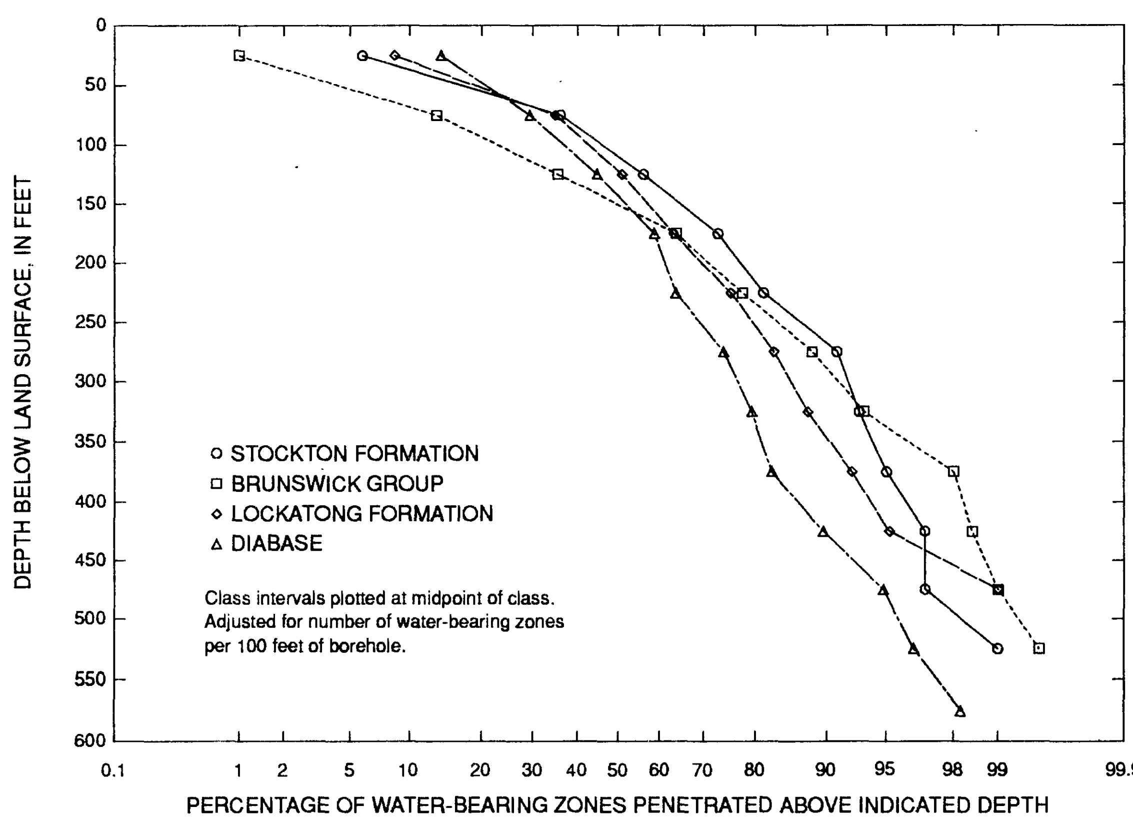


Figure 19. Distribution of water-bearing zones with depth.

Table 3. *Number of water-bearing zones per 100 feet of uncased borehole*

Interval (feet)	Stockton Formation (42 wells)			Lockatong Formation (39 wells)			Brunswick Group (76 wells)			Diabase (32 wells)			All hydrogeologic units (217 wells)		
	Number of water-bearing zones		Footage drilled (feet)	Number of water-bearing zones		Footage drilled (feet)	Number of water-bearing zones		Footage drilled (feet)	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		Penetrated	Per 100 feet of borehole		Penetrated	Per 100 feet of borehole		Penetrated	Per 100 feet of borehole	
0-50	9	1.95	461	9	1.92	470	2	0.86	231	8	3.53	227	29	1.90	1,529
51-100	47	2.83	1,660	2	1.55	1,801	22	1.16	1,899	9	1.10	821	118	1.75	6,750
101-150	31	1.68	1,849	17	.95	1,790	32	1.14	2,800	9	.89	1,007	106	1.27	8,346
151-200	26	1.89	1,377	13	.81	1,597	49	1.55	3,170	8	.81	982	109	1.37	7,939
201-250	13	1.27	1,025	13	.9	1,415	25	.99	2,529	3	.31	958	60	.92	6,507
251-300	15	1.78	845	8	.66	1,221	18	1.03	1,749	6	.65	927	55	1.04	5,266
301-350	3	.47	635	5	.46	1,090	10	.88	1,140	3	.42	710	24	.61	3,965
351-400	3	.55	550	5	.49	1,011	8	1.05	760	2	.55	364	20	.67	2,995
401-450	3	.66	455	3	.38	793	1	.24	419	4	1.24	323	14	.63	2,229
451-500	0	0	350	4	.73	550	1	.40	250	3	1.18	255	9	.57	1,570
501-550	3	1.09	275	1	.31	318	1	1.00	100	1	.71	140	9	.92	983
551-600	1	.65	155	0	0	265	0	0	50	1	1.00	100	3	.42	720
Over 600	1	2.27	44	0	0	528	1	1.33	75	1	1.67	60	4	.53	753
Total (mean)	155	(1.60)	9,681	106	(.82)	12,849	170	(1.12)	15,172	58	(.84)	6,874	560	(1.13)	49,552

More than 1.7 water-bearing zones per 100 ft of uncased borehole for all hydrogeologic units are in the upper 100 ft, more than 1.4 water-bearing zones per 100 ft are in the upper 200 ft, and less than 1.0 water-bearing zone per 100 ft are below 300 ft. For diabase, the Brunswick Group, Lockatong Formation, and Stockton Formation, the large number of water-bearing zones per 100 ft below 300 ft is because of small sample sizes.

The Stockton Formation had 1.6 water-bearing zones per 100 ft of uncased borehole, which is more than any other hydrogeologic unit (table 3). The Lockatong Formation and diabase had the fewest water-bearing zones per 100 ft of uncased borehole (0.82 and 0.84, respectively). In diabase, water-bearing zones deeper than 200 ft are probably in the underlying sedimentary rocks.

Water-bearing-zone data from hydrogeologic units or rock types with less than 30 wells are summarized below. For 9 wells in quartzite conglomerate, 24 water-bearing zones are reported in 1,163 ft of uncased borehole; 75 percent of the water-bearing zones are within 200 ft of land surface. For 11 wells in carbonate rocks, 26 water-bearing zones are reported in 2,445 ft of uncased borehole; 35 percent of the water-bearing zones are within 200 ft of land surface. For 8 wells in crystalline rocks, 21 water-bearing zones are reported in 1,368 ft of uncased borehole; 76 percent of the water-bearing zones are within 200 ft of land surface. Fewer water-bearing zones per 100 ft of uncased borehole are penetrated in carbonate rock (1.06) than in quartzite conglomerate (2.06) or crystalline rock (1.54).

Nearby wells may not tap water-bearing zones in the same beds. Wells BK-1483 and BK-1484 were drilled for public supply in the Lockatong Formation and are 700 ft apart. Well BK-1484 is 285 ft deep and yields 450 gal/min. Well BK-1483 is 416 ft deep and yields 140 gal/min. Well BK-1484 was flowing at 36 gal/min at the time of geophysical logging. Water enters well BK-1484 through a highly-fractured zone between 212 and 224 ft below land surface and flows upward at 36 gal/min (fig. 20). Water enters well BK-1483 through a water-producing fracture at 163 ft below land surface and flows upward at 1.3 gal/min to a water-receiving fracture between 112 and 114 ft below land surface where it exits the well (fig. 20). The highly fractured bed between 212 and 224 ft below land surface that produces most of the yield of well BK-1484 is not fractured 700 ft away where it is penetrated by well BK-1843. The bed is correlated in both wells on the basis of the natural-gamma logs (fig. 20). The logs show that fractures or joints that provide water to a well are not laterally continuous and a nearby well tapping the same bed may derive no water from it. The logs also show that fractures, water-producing zones, and water-receiving zones may not be located in the same beds in nearby wells.

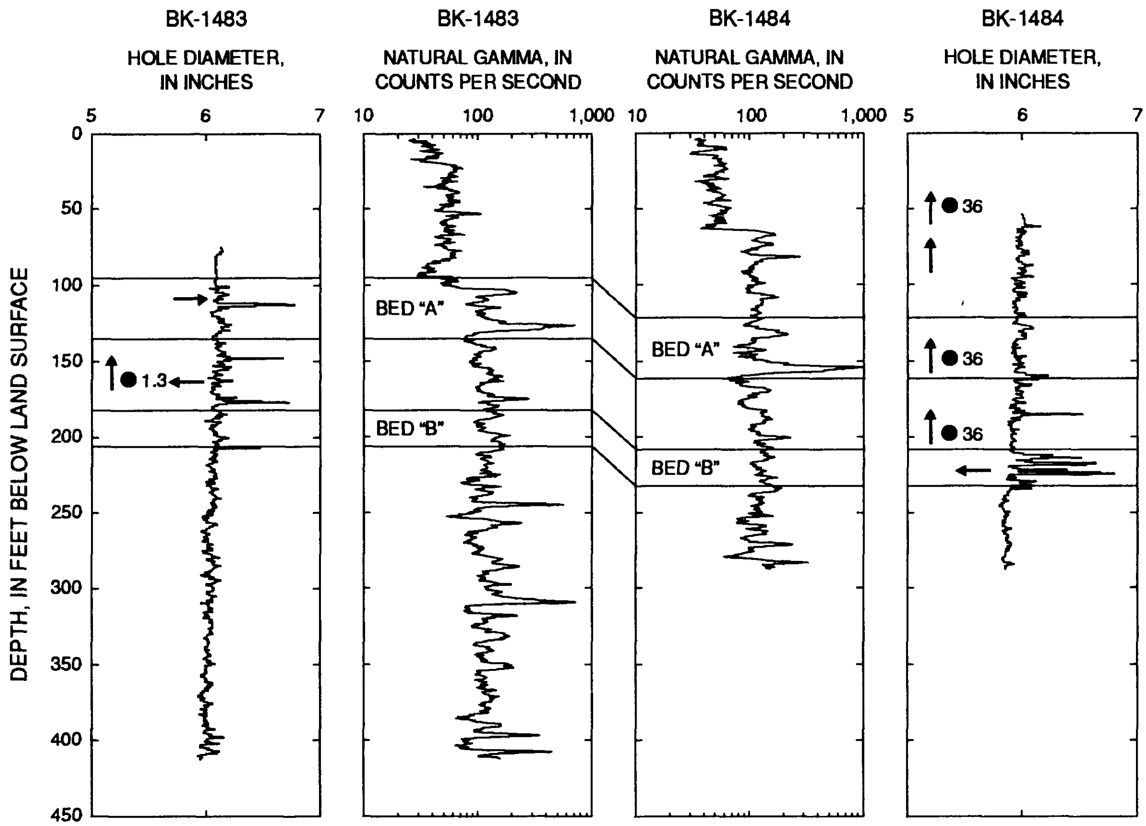


Figure 20. Caliper and natural-gamma logs of wells BK-1483 and BK-1484, Plumstead Township, northern Bucks County.

EXPLANATION

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

↑ DIRECTION OF VERTICAL BOREHOLE FLOW—Arrow indicates upward flow

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

Specific Capacity

Specific capacity is a better measure of aquifer productivity than well yield because it is calculated by use of yield and drawdown data from a pumped well. Specific capacity is calculated by dividing the pumping rate of a well by the drawdown. Specific capacity for a well pumped at a constant yield decreases with time. Reported specific-capacity data for wells in northern Bucks County are given in Schreffler and others (1994) and are summarized in table 4. The specific-capacity data are based on aquifer tests conducted by drillers, water purveyors, and consultants. Some wells drilled in the low yielding diabase tap more productive underlying formations; therefore, the specific capacity for diabase given in table 4 is higher than it actually is.

The specific capacity of nondomestic wells provides a better estimate of maximum aquifer productivity than does the specific capacity of domestic wells. Nondomestic wells include public, industrial, and institutional supply wells. Domestic wells include household wells and wells used by small business and commercial establishments. Nondomestic wells are purposefully located and constructed for maximum yield. Domestic wells are usually located for convenience and are drilled only until an adequate yield for domestic use is obtained. The difference in well yields is attributed to nondomestic wells generally being deeper, penetrating more water-bearing zones, and having larger diameters than domestic wells.

Specific-capacity data for nondomestic wells, together with available drawdown data, provide a reasonable base for comparing yields of wells penetrating various hydrogeologic units. This information can be used to determine which hydrogeologic units are the better water-producing units. On the basis of the median specific capacity of nondomestic wells (table 4), the Stockton Formation is the most productive hydrogeologic unit.

One-way analysis-of-variance tests for statistically significant differences in specific capacity at the 95-percent confidence level (Kruskal-Wallis rank test) were made on nondomestic well data in three hydrogeologic units with eight or more values. A statistically significant difference among the groups was shown by the Kruskal-Wallis test (p-value of 0.004). Therefore, Tukey's MCT was used to determine which units were significantly different. Tukey's MCT showed that the median specific capacity of nondomestic wells drilled in the Brunswick Group and Stockton Formation are significantly higher than the median specific capacity of nondomestic wells drilled in the Lockatong Formation, but the median specific capacities of the two units are not significantly different from each other (p-value of 0.002).

Table 4. *Reported specific capacity and well yield for wells in northern Bucks County*

[P10, tenth percentile; P25, twenty-fifth percentile; P75, seventy-fifth percentile; P90, ninetieth percentile; --, too few data to compute statistic]

Hydrogeologic unit	Nondomestic wells						Domestic wells					
	Number of wells	P10	P25	Median	P75	P90	Number of wells	P10	P25	Median	P75	P90
	Specific capacity (gallons per minute per foot of drawdown)											
Diabase	--	--	--	--	--	--	20	0.00	0.01	0.08	0.27	0.96
Quartzite conglomerate	--	--	--	--	--	--	7	--	.04	.17	.29	--
Brunswick Group	15	0.19	0.40	1.5	5.5	8.0	34	.03	.05	.13	.27	2.6
Lockatong Formation	8	--	.05	.18	.43	--	25	.01	.02	.12	.33	1.4
Stockton Formation	16	.34	.87	1.3	3.2	7.6	17	.07	.12	.20	.33	6.2
Carbonate rocks	4	--	.71	3.5	70	--	5	--	.04	.14	3.2	--
Crystalline rocks	1	--	--	.30	--	--	5	--	.11	.13	.33	--
	Yield (gallons per minute)											
Diabase	--	--	--	--	--	--	76	1.5	3.1	7.5	15	30
Quartzite conglomerate	--	--	--	--	--	--	12	4.5	11	18	35	47
Brunswick Group	42	12	20	52	122	221	201	4.0	8.0	15	25	40
Lockatong Formation	17	2.0	10	22	65	187	100	1.7	3.4	6.8	15	36
Stockton Formation	27	37	64	120	175	238	59	5.0	13	20	30	50
Carbonate rocks	6	--	54	156	331	--	14	1.5	4.8	7.0	21	50
Crystalline rocks	2	--	--	--	--	--	8	--	10	14	20	--

Well Yield

Reported well-yield data for wells in northern Bucks County are given by Schreffler and others (1994) and are summarized in table 4. The yield of nondomestic wells provides a better measure of maximum aquifer yield than the yield of domestic wells for the same reasons cited in the Specific Capacity section. Many aquifer and well-construction characteristics control the volume of water a formation yields to a well. Aquifer characteristics affecting well yield include the number, interconnection, and size of the water-bearing zones penetrated.

Carbonate rocks and the Stockton Formation have the highest median nondomestic well yields (156 and 120 gal/min, respectively) among the hydrogeologic units and rock types; the Lockatong Formation has the lowest median nondomestic well yield (22 gal/min). No nondomestic wells are reported in diabase or quartzite conglomerate.

The Stockton Formation has the highest median domestic well yields among the hydrogeologic units and rock types. Ten percent of all domestic wells drilled in northern Bucks County, except for wells drilled in the Stockton Formation, yield less than 5 gal/min, which is considered an adequate supply for domestic use (table 4). Thirty-four percent of domestic wells drilled in diabase, 30 percent in the Lockatong Formation, and 21 percent in carbonate rock yield less than 5 gal/min.

One-way analysis-of-variance tests for statistically significant differences in yield at the 95-percent confidence level (Kruskal-Wallis test) were made on nondomestic well data in three hydrogeologic units with eight or more values. A statistically significant difference among the units was shown by the Kruskal-Wallis test (p-value of 0.0001). Therefore, Tukey's MCT was used to determine which units were significantly different. Tukey's MCT showed that the median yield of nondomestic wells drilled in the Stockton Formation is significantly higher than the median yield of nondomestic wells drilled in the Brunswick Group and the Lockatong Formation (p-value of 0.00006). Tukey's MCT also showed that although the median yield of nondomestic wells drilled in the Brunswick Group is higher than the median yield of nondomestic wells drilled in the Lockatong Formation, the median yield of nondomestic wells drilled in the Brunswick Group is not significantly different from the median yield of nondomestic wells drilled in the Lockatong Formation.

Transmissivity

Transmissivity gives an indication of the capacity of an aquifer to transmit water. Transmissivity is defined as the rate at which water is transmitted through a unit width of the aquifer under a unit hydraulic gradient (Lohman, 1979). Transmissivity has units of length squared per time.

Transmissivity commonly is determined by aquifer tests. An aquifer test is a controlled field experiment where a well is pumped, generally at a constant rate, and the resulting water-level declines are measured in the pumped well and observation wells. From the aquifer test drawdown and recovery data, transmissivity is determined. However, most analytical aquifer-test techniques are based on many assumptions that are violated when applied to fractured-rock aquifers.

Aquifer-test data from hydrogeologic investigations in northern Bucks County, done primarily by environmental consulting firms in compliance with state and local regulations, were used to calculate aquifer transmissivities for nondomestic wells (table 5). Each aquifer test was treated as a single-well test. Recovery data were analyzed by use of the Theis (1935) recovery method because recovery data are more reliable than drawdown data because of the elimination of well-bore effects and fluctuations in discharge rate. For well BK-2094, drawdown data were analyzed by use of the Cooper and Jacob (1946) method because recovery data were not available.

All aquifer tests were either 48-hour or 72-hour tests. Transmissivities based on analysis of five aquifer tests in the Brunswick Group ranged from 94 to 2,200 ft^2/d; the median was 190 ft^2/d. Transmissivities based on analysis of three aquifer tests in the Lockatong Formation ranged from 250 to 1,500 ft^2/d; the median was 820 ft^2/d. Transmissivities based on analysis of seven aquifer tests in the

Table 5. *Aquifer transmissivity determined from aquifer-test data*

[All aquifer tests were analyzed by use of the Theis (1935) recovery method unless otherwise noted; ft^2/d, square foot per day; gal/min, gallon per minute]

Well identification number	Hydrogeologic unit	Length of test (hours)	Average pumping rate (gal/min)	Transmissivity (ft^2/d)	Source of data
BK-1218	Brunswick Group	48	100	94	A.W. Martin Associates, Inc. (1980)
BK-1219	Brunswick Group	48	175	220	A.W. Martin Associates, Inc. (1980)
BK-1297	Brunswick Group	48	180	2,220	Mercuri Associates, Inc. (1988)
BK-2461	Brunswick Group	48	60	330	Earth Data, Inc. (1990)
BK-2519	Brunswick Group	72	65	190	Earth Data, Inc. (1988b)
BK-1483	Lockatong Formation	48	140	820	International Hydrogeologists, Inc. (1991b)
BK-1484	Lockatong Formation	48	280	1,500	International Hydrogeologists, Inc. (1991b)
BK-2094[1]	Lockatong Formation	72	50	250	Walter B. Satterthwaite Associates, Inc. (1989)
BK-1282	Stockton Formation	48	210	1,800	Earth Data, Inc. (1987b)
BK-1283	Stockton Formation	48	210	930	Earth Data, Inc. (1987b)
BK-1289	Stockton Formation	48	125	330	Earth Data, Inc. (1987a)
BK-1290	Stockton Formation	48	140	670	Earth Data, Inc. (1987a)
BK-1299	Stockton Formation	48	50	310	Earth Data, Inc. (1989)
BK-1323	Stockton Formation	48	120	260	Earth Data, Inc. (1988a)
BK-1846	Stockton Formation	48	70	410	International Hydrogeologists, Inc. (1991a)

[1] Cooper and Jacob (1946) method used for analysis.

Stockton Formation ranged from 260 to 1,800 ft^2/d; the median was 410 ft^2/d. The high median transmissivity for the Lockatong Formation is because the small sample size includes only high-yielding wells. Although specific-capacity and yield data show the Lockatong Formation to be a relatively low-yielding aquifer, the aquifer-test data show that high-yielding production wells can be successfully located in the Lockatong.

Techniques for estimating transmissivity from other types of hydrologic data have been developed. Theis and others (1963), for example, present a technique for estimating transmissivity from specific-capacity data.

Well Depth and Casing Length

Well-depth and casing length data for northern Bucks County are given in table 6. The median depth of wells ranges from 155 ft for domestic wells drilled in quartzite conglomerate to 400 ft for nondomestic wells drilled in the Stockton Formation. The median depth of wells drilled in diabase includes wells that are drilled through the diabase into the underlying formations. Wells drilled through the diabase into the underlying formations generally have deeper water levels, often greater than 100 ft below land surface, than do wells completed in the diabase, which generally have water levels less than 100 ft below land surface. Sixty-seven wells that start in diabase, which had a depth to water less than 100 ft, had a median depth of 180 ft. Fifty-eight wells that start in diabase, which had a depth to water greater than 100 ft, had a median depth of 450 ft. Figure 21 shows the caliper and natural-gamma logs of well BK-1498, which is drilled through the diabase into the Brunswick Group and had a water level of 134 ft below land surface at the time of geophysical logging. The natural-gamma log shows that the well penetrates the Brunswick Group at 114 ft below land surface. The well obtains water from a fracture at 250 ft below land surface in the Brunswick Group. The fracture at the contact between the diabase and the Brunswick Group does not yield water.

Well drilling usually stops when a sufficient yield for the specific use of the well is obtained. Domestic wells usually are not drilled as deep as nondomestic wells (table 6). For example, for 119 domestic wells drilled in the Stockton Formation, the median depth was 160 ft. For 29 nondomestic wells drilled in the Stockton Formation, the median depth was 400 ft.

Median casing length for nondomestic wells ranges from 37 ft for wells drilled in the Brunswick Group to 85 ft for wells drilled in carbonate rock. Median casing lengths for domestic wells range from 29.2 ft for wells drilled in diabase to 70 ft for wells drilled in quartzite conglomerate. Except for the Brunswick Group, more casing is used in nondomestic wells than in domestic wells.

Table 6. *Reported well depths and casing lengths for wells in northern Bucks County*

[Well depths and casing lengths given in feet; P10, tenth percentile; P25, twenty-fifth percentile; P75 seventy-fifth percentile; P90, ninetieth percentile]

Hydrogeologic unit	Nondomestic wells						Domestic wells					
	Number of wells	P10	P25	Median	P75	P90	Number of wells	P10	P25	Median	P75	P90
				Well depth								
Diabase	1	–	–	–	–	–	129	55	150	300	460	600
Quartzite conglomerate	–	–	–	–	–	–	22	85	100	155	300	382
Brunswick Group	45	206	256	310	404	531	359	99	150	240	320	410
Lockatong Formation	27	156	200	390	495	696	155	76	120	198	360	504
Stockton Formation	29	208	280	400	510	600	119	75	113	160	210	300
Carbonate rocks	8	–	162	220	524	–	41	87	128	275	392	590
Crystalline rocks	2	–	–	–	–	–	17	82	100	190	268	372
				Casing length								
Diabase	1	–	–	–	–	–	70	14	20	29.2	40	59.6
Quartzite conglomerate	–	–	–	–	-	–	11	32	52	70	87	129
Brunswick Group	24	20	23.5	37	50	58	171	18	30	40	40	60
Lockatong Formation	11	30.2	35	53	60	92.4	69	18	21	30	40	42
Stockton Formation	24	35	46.8	70	104	142	5	35.4	40	40	60	80.3
Carbonate rocks	5	–	53	85	118	–	14	17	37.5	59	116	193
Crystalline rocks	2	–	–	–	–	–	10	23	40	62.5	104	251

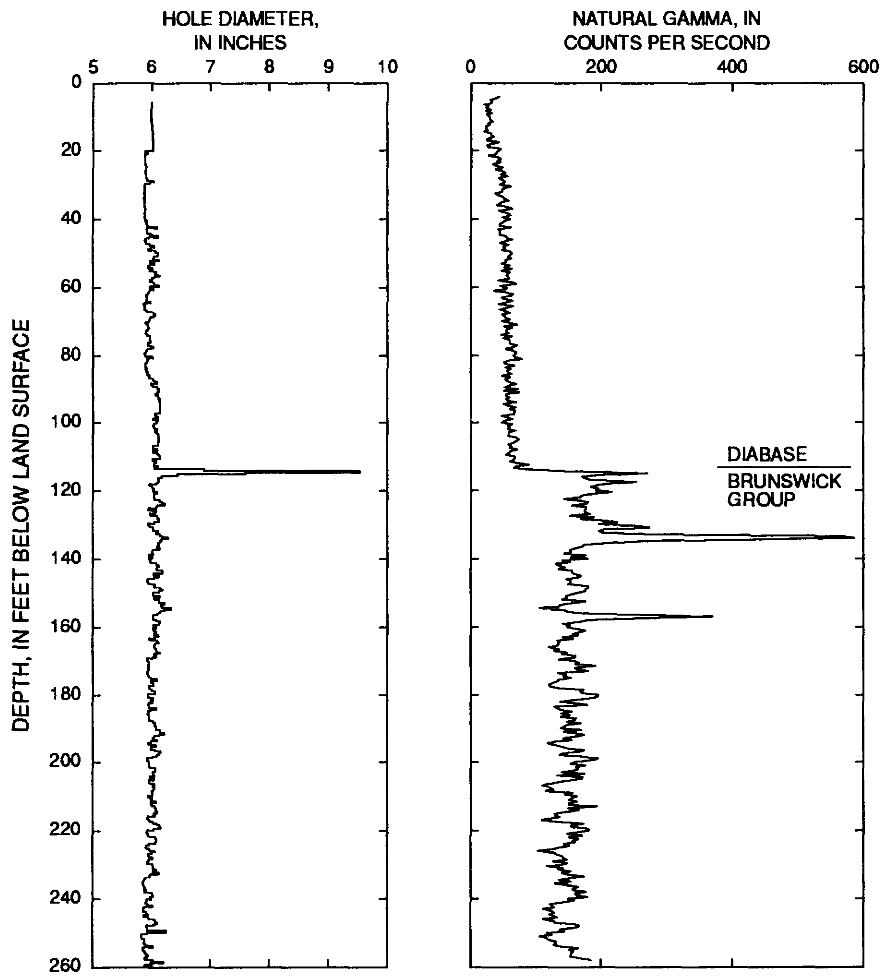


Figure 21. Caliper and natural-gamma logs of well BK-1498, Nockamixon Township, northern Bucks County.

Water Levels

For this study, seven wells were equipped with continuous water-level recorders. The wells were located in different townships and in six different hydrogeologic units. The graphical charts recorded aquifer response to precipitation and seasonal water-level trends for a 13-month period from December 1991 to January 1993. The hydrographs are published in Schreffler and others (1994).

Twenty-one wells were measured monthly during January 1991-December 1992, to determine the change in ground-water storage in the Cooks, Tinicum, Paunnacussing, and Mill Creek Basins. The measurements are published in Schreffler and others (1994).

Approximately 1,100 wells were measured on a one-time only basis to construct potentiometric-surface maps of the study area. On the maps, the potentiometric surface represent the hydraulic head in wells. Where a well penetrates several hydrogeologic units, the hydraulic head is a composite of the hydraulic heads in the penetrated units. In many hydrogeologic units, hydraulic head varies with depth.

Water-Level Fluctuations

Water levels fluctuate in response to recharge to the ground-water system from precipitation and discharge from the ground-water system to pumped wells and quarries, ground-water evapotranspiration, and streams. Water levels generally rise during the late fall, winter, and early spring when ground-water evapotranspiration and soil-moisture evapotranspiration is at a minimum and recharge is at a maximum. Water levels generally decline during the late spring, summer, and early fall when ground-water evapotranspiration and soil-moisture evapotranspiration is at a maximum and recharge is at a minimum.

Water-level fluctuations in 20 wells measured monthly (Schreffler and others, 1994) during January 1, 1990-December 30, 1992, ranged from 3.93 ft in well BK-1162 (drilled in the Brunswick Group) to 68.78 ft in well BK-1342 (drilled in the Limeport Formation). The median range in fluctuation was 7.29 ft. Water-level fluctuations in seven wells equipped with continuous water-level recorders during December 1991-January 1993 ranged from 3.86 ft in well BK-1744 (drilled in the Lockatong Formation) to 21.28 ft in well BK-1341 (drilled in the Stockton Formation). The median range in fluctuation was 12.60 ft. Figure 22 shows hydrographs of three observation wells drilled in different hydrogeologic units in different parts of northern Bucks County. The wells have similar hydrographs with water levels rising from January through May and declining from June through October. Water-level fluctuations in well BK-2128 have smaller amplitudes in response to precipitation and seasonal trends because the well is completed in diabase, which receives less recharge than the Limeport and Stockton Formations. Well BK-1341 in the Stockton Formation shows a better response to precipitation than well BK-2128 in diabase or well BK-1840 in the Limeport Formation. Figure 23 is the hydrograph of well BK-929 (Brunswick Group), which shows seasonal water-level trends over a 5-year period from January 1987 to December 1992.

The continuous water level recorded in observation well BK-1840 shows the influence of earth tides, which indicate confined ground water (fig. 24). Earth tides are caused by the force of gravity exerted by the moon and sun on the earth and by centrifugal forces produced by the revolution of the earth and moon around their common center of gravity. Earth tides are characterized by semi-diurnal fluctuations that correspond to the moon's transit at upper and lower culmination. Water levels peak at low tide when the earth is compressed; confined ground water is under increased pressure, and water levels in wells rise. The larger amplitude and more regular fluctuations coincide with the new and full moon; the smaller and less regular fluctuations coincide with the first and third quarters (Talley, 1980, p. 9-10).

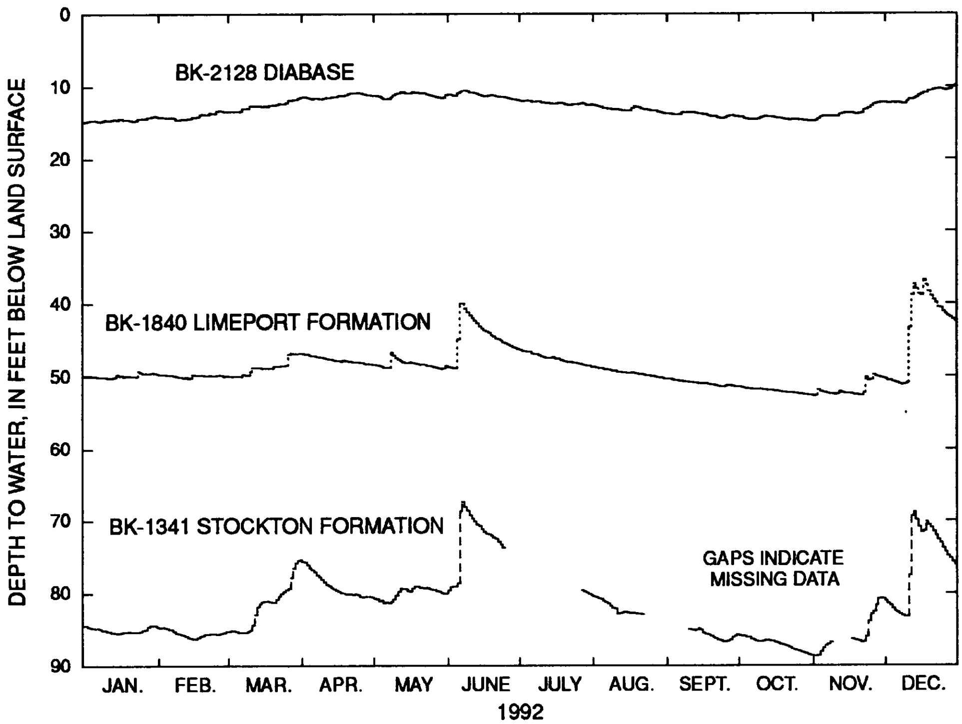


Figure 22. Depth to water in wells BK-2128, BK-1840, and BK-1341, 1992.

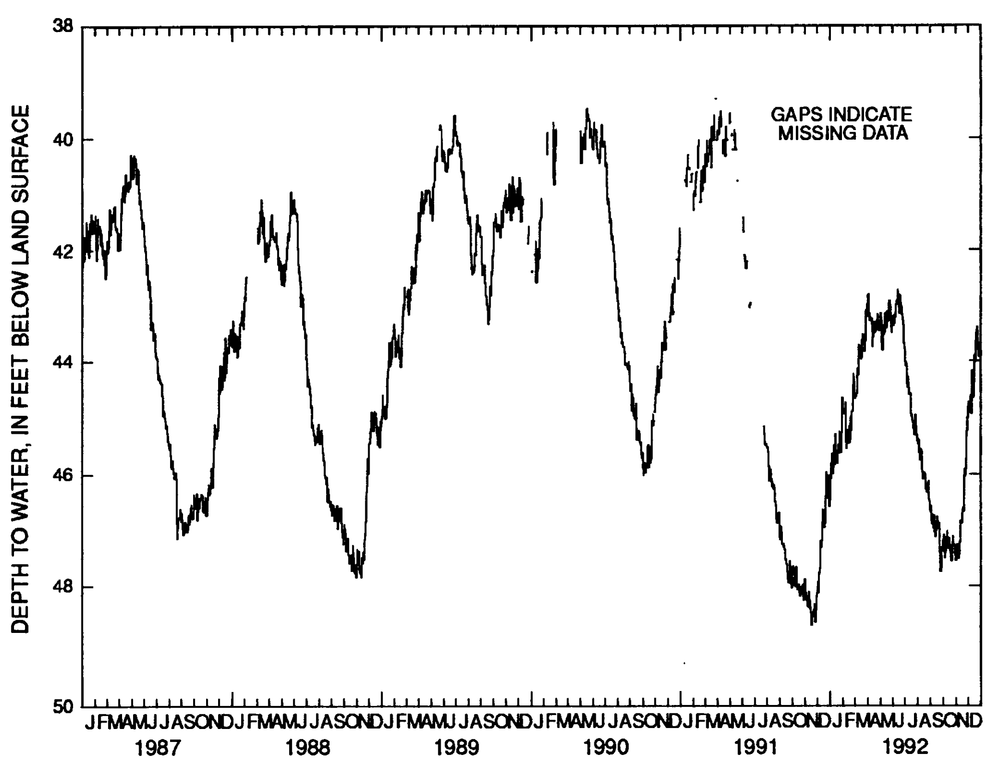


Figure 23. Depth to water in well BK-929, January 1987 - December 1992.

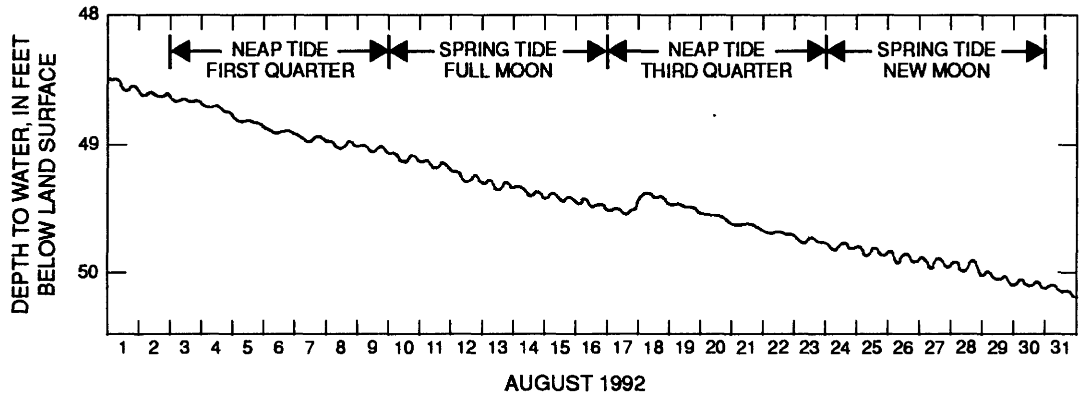


Figure 24. Depth to water in well BK-1840 showing water-level fluctuations caused by earth tides, August 1992.

Depth to Water

Depth to water depends on many factors, including geology, topography, and proximity to pumped wells and quarries. Geologic controls often influence depth to water. For example, a well drilled in the Lockatong Formation near the contact with the Stockton Formation may penetrate the underlying Stockton Formation. The Stockton Formation may have a lower hydraulic head than the Lockatong Formation, and the water level in the well would be a composite of heads in the Lockatong and the Stockton Formations. The composite head would be higher than the head in the Stockton Formation and lower than the head in the Lockatong Formation.

Some anthropogenic activities, such as pumping of nondomestic wells or dewatering of a quarry, may lower water levels and create a cone of depression around the pumping well or quarry. For example, the potentiometric-surface map of McManus and others (1994) shows a cone of depression in Buckingham Township and Doylestown Borough around pumping public-supply well BK-700. The potentiometric-surface map of Schreffler (1993c) shows a cone of depression that is approximately 1 mi long and 0.5 mi wide around the active quarry northwest of New Hope Borough in Solebury Township.

Measured or reported depths to water are summarized in table 7. The median depth to water for both domestic and nondomestic wells is greatest in the lower beds of the Brunswick Group (101 and 81 ft, respectively). The median depth to water for both domestic and nondomestic wells is least in the Lockatong Formation (18 and 10 ft, respectively).

The median depth to water in 167 wells in diabase is 80 ft. However, some wells are drilled through the diabase, and water levels may be those in the underlying sedimentary rocks. If these underlying units have lower heads, water levels will be deeper. Of 96 wells with water levels less than 100 ft, the median depth to water was 23 ft. Of 71 wells with water levels greater than 100 ft, the median depth to water was 155 ft. Water levels in deeper wells reflect the head in the underlying sedimentary rocks or are a composite of the heads in diabase and the underlying sedimentary rocks.

The median depth to water for all the units of the Brunswick Group is 60 ft. Median depth to water for all wells in each unit in the Brunswick Group is 55, 67, and 101 ft for the red beds, hornfels, and lower beds, respectively. The Kruskal-Wallis rank sum test showed a statistically significant difference (p-value of 0.004) among water levels in the units. Thus, the units could not be combined for statistical analysis. Tukey's MCT showed that the median depth to water of the red beds and lower beds were significantly different (p-value of 0.005). Most of the lower beds lie south of the Coffman Hill diabase sheet, north of the Lockatong Formation in the area of Nockamixon and Tinicum Townships, and north of Plumstead

Table 7. *Measured or reported depth to water for wells in northern Bucks County*

[Depth to water given in feet; P10, tenth percentile; P25, twenty-fifth percentile; P75 seventy-fifth percentile; P90, ninetieth percentile]

Hydrogeologic unit	Nondomestic wells						Domestic wells					
	Number of wells	P10	P25	Median	P75	P90	Number of wells	P10	P25	Median	P75	P90
Diabase	1	--	--	--	--	--	166	4.9	17	80	142	194
Quartzite conglomerate	--	--	--	--	--	--	28	13	34	64	78	100
Brunswick Group (red beds)	22	7.8	18	35	57	72	319	13	25	56	102	168
Brunswick Group (lower beds)	5	--	45	81	107	--	67	9.5	34	101	144	179
Brunswick Group (hornfels)	1	--	--	--	--	--	77	14	27	66	155	221
Lockatong Formation	11	.64	8.0	10	44	51	165	5.2	9.8	18	33	72
Stockton Formation	19	1.8	10	34	60	102	182	13	21	33	50	75
Carbonate rocks	8	--	17	46	99	--	50	9.5	19	32	84	128
Crystalline rocks	1	--	--	--	--	--	26	2.1	14	44	78	105

Township. In Nockamixon and Tinicum Townships, both an upper and lower aquifer system was mapped by McManus and Rowland (1993). The shallow system supplies base flow to the local surface-water system. The deeper regional system does not discharge to the local surface-water system and most likely discharges to the Delaware River.

Water Budgets

A water budget is an estimate of water entering and leaving a basin plus or minus storage changes for a given time period. For a basin where ground-water divides and surface-water divides coincide, water enters as precipitation and leaves as streamflow, evapotranspiration (ET), and diversions, such as ground-water pumpage. For a basin where ground-water divides and surface-water divides do not coincide, water also enters and (or) leaves a basin as ground-water underflow. Water also is taken into or released from ground-water and soil-moisture storage. Sewer systems can export water, both waste water and infiltrated ground water, out of a basin. The effect of sewer systems on water budgets is discussed by Sloto and Davis (1983, p. 29-30), and infiltration of ground water into sewer systems is described by Sloto and Davis (1983, p. 19-22) and Sloto (1987, p. 24-30). However, little of the study area is sewered (Bucks County Planning Commission, 1992b), and the effect of sewering on the water budgets presented in this report is considered negligible.

Because the water budgets in this report begin and end in winter when soil moisture is usually at field capacity, the change in soil moisture is equal to zero, and a soil-moisture term is not included in the water-budget equation. Therefore, a simple annual water budget for basins where ground-water divides and surface-water divides coincide can be expressed as

$$P = SF + \Delta GWS + \Delta SWS + ET, \quad (1)$$

where P is precipitation,
SF is streamflow,
ΔGWS is change in ground-water storage,
ΔSWS is change in surface-water storage, and
ET is evapotranspiration.

All terms in the water-budget equation can be measured or estimated except ET; equation 1 is solved for ET.

Water budgets are presented in table 8 for Cooks, Tinicum, Paunnacussing, and Mill Creeks for 1991-92. Ground-water divides and surface-water divides generally coincide for these basins. No water is exported or imported from these basins. Equation 1 was used to calculate the water budgets. Data-collection sites necessary to calculate a water budget include a precipitation gage (*P*), a streamflow-measurement station (*SF*), observation wells to estimate the change in ground-water storage (ΔGWS), and data on storage changes in surface-water impoundments (ΔSWS). Only the Tohickon Creek Basin has a surface-water impoundment. Figure 25 shows the basins for which water budgets were prepared and the location of data-collection stations.

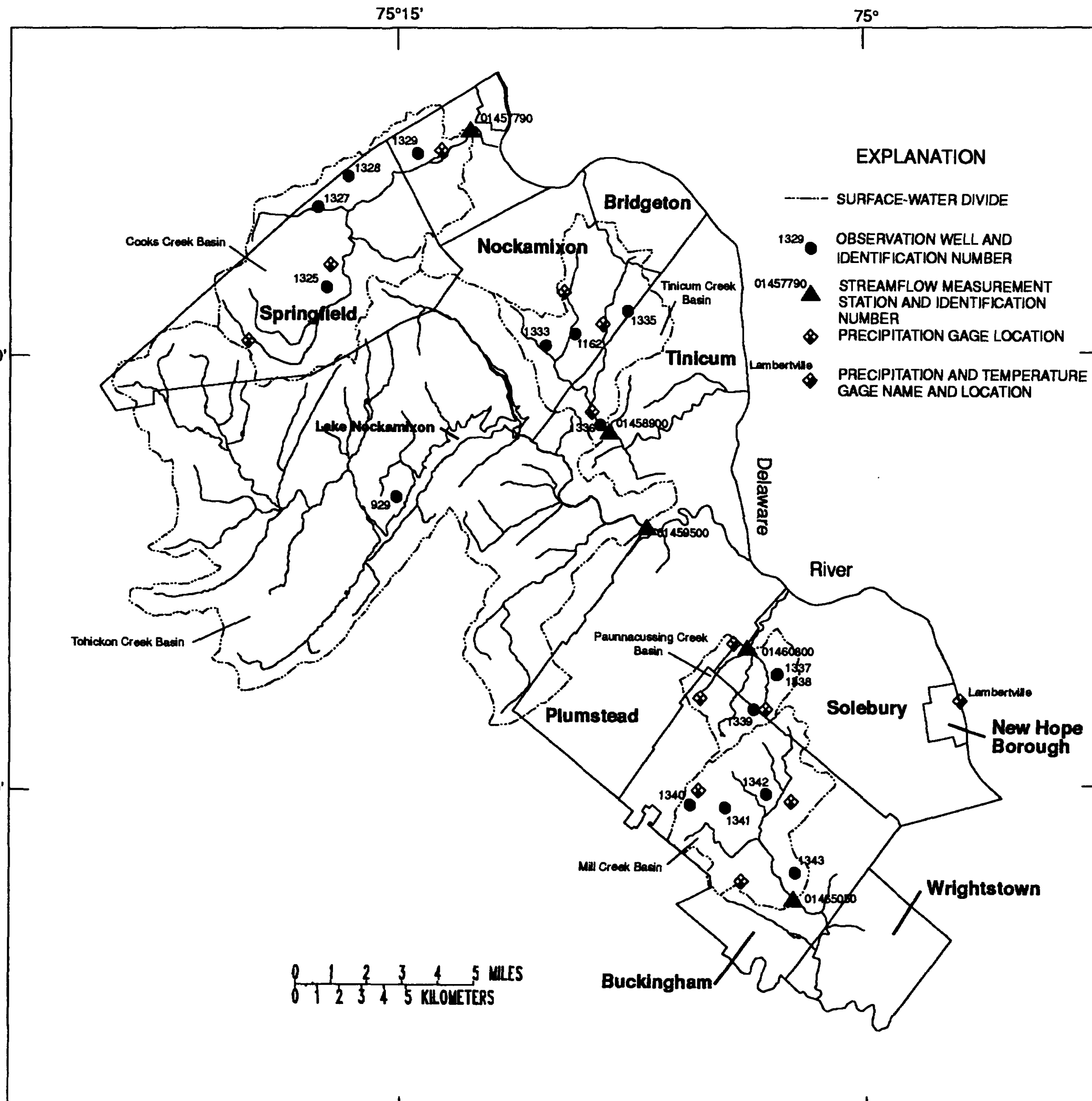


Figure 25. Locations of water budget data-collection sites in northern Bucks County.

Table 8. *Annual water budgets for Cooks, Tinicum, Paunnacussing, and Mill Creeks, 1991-92*
[<, less than]

	Precipitation (inches)	Streamflow (inches)	Percentage of precipitation as streamflow	Change in ground-water storage (inches)	Percentage of precipitation as change in ground-water storage	Evapotranspiration and other losses (inches)	Percentage of precipitation as evapotranspiration
Cooks Creek							
1991	41.1	18.6	45	-0.7	2	23.2	56
1992	43.9	19.4	44	+.3	1	24.3	55
Average	42.5	19.0	45	-.2	<1	23.8	56
Tinicum Creek							
1991	39.8	13.1	33	-.5	1	27.1	68
1992	43.3	14.7	34	.0	0	28.6	66
Average	41.5	13.9	33	-.2	<1	27.9	67
Paunnacussing Creek							
1991	43.3	14.8	34	-.8	2	29.4	68
1992	40.0	19.5	49	+.6	2	20.0	50
Average	41.7	17.2	41	-.1	<1	24.7	59
Mill Creek							
1991	39.8	11.6	29	-2.0	5	30.1	75
1992	40.5	9.9	24	+.2	<1	30.5	75
Average	40.2	10.8	27	-.9	2	30.3	75
Four basin weighted average							
1991-92	41.7	15.9	38	-.3	<1	26.2	63

Precipitation data for the Cooks, Tinicum, Paunnacussing, and Mill Creek Basins were collected at two or three sites in each basin by volunteer observers. Annual precipitation for each basin is the average precipitation measured at the gages in the basin. Water-level data from observation wells in each basin were used to calculate the change in ground-water storage. Water levels were measured in January of each year to determine the annual water-level change. The annual water-level change was multiplied by 0.02, the estimated specific yield of the zone of water-level fluctuation (Wood, 1980, p. 18-19; Nutter, 1975, p. 10), to calculate the annual change in ground-water storage. Ground water is not exported from any of the basins. ET in the water budgets includes ET and other losses, interbasin underflow, and any errors in the measurement of the other water-budget components. Water budgets in table 8 are expressed in inches so that water budget components can be related to precipitation and basins with different drainage areas can be easily compared. Inches can be converted to million gallons per day per square mile by multiplying by 0.048.

Normal (1961-90) annual precipitation measured at the NOAA Lambertville, N.J., precipitation gage is 45.43 in. Annual precipitation in the four basins for 1991 and 1992 ranged from 39.8 to 43.9 in. Therefore, the water budgets for 1991 and 1992 represent water budgets for years of below normal precipitation (see fig. 2).

Cooks Creek Basin

The Cooks Creek Basin is in Springfield Township in the northern part of the study area (fig. 25). The drainage area above the streamflow-measurement station (01457790) is 29.4 mi^2. The basin is underlain by the Brunswick Group (36 percent of the basin), gneiss (20 percent), quartzite conglomerate (17 percent), carbonate rocks (16 percent), Hardyston Quartzite (7 percent), diabase (4 percent), and limestone conglomerate (1 percent).

Precipitation was measured at three gages in the basin. The average annual precipitation for 1991-92 was 42.5 in. (table 8). Average annual ET and other losses were 23.8 in. or 56 percent of the average annual precipitation. The lowest average annual ET was calculated for the Cooks Creek Basin, which also had the highest average annual streamflow of the four basins. Annual streamflow for 1991-92 was 19 in., which was 45 percent of the average annual precipitation. Water-level data for four wells (BK-1325, BK-1327, BK-1328, and BK-1329) in the basin were used to calculate the change in ground-water storage. The average annual change in ground-water storage was a decrease of 0.2 in., which was less than 1 percent of the average annual precipitation.

Tinicum Creek Basin

Tinicum Creek above the streamflow-measurement station (01458900) drains 14.7 mi^2 in Bridgeton, Nockamixon, and Tinicum Townships (fig. 25). The basin is underlain by diabase (54 percent of the basin) and the Brunswick Group (46 percent).

Precipitation was measured at three gages in the basin. The average annual precipitation for 1991-92 was 41.5 in. (table 8). Average annual ET and other losses were 27.9 in. or 67 percent of the average annual precipitation. Annual streamflow for 1991-92 was 13.9 in., which was 33 percent of the average annual precipitation. Water-level data for four wells (BK-1162, BK-1333, BK-1335, and BK-1336) in the basin were used to calculate the change in ground-water storage. The average annual change in ground-water storage was a decrease of 0.2 in., which was less than 1 percent of the average annual precipitation.

Paunnacussing Creek Basin

Paunnacussing Creek above the streamflow-measurement station (01460800) drains 6.49 mi^2 in Buckingham, Plumstead, and Solebury Townships (fig. 25). The basin is underlain by the Stockton Formation (95 percent of the basin) and the Lockatong Formation (5 percent).

Precipitation was measured at three gages in the basin. The average annual precipitation for 1991-92 was 41.7 in. (table 8). Average annual ET and other losses were 24.7 in. or 59 percent of the average annual precipitation. Annual streamflow for 1991-92 was 17.2 in., which was 41 percent of the average annual precipitation. Water-level data for three wells (BK-1337, BK-1338, and BK-1339) in the basin were used to calculate the change in ground-water storage. The average annual change in ground-water storage was a decrease of 0.1 in., which was less than 1 percent of the average annual precipitation.

Mill Creek Basin

Mill Creek above the streamflow-measurement station (01465050) drains 14 mi^2 in Buckingham and Solebury Townships (fig. 25). The basin is underlain by the Stockton Formation (49 percent of the basin), carbonate rocks (29 percent), the Brunswick Group (15 percent), Hardyston Quartzite (6 percent), and other rocks (1 percent).

Precipitation was measured at two gages in the basin in 1991 and at one gage in 1992. The average annual precipitation for 1991-92 was 40.2 in. (table 8). Average annual ET and other losses were 30.3 in. or 75 percent of the average annual precipitation. The highest average annual ET was calculated for the Mill Creek Basin, which also had the lowest average annual streamflow of the four basins. Annual streamflow for 1991-92 was 10.8 in., which was 27 percent of the average annual precipitation. Water-level data for four wells (BK-1340, BK-1341, BK-1342, and BK-1343) in the basin were used to calculate the change in ground-water storage. The average annual change in ground-water storage was a decrease of 0.9 in., which was 2 percent of the average annual precipitation.

Average water-budget components for 1991-92, weighted by drainage area, for the four basins are given in table 8. Average annual precipitation for 1991-92 was 41.7 in. Average annual ET and other losses for 1991-92 were 26.2 in. or 63 percent of precipitation. Average annual streamflow for 1991-92 was 15.9 in., which was 38 percent of the average precipitation. The average annual change in ground-water storage for 1991-92 was a decrease of 0.3 in., which was less than 1 percent of the average annual precipitation.

Tohickon Creek Basin

Tohickon Creek above the streamflow-measurement station near Pipersville (01459500) drains 97.4 mi^2 in northern and central Bucks County (fig. 25). Although most of the Tohickon Creek Basin lies outside the study area, Tohickon Creek drains the same hydrogeologic units that are found in the study area. Lake Nockamixon, 6.2 mi upstream of the streamflow-measurement station, is a large surface-water impoundment on Tohickon Creek that affects record at the station. Construction of the Lake Nockamixon dam began in September 1971. Filling of the impoundment began in December 1973. A change in surface-water storage term is included in the water budgets for the Tohickon Creek Basin to account for water stored or released from Lake Nockamixon. Table 9 presents water budgets for the Tohickon Creek Basin for 1968-91. The annual change in ground-water storage was calculated from water-level data from well BK-929 (period of record, November 1967 to current year). Water-level measurements on or close to January 1 of each year were used to calculate the annual water-level change. The annual water-level change was multiplied by 0.02, the estimated specific yield of the zone of water-level fluctuation, to calculate the change in ground-water storage.

Table 9. *Annual water budget for Tohickon Creek, 1968-91*

[All values are in inches.]

Year	Precipitation	Streamflow	Change in surface-water storage	Change in ground-water storage	Evapotranspiration, other losses, and error
1968	47.0	18.3	0.0	0.0	28.7
1969	44.8	14.9	.0	+.9	29.0
1970	42.1	21.6	.0	-.2	20.7
1971	51.1	29.1	.0	+.4	21.6
1972	52.0	33.0	.0	+.1	18.9
1973	51.6	27.9	1.3	-.3	22.7
1974	45.5	15.6	5.3	+1.1	23.5
1975	60.5	33.6	-3.7	-.1	30.7
1976	39.2	10.8	4.5	-1.0	25.0
1977	51.9	26.3	-.5	+.8	25.1
1978	48.6	23.1	.5	+.9	24.1
1979	59.2	37.8	.0	+.7	20.7
1980	35.3	11.3	-.1	-1.7	25.8
1981	41.1	12.0	.2	+1.1	27.9
1982	41.0	17.1	.0	-.8	24.6
1983	56.2	32.6	.1	+.7	22.7
1984	55.2	34.3	.0	+.1	20.8
1985	41.3	15.3	.0	-.1	26.0
1986	44.7	21.9	.0	+.4	22.4
1987	43.1	17.4	.0	-.3	26.0
1988	38.7	18.3	.0	-.5	20.9
1989	56.9	30.0	.0	+.7	26.2
1990	44.6	24.8	.0	+.2	19.6
1991	42.4	14.8	-.1	-1.2	28.9
Average	47.2	22.6	.3	+.1	24.3

Precipitation data from a single station in the Tohickon Creek Basin during 1968-91 are not available. NOAA precipitation gages in and near the basin operating in 1968 were discontinued or have missing record. Average annual precipitation for the Tohickon Creek Basin for 1968-91 was provided by the National Weather Service (Joseph Miketta, National Weather Service, written commun., 1994). Annual precipitation given in table 9 is an average annual precipitation derived from published and unpublished data from the Palm, Sellersville, Bucksville, Lambertville, Quakertown, Perkasie, Doylestown, and George School NOAA precipitation gages. Precipitation measured at these gages may not be representative of precipitation falling on the basin and may introduce error into the water budgets. Errors in precipitation measurement are included in the ET term in equation 1.

Averages for precipitation and ET given in table 9 for the Tohickon Creek Basin are probably reasonable estimates of a long-term average. The average annual precipitation for 1968-91 was 47.2 in. Average annual ET and other losses were 24.3 in. or 52 percent of the average annual precipitation. Annual streamflow for 1968-91 was 22.6 in., which was 48 percent of the average annual precipitation.

Recharge

All recharge to the ground-water system is derived from local precipitation. Infiltrated precipitation first replenishes soil moisture. After the soil-moisture deficit has been satisfied, infiltrated precipitation recharges the ground-water system. Recharge to the ground-water system depends on many factors, including the duration and intensity of precipitation, antecedent soil-moisture conditions, slope, degree of urbanization, and soil and bedrock characteristics. Recharge varies from season to season and from year to year. Generally, recharge occurs on hilltops and hillsides; topographically low areas commonly are discharge areas.

Recharge was estimated for the Cooks, Tinicum, Paunnacussing, and Mill Creek Basins for 1991-92 (table 10) by use of the following equation:

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

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

Base flow was estimated by hydrograph-separation techniques described in the following section. Ground-water ET is ET directly from the saturated zone; it takes place where the water table is close to the land surface. Ground-water ET is estimated to be 2 in/yr on the basis of simulation of hydrologic budgets that use a ground-water-flow model by Sloto (1991a). Olmsted and Hely (1962, p. 13) estimated an annual ground-water ET of 5.5 in. for the Piedmont. Most observation wells used to calculate change in ground-water storage do not have water levels close to land surface; therefore, loss to ground-water ET is not reflected in water levels from these wells. The same assumptions made for equation 1 in the Water Budget section are made for equation 2. Estimated recharge in table 10 is given in inches so that recharge can be related to precipitation and basins with different drainage areas can be easily compared. Inches can be converted to million gallons per day per square mile by multiplying by 0.048.

Precipitation for 1991 and 1992 is similar (table 8). Precipitation differences between 1991 and 1992 range from 0.7 in. in the Mill Creek Basin to 3.5 in. in the Tinicum Creek Basin. Therefore, recharge can be expected to be similar in 1991 and 1992. The recharge estimates presented in table 10 are representative of years with below normal precipitation and probably are not representative of a long-term average.

For 1991, estimated recharge ranged from 8.2 in. in the Tinicum and Mill Creek Basins to 12.4 in. in the Cooks and Paunnacussing Creek Basins. Estimated recharge for the four basins for 1991 weighted by drainage area was 10.5 in. [0.504 (Mgal/d)/mi^2]. For 1992, estimated recharge ranged from 8.2 in. in the Mill Creek Basin to 12.1 in. in the Paunnacussing Creek Basin. Estimated recharge for the four basins for 1992 weighted by drainage area was 9.5 in. [0.456 (Mgal/d)/mi^2]. Average estimated recharge for the four basins for 1991-92 weighted by drainage area was 10.1 in. [0.485 (Mgal/d)/mi^2]; this is equal to a recharge rate of 758 gal/d per acre.

Table 10. *Estimated recharge for the Cooks, Tinicum, Paunnacussing, and Mill Creek Basins, 1991-92*

	Recharge (inches)	Percentage of precipitation as recharge	Base flow (inches)	Change in ground-water storage (inches)	Estimated ground-water evapotranspiration (inches)
Cooks Creek					
1991	12.4	30	11.1	-0.7	2.0
1992	9.9	23	7.7	+.3	2.0
Average	11.2	26	9.4	-.2	2.0
Tinicum Creek					
1991	8.2	21	6.7	-.5	2.0
1992	8.6	20	6.6	0.0	2.0
Average	8.4	20	6.7	-.2	2.0
Paunnacussing Creek					
1991	12.4	29	11.3	-.8	2.0
1992	12.1	30	9.5	.6	2.0
Average	12.3	29	10.4	-.1	2.0
Mill Creek					
1991	8.2	20	8.2	-2.0	2.0
1992	8.2	20	6.1	+.2	2.0
Average	8.2	20	7.1	-.9	2.0
Four basin weighted average					
1991-92	10.1	24	8.4	-.3	2.0

Ground-Water/Surface-Water Relations

The ground-water and surface-water systems are well connected in northern Bucks County. In most areas, streams act as drains for the shallow ground-water system and gain water. In some places, stream reaches may lose water and recharge the ground-water system. Potentiometric-surface maps for northern Bucks County (Schreffler, 1993a, 1993b, 1993c; McManus and Rowland, 1993; and McManus and others, 1994) show that water levels in wells near streams are higher than stream elevations, indicating that ground water discharges to streams and most stream reaches are gaining reaches.

Seepage investigations were conducted during base-flow conditions in the Paunnacussing Creek Basin and on a reach of Tohickon Creek below Lake Nockamixon dam. The potentiometric-surface maps of Schreffler (1993c) and McManus and others (1994) indicated that Paunnacussing Creek was a gaining stream throughout its entire length. Discharge data for Paunnacussing Creek (table 11 and fig. 26) show that all reaches measured were gaining reaches.

The potentiometric-surface map of McManus and Rowland (1993) indicated that the reach of Tohickon Creek below Lake Nockamixon dam was a losing reach. Discharge data for Tohickon Creek (table 12 and fig. 27) show a streamflow gain of 2.8 ft^3/s between sites 13 and 11, a streamflow loss of 3.44 ft^3/s between sites 11 and 7, and streamflow gains between sites 7 and 3 and between sites 3 and 1. The potentiometric-surface map of McManus and Rowland (1993) shows that water levels measured in wells in the area between measurement sites 11 and 7 are below the elevation of Tohickon Creek, indicating loss of water from the stream into the aquifer. Discharge measurements of Tohickon Creek confirm that this loss is occurring. The potentiometric-surface map of McManus and Rowland (1993) shows that a hydraulic gradient exists between Tohickon Creek and Tinicum Creek in this area, and that the direction of ground-water flow is from Tohickon Creek to Tinicum Creek. Streamflow lost from Tohickon Creek to the ground-water system in the reach between sites 11 and 7 is discharged to Tinicum Creek.

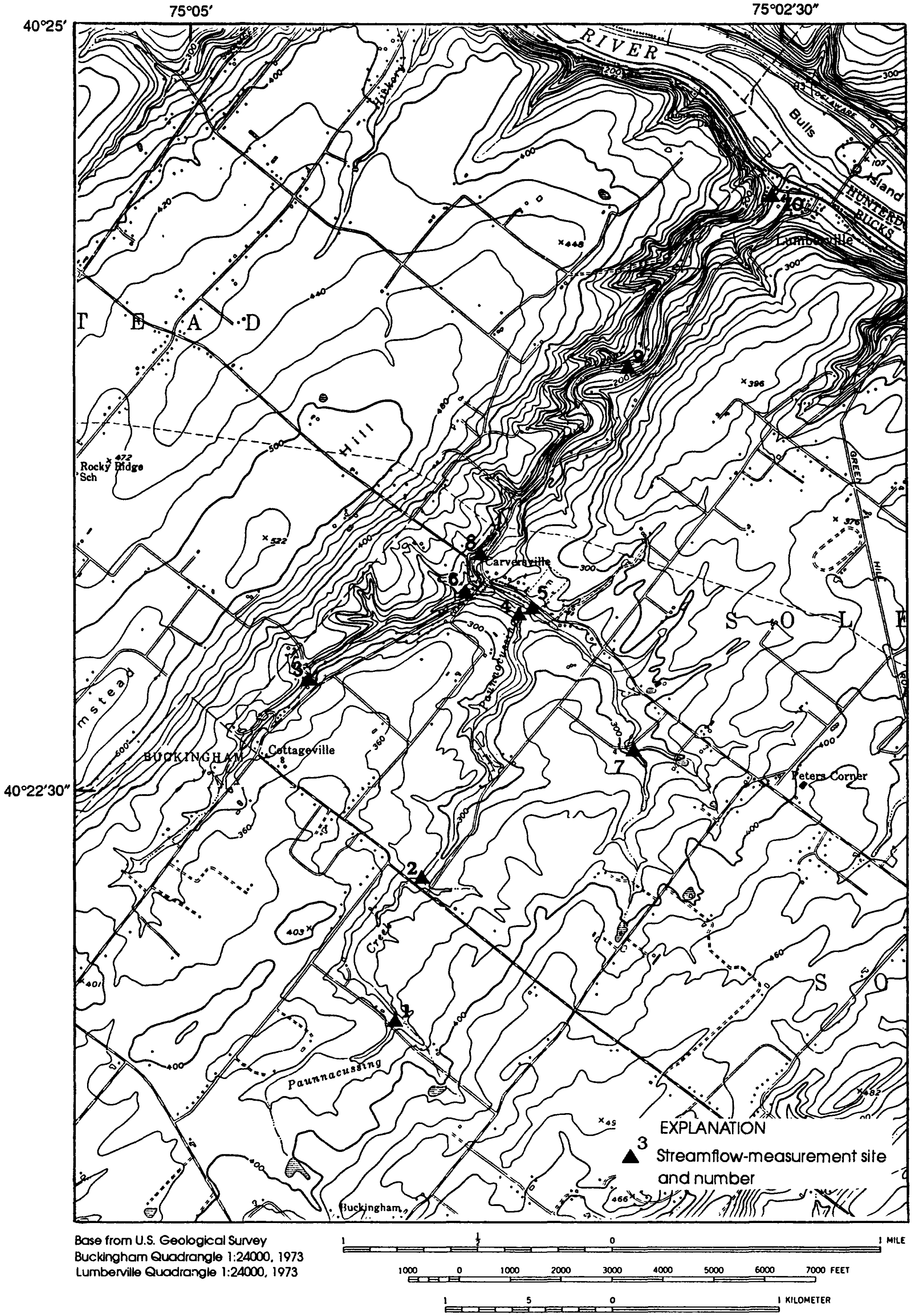


Figure 26. Locations of discharge-measurement sites on Paunnacussing Creek, December 9, 1992.

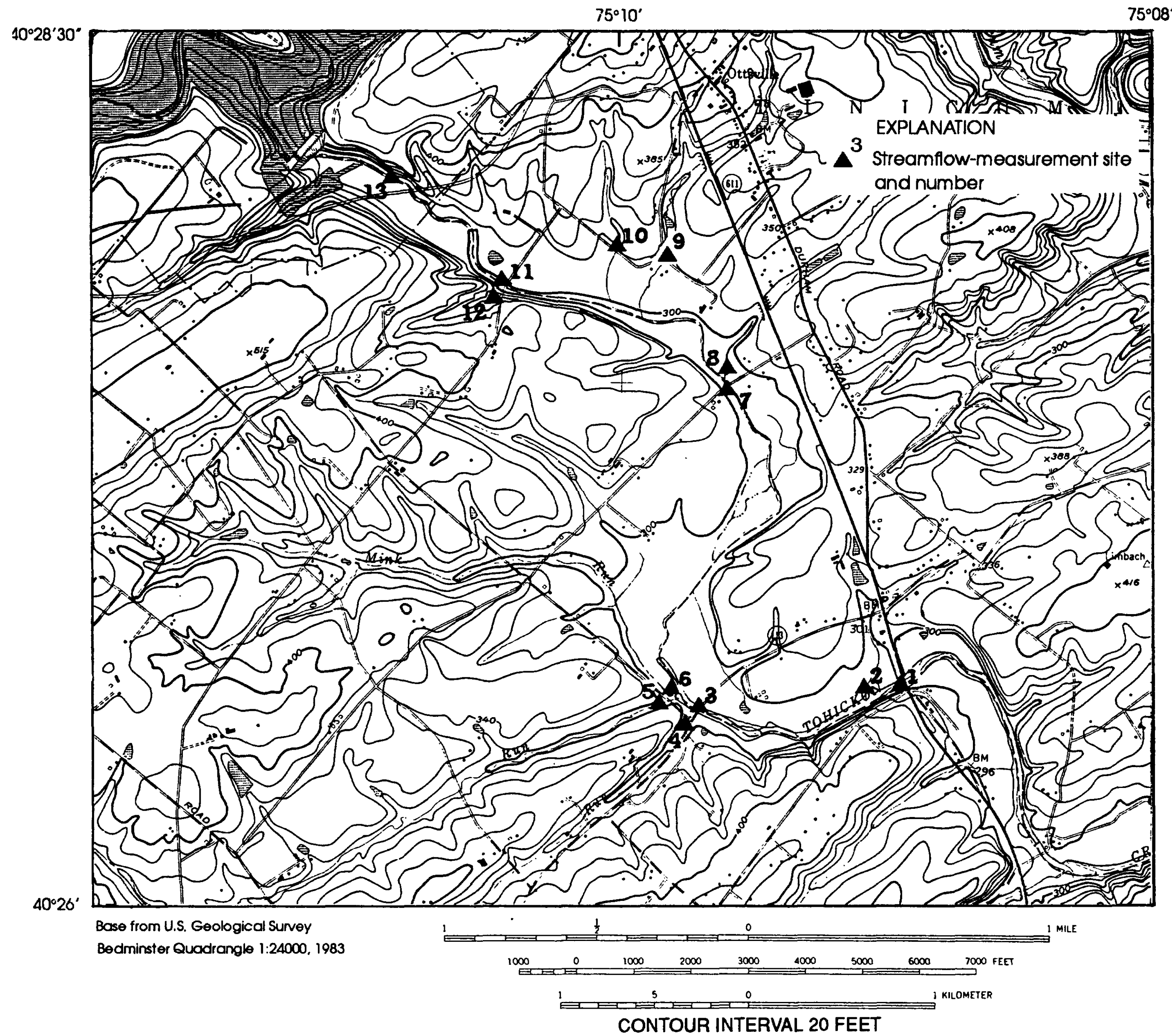


Figure 27. Locations of discharge-measurement sites on Tohickon Creek, December 8, 1992.

***Table 11.** Discharge measured during seepage investigation of Paunnacussing Creek, December 9, 1992*

[Measurement sites shown on figure 26; --, no data]

Site number	Stream location and latitude-longitude or station number	Discharge (cubic feet per second)			
		Tributary	Main stream	Gain or loss	
				Segment	Cumulative
1	Paunnacussing Creek at Indian Springs Road, 20 feet downstream from culvert (402143 0750410)	--	0.51	--	--
2	Paunnacussing Creek at Street Road, 50 feet downstream from bridge (402211 0750404)	--	1.21	0.70	0.70
4	Paunnacussing Creek near Carversville, 100 feet upstream from unnamed tributary near Aquetong Road (402305 0750337)	--	1.80	.59	1.29
7	Unnamed tributary to Paunnacussing Creek near Aquetong Road, 3,500 feet upstream from mouth (402237 0750310)	0.89	--	--	--
5	Unnamed tributary to Paunnacussing Creek near Aquetong Road, 100 feet upstream from mouth (402305 0750336)	1.60	--	.71	--
3	Unnamed tributary to Paunnacussing Creek near Carversville Road, 70 feet upstream from McNeal Road bridge (402252 0750430)	.57	--	--	--
6	Unnamed tributary to Paunnacussing Creek at Carversville near Carversville Road, 500 feet upstream from mouth (402307 0750351)	1.00	--	.43	--
8	Paunnacussing Creek at Carversville Road, 25 feet downstream from streamflow measurement-station (01460800)	--	5.10	.70	1.99
9	Paunnacussing Creek near Lumberville near Fleecy Dale Road, 200 feet below Fretz Mill Road intersection (402352 0750310)	--	5.22	.12	2.11
10	Paunnacussing Creek at Lumberville, 200 feet upstream from Route 32 bridge (402427 0750232)	--	5.60	.38	2.50

***Table 12.** Discharge measured during seepage investigation of Tohickon Creek, December 8, 1992*

[Measurement sites shown on figure 27; --, no data]

Site number	Stream location and latitude-longitude	Discharge (cubic feet per second)			
		Tributary	Gain or loss		
			Main stream	Segment	Cumulative
13	Tohickon Creek at South Park Road, 500 feet upstream from bridge (402805 0751052)	--	29.2	--	--
11	Tohickon Creek at Fretz Valley Road, 100 feet upstream from bridge (402747 0751027)	--	32.0	2.80	2.80
12	Unnamed tributary to Tohickon Creek at Fretz Valley Road, 15 feet upstream from mouth (402746 0751028)	0.06	--	--	--
10	Unnamed tributary to Tohickon Creek at Creamery Road, 10 feet upstream from culvert (402753 0751000)	.51	--	--	--
9	Unnamed tributary to Tohickon Creek at Tohickon Valley Road, 100 feet upstream from culvert (402755 0750950)	.16	--	--	--
8	Unnamed tributary to Tohickon Creek near Farm School Road, 25 feet upstream from mouth (402733 0750936)	.21	--	--	--
7	Tohickon Creek at Farm School Road, 25 feet upstream from bridge (402730 0750936)	--	29.5	-3.44	-.64
6	Mink Run at Deer Run Road, 50 feet upstream from mouth (402636 0750950)	.01	--	--	--
5	Deer Run at Deer Run Road, 250 feet upstream from mouth (402635 0750950)	1.25	--	--	--
4	Wolf Run at Deer Run Road, 50 feet upstream from mouth (402632 0750945)	.47	--	--	--
3	Tohickon Creek below Wolf Run, 50 feet upstream from Bedminster Road bridge (402633 0750942)	--	32.1	.87	.23
2	Unnamed tributary to Tohickon Creek near Pipersville, 50 feet upstream from mouth (402637 0750905)	.14	--	--	--
1	Tohickon Creek near Pipersville, 100 feet upstream from Route 611 bridge (402638 0750857)	--	33.4	1.16	1.40

The capacity of a basin to store ground water can be illustrated by flow-duration curves. Flow-duration curves for Cooks, Tinicum, Paunnacussing, and Mill Creeks for 1991-92 are shown in figure 28. A flow-duration curve is a cumulative frequency curve that shows the percentage of time specified discharges were equaled or exceeded during a given period. The curves describe the flow characteristics of a stream without regard to the sequence of occurrence. Flow-duration curves in figure 28 are mean daily discharge in cubic feet per second per square mile so that drainage basins of different sizes can easily be compared. Although the flow-duration curves for 1991-92 represent flow for a period of slightly below normal precipitation and are not representative of the long-term probability distribution, they give an indication of the variability of streamflow among the basins. Flatter slopes, particularly at the lower end of the flow-duration curve, indicate streamflow contributions from the ground-water system. The flow-duration curves in figure 28 shows that the flow of Cooks Creek is better sustained by ground-water discharge at the low end of the discharge range than the flow in other basins. The flow of Tinicum Creek is poorly sustained by ground-water discharge at the low end of the discharge range, largely because 54 percent of the basin is underlain by diabase.

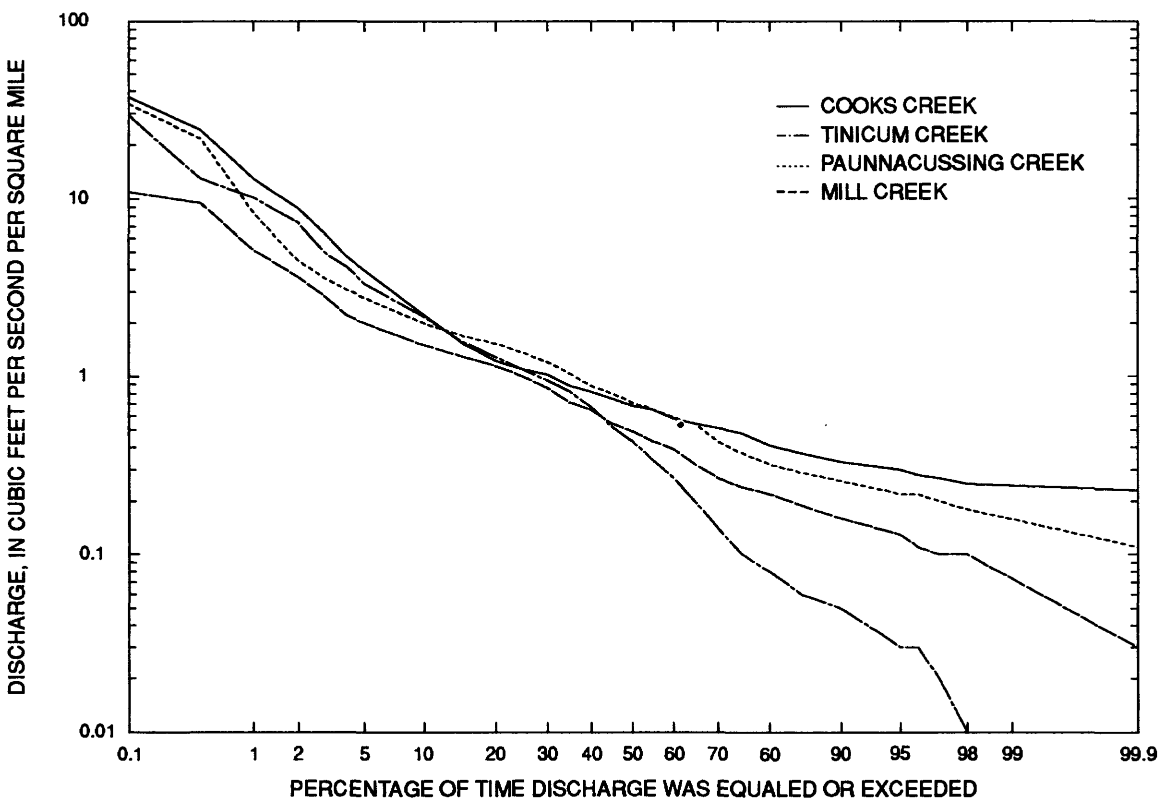


Figure 28. Duration of daily discharge of Cooks, Tinicum, Paunnacussing, and Mill Creeks, 1991-92.

Discharge ratios taken from the flow-duration curves can be used to quantitatively compare the capacity of the four basins to store ground water (Walton, 1970). The discharge ratio is calculated by the following equation:

$$\text{discharge ratio} = (Q_{25}/Q_{75})^{0.5} , \qquad (3)$$

where Q_{25} is discharge that is equalled or exceeded 25 percent of the time, and
Q_{75} is discharge that is equalled or exceeded 75 percent of the time.

Small ratios represent relatively permeable basins with a large storage capacity; larger ratios represent less permeable basins with a smaller storage capacity. Discharge ratios are given in table 13. The smallest discharge ratio was calculated for the Cooks Creek Basin, indicating that it has the largest storage capacity. The largest discharge ratio was calculated for the Tinicum Creek Basin, indicating that it has the smallest storage capacity.

Table 13. *Discharge ratios for Cooks, Tinicum, Paunnacussing, and Mill Creeks*

Basin	Discharge ratio
Cooks Creek	1.56
Mill Creek	2.18
Paunnacussing Creek	2.30
Tinicum Creek	3.32

Streamflow is composed of ground-water discharge (base flow) and surface runoff. Olmsted and Hely (1962, p. 9-16) found a direct, linear relation between the monthly average ground-water level in shallow wells and base flow during winter months.

Figure 29 shows the relation among precipitation, the water level observed in well BK-1840, and streamflow and base flow at the streamflow-measurement station in the Mill Creek Basin during 1992. The shape of the base-flow hydrograph and water-level hydrograph is very similar. Base flow generally declines as ground-water levels decline and increases when ground-water levels increase. The time of lowest base flow generally coincides with the lowest ground-water levels.

Precipitation during the summer (June through September) generally produces little increase in ground-water levels (fig. 29); most of the infiltrated precipitation replenishes soil moisture and does not recharge the ground-water system. For example, the storm of September 26-28, 1992, produced 1.95 in. of precipitation; however, the discharge of Mill Creek at the streamflow-measurement station increased only 10.3 ft^3/s, and the water level in well BK-1840 rose only 0.17 ft (fig. 29). Precipitation during the late fall and winter, after the soil-moisture deficit has been satisfied, produces a much larger increase in ground-water levels and discharge. For example, the storm of November 23-25, 1992, produced 1.6 in. of precipitation; the discharge of Mill Creek at the streamflow-measurement station increased 66 ft^3/s, and the water level in well BK-1840 rose 2.74 ft (fig. 29). The storm of December 11-12, 1992, produced 3.14 in. of precipitation; the discharge of Mill Creek at the streamflow-measurement station increased 290 ft^3/s, and the water level in well BK-1840 rose 13.43 ft.

Streamflow is separated into base-flow and surface-runoff components by use of hydrograph-separation techniques. Hydrographs for 1991 and 1992 for Cooks, Tinicum, Paunnacussing, and Mill Creeks were separated into base-flow and surface-runoff components by use of the local-minimum technique of the computer program of Sloto (1991b). A detailed discussion of hydrograph separation for Pennsylvania streams is given by White and Sloto (1991). Daily streamflows for Cooks, Tinicum, Paunnacussing, and Mill Creeks (for 1991 and 1992) were published by Kolva and others (1992) and White and others (1993). The results of the hydrograph separations are given in table 14. The data in table 14 represent base flow and surface runoff for years of below normal precipitation and probably are not representative of a long-term average. Streamflow, base flow, and surface runoff in table 14 are expressed in inches so that basins with different drainage areas can be easily compared. Inches can be converted to million gallons per day per square mile by multiplying by 0.048.

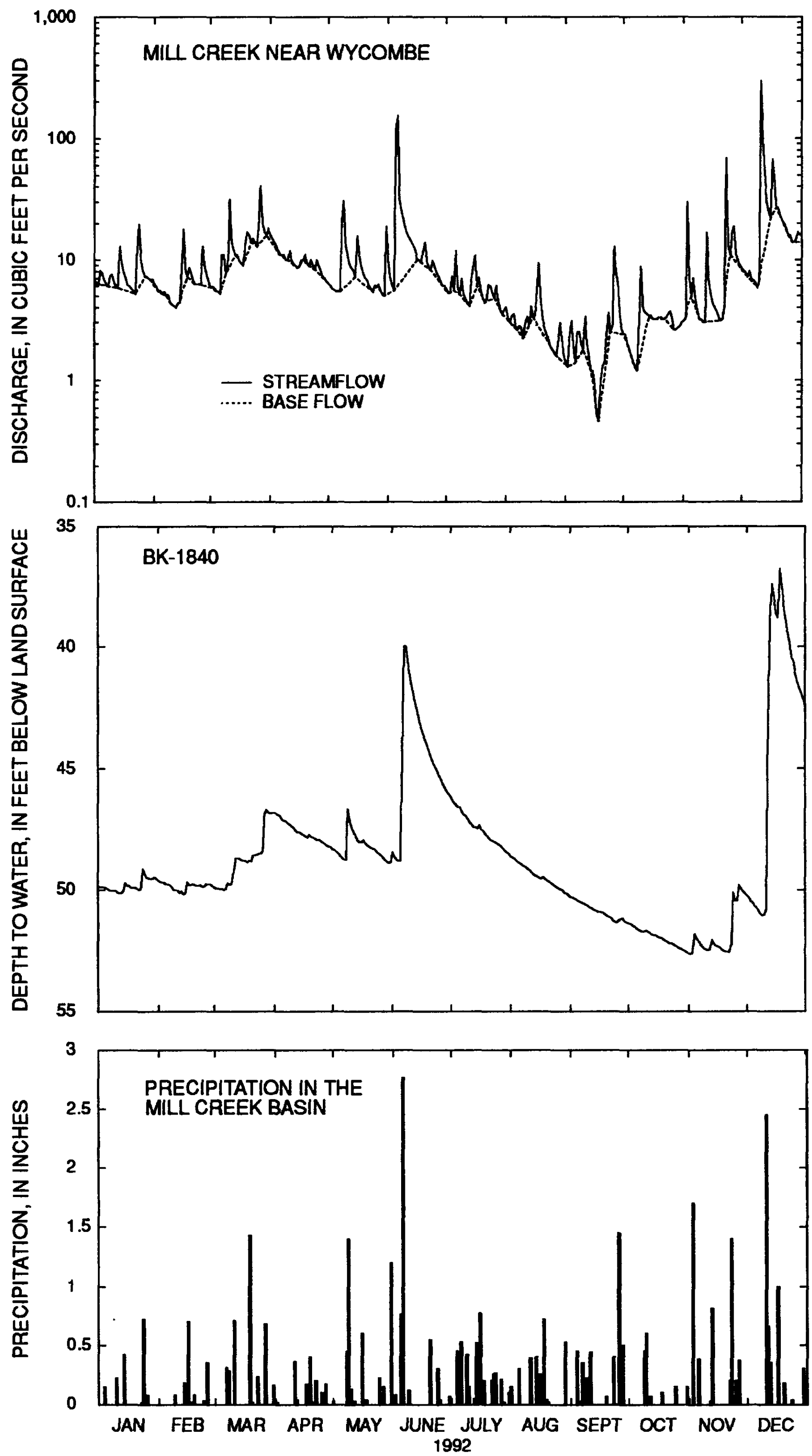


Figure 29. Relations among precipitation, ground-water levels, streamflow, and base flow in the Mill Creek Basin, 1992.

Table 14. *Annual streamflow and estimated base flow for Cooks, Tinicum, Paunnacussing, and Mill Creeks, 1991-92*

	Total streamflow (inches)	Base flow (inches)	Percentage of streamflow as base flow	Percentage of precipitation as base flow	Surface runoff (inches)	Percentage of streamflow as surface runoff	Percentage of precipitation as surface runoff
Cooks Creek							
1991	18.6	11.1	60	28	7.4	40	18
1992	19.4	7.7	40	18	11.7	60	27
Average	19.0	9.4	49	22	9.6	51	23
Tinicum Creek							
1991	13.1	6.7	51	17	6.4	49	16
1992	14.7	6.6	45	15	8.1	55	19
Average	13.9	6.7	48	16	7.2	52	17
Paunnacussing Creek							
1991	14.8	11.3	76	26	3.6	24	8
1992	19.5	9.5	49	24	10.0	51	2
Average	17.1	10.5	61	25	6.8	39	16
Mill Creek							
1991	11.6	8.2	71	21	3.5	29	9
1992	9.9	6.1	62	15	3.8	38	9
Average	10.8	7.1	66	18	3.6	34	9
Four basin weighted average							
1991-92	15.8	8.4	53	20	7.4	47	18

In the Cooks Creek Basin (fig. 30), average annual ground-water discharge to streams (base flow) for 1991-92 was 9.4 in., which was 22 percent of the average annual precipitation and 49 percent of the average annual streamflow (table 14). Average annual surface runoff for 1991-92 was 9.6 in., which was 23 percent of the average annual precipitation and 51 percent of the average annual streamflow. However, in 1991, ground-water discharge to streams was 60 percent of the streamflow, and in 1992, it was 40 percent of streamflow. The quantity of precipitation that becomes surface runoff depends on the season; form, intensity, and duration of precipitation; and soil-moisture conditions. Frozen ground and snowmelt also may be contributing factors. The Cooks Creek Basin had the highest percentage of precipitation as surface runoff (23 percent) of the four basins.

In the Tinicum Creek Basin (fig. 30), average annual ground-water discharge to streams for 1991-92 was 6.7 in., which was 16 percent of the average annual precipitation and 48 percent of the average annual streamflow (table 14). Average annual surface runoff for 1991-92 was 7.2 in., which was 17 percent of the average annual precipitation and 52 percent of the average annual streamflow. In 1991, ground-water discharge to streams was 51 percent of the streamflow, and in 1992, it was 45 percent of streamflow. The lowest percentage of streamflow and precipitation as base flow (48 and 16 percent, respectively) of the four basins was measured in the Tinicum Creek Basin. The percentage of streamflow as surface runoff (52 percent) of the four basins was highest for the Tinicum Creek Basin. The higher ratio of surface runoff to base flow in the Tinicum Creek Basin is because 54 percent of the basin is underlain by low permeability diabase.

In the Paunnacussing Creek Basin (fig. 30), average annual ground-water discharge to streams for 1991-92 was 10.5 in., which was 25 percent of the average annual precipitation and 61 percent of the average annual streamflow (table 14). Average annual surface runoff for 1991-92 was 6.8 in., which was 16 percent of the average annual precipitation and 39 percent of the average annual streamflow. In 1991, ground-water discharge to streams was 76 percent of the streamflow, and in 1992, it was 49 percent of streamflow. The lower percentage of streamflow as base flow in 1992 was because of a storm on December 11-12, 1992, that produced a large quantity of surface runoff in this small (6.49 mi^2) basin; the mean daily discharge on December 11 was 493 ft^3/s; the mean annual daily discharge for 1992 was 9.3 ft^3/s. On December 11, this storm produced 76 $(ft^3/s)/mi^2$ of surface runoff in the Paunnacussing Creek Basin and

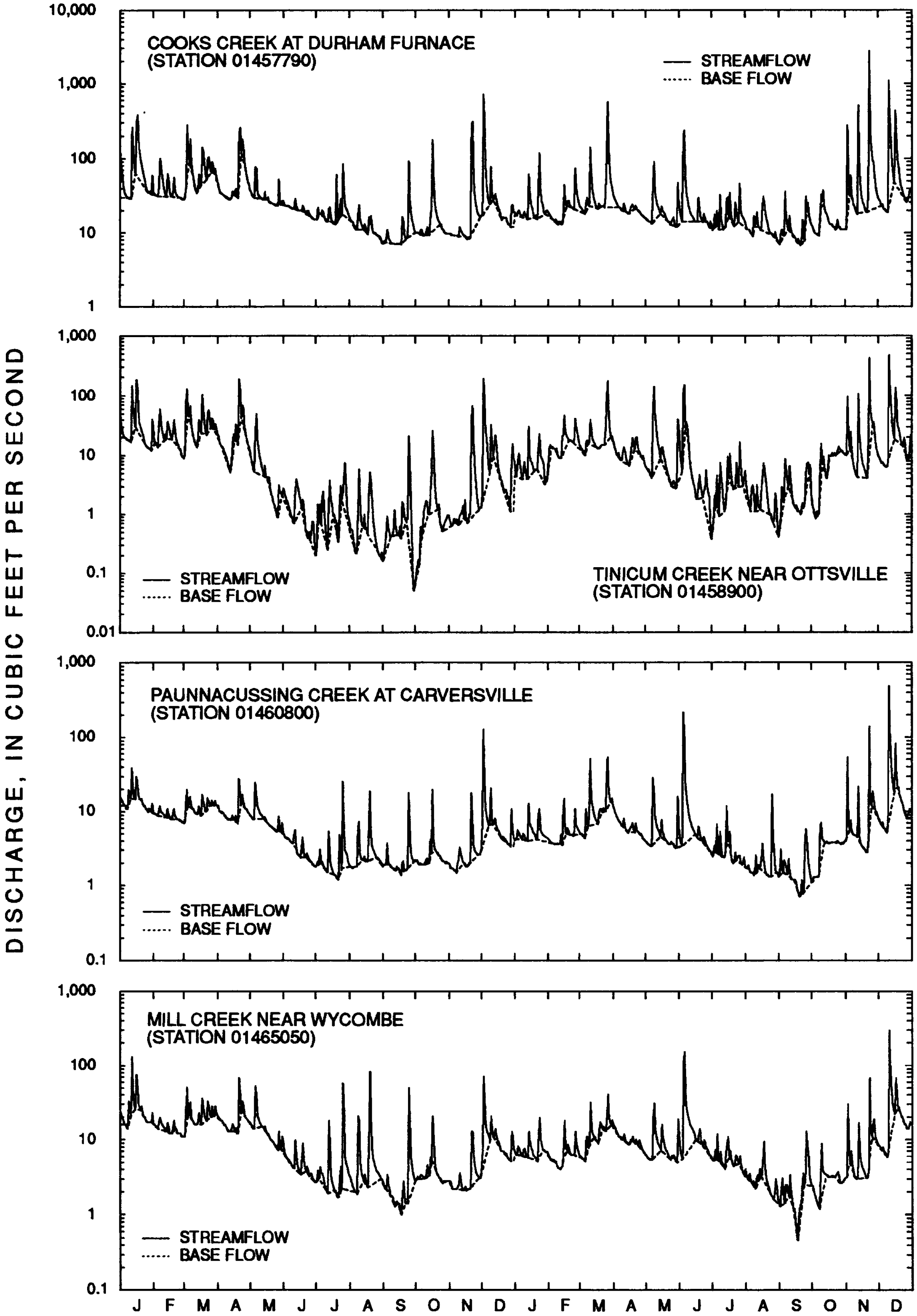


Figure 30. Streamflow and base flow of Cooks, Tinicum, Paunnacussing, and Mill Creeks, 1991-92.

37.1, 32.1, and 21.1 $(ft^3/s)/mi^2$ of surface runoff in the Cooks, Tinicum, and Mill Creek Basins, respectively. The percentage of precipitation as base flow of the four basins was the highest in the Paunnacussing Creek Basin because it is underlain by the high permeability Stockton Formation.

In the Mill Creek Basin (fig. 30), average annual estimated ground-water discharge to streams for 1991-92 was 7.1 in., which was 18 percent of the average annual precipitation and 66 percent of the average annual streamflow (table 14). Average annual surface runoff for 1991-92 was 3.6 in., which was 9 percent of the average annual precipitation and 34 percent of the average annual streamflow. In 1991, ground-water discharge to streams was 71 percent of the streamflow, and in 1992, it was 62 percent of streamflow. The Mill Creek Basin had the highest average percentage of streamflow as base flow and the lowest percentage of streamflow and precipitation as surface runoff of all four basins.

Average annual estimated ground-water discharge to streams for the four basins for 1991-92 weighted by drainage area was 8.4 in. [0.403 $(Mgal/d)/mi^2$], which was 20 percent of the average annual precipitation and 53 percent of the average annual streamflow. Average annual surface runoff for the four basins for 1991-92 weighted by drainage area was 7.4 in., which was 18 percent of the average annual precipitation and 47 percent of the average annual streamflow.

Separation of the hydrograph from the streamflow-measurement station on Tohickon Creek into base-flow and surface-runoff components was done for 1936-71, which is the period of record for the station prior to regulation by Lake Nockamixon. Annual base flows are shown on figure 31, which is a base-flow-frequency curve. A base-flow-frequency curve relates magnitude of base flow to frequency of occurrence. Annual base flow ranged from 2.5 in. [0.12 $(Mgal/d)/mi^2$] in 1965 to 8.4 in. [0.403 $(Mgal/d)/mi^2$] in 1945. The maximum annual base flow for Tohickon Creek for 1936-71 is less than the 1991-92 base flow for Cooks and Paunnacussing Creek (table 14), which represents base flow for years of below normal precipitation. The median base flow was 5.3 in. [0.25 $(Mgal/d)/mi^2$].

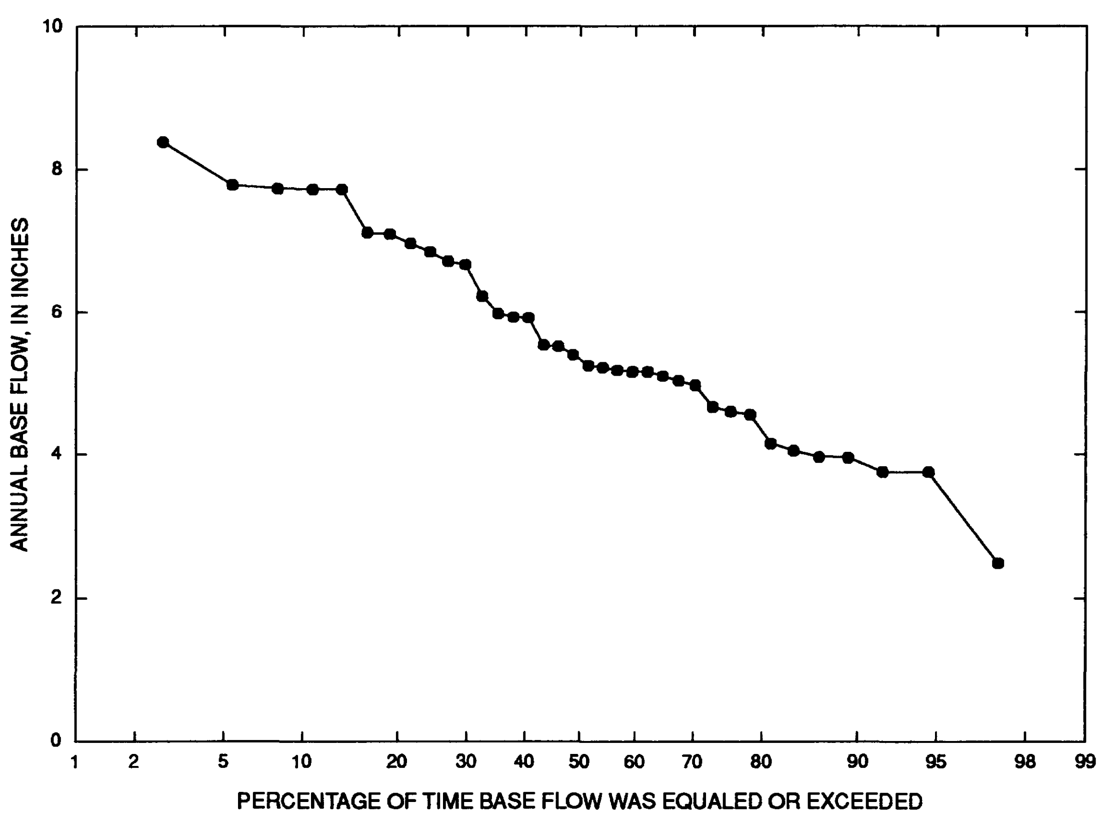


Figure 31. Cumulative base-flow frequency of Tohickon Creek (station 01459500), 1936-71.

Water Use

Approximately 90 percent of residents in the study area rely on domestic wells for their source of water supply. Annual domestic usage is estimated to be 740 Mgal/yr. The estimate was based on the median per capita daily water use of 57 gal/d determined from 21 public water purveyors (Bucks County Planning Commission, 1992a) and 1990 population data (Bucks County Planning Commission, 1993).

Public water purveyors (table 15) supply approximately 10 percent of the residents in the study area. Ground water supplied all of the water for public supplies, except for one small supplier in New Hope Borough that uses a surface-water source. A report by the Bucks County Planning Commission (1992a) contains maps showing the areas served by public water.

***Table 15.** Public water systems in northern Bucks County*

[Mgal/yr, million gallons per year, --, no data]

Name	Source of supply	Well numbers	Year of reported data	Water use (Mgal/yr)
Apple Hill Resident Association	2 wells	BK-1360, 1361	1991	1.4
Buckingham Knoll	2 wells	BK-2289, 2290	1992	1.4
Buckingham Springs	2 wells	BK-1231, 1232	1991	3.4
Buckingham Valley Nursing Center	2 wells	--	1992	2.8
Buckingham Water Company	4 wells	BK-1230, 1289, 1290, 1376	1991	6.0
Bucks County Water and Sewer Authority[1]	2 wells	BK-2519, 2520	1992	3.3
Canterbury Homeowners Association	2 wells	--	1991	1.0
Coopersburg Borough[1]	2 wells	BK-797, 941	1992	105
Country Greene Estates	2 wells	BK-1483, 1484	--	--
Cross Keys Development	1 well	BK-1299	[2]1992	[2]5.4
Doylestown Borough Water Department[1]	1 well	BK-700	1992	76
Durham Ridge	1 well	BK-1846	[2]1992	[2]12
Durham Village Residents Association	2 wells	BK-1362, 1363	1993	7.3
Fieldstone Place	2 wells	BK-1191, 1192	1992	5.2
Hermitage Condominium Association	2 wells	BK-1373, 1374	1991	0.3
Ingham Mews Condominium Association	2 wells	BK-1356, 1357	1991	4.2
Ottshill Apartments	1 well	BK-1372	1988	12
Peddlars Village Partnership	2 wells	BK-1482, 1804	[2]1992	[2]10
Pleasant Manor	2 wells	BK-1381, 2254	1991	1.8
Red Cliff Village Mobile Home Park	1 well	BK-1351	1992	1.2
Springfield Township Water Authority	2 wells 3 springs	BK-921, 940	1992	15
Tohickon Creek Apartments	1 well	BK-1371	--	--
Valley View Mobile Home Park	7 wells	BK-771, 1252, 1253, 1254, 1255, 1256, 1257	1992	17
Village II at New Hope	1 well	BK-1239	1989	23
Yorkshire Meadows Condominium Association	2 wells	BK-1358, 1359	1989	4.4

[1] Wells in study area only.

[2] Estimated use.

GROUND-WATER QUALITY

As water moves through the hydrologic cycle, chemical and mineral substances from the atmosphere, the soil, and rocks are dissolved. The type and quantity of these dissolved substances constitute the quality of ground water. Anthropogenic activities also add substances to ground water and may affect its quality.

Statistical analyses presented below are based on water samples from 87 wells analyzed for physical properties and inorganic compounds and water samples from 34 wells analyzed for volatile organic compounds (VOC's). The data are published by Schreffler and others (1994).

Physical Properties

Physical properties include pH, specific conductance, alkalinity, dissolved oxygen, and temperature. These properties are determined when a water sample is collected because they are unstable and may be affected by storage (Hem, 1985). Physical properties are summarized in table 16.

pH is a measurement of hydrogen ion activity in water. pH is expressed in logarithmic units, and a pH of 7 is considered neutral. Water with a pH less than 7 is acidic; water with a pH greater than 7 is basic. The median pH of water from wells in the Stockton Formation and crystalline rocks is acidic; the median pH of water from wells in quartzite conglomerate is near neutral; and the median pH of water from wells in the diabase, Brunswick Group, Lockatong Formation, and carbonate rocks is basic. Water from wells in the crystalline rocks (median pH of 5.8) has the lowest (most acidic) median pH of the hydrogeologic units. Water from wells in carbonate rocks (median pH of 7.8) has the highest (most basic) median pH of the hydrogeologic units.

Specific conductance is a measurement of the ability of water to conduct an electric current. It is expressed in units of microsiemens per centimeter at 25°C. Water from wells in crystalline rocks has the lowest median specific conductance of the hydrogeologic units (139 µS/cm). Water from wells in the Lockatong Formation has the highest median specific conductance of the hydrogeologic units (428 µS/cm).

In dilute solutions, specific conductance is directly related to the concentration of total dissolved solids (TDS), and TDS concentrations can be estimated from specific-conductance measurements. The TDS concentration of a water sample from carbonate rocks can be estimated by multiplying the specific conductance by 0.58, the median ratio of TDS to the specific conductance of 11 water samples. The TDS concentration of a water sample from the Lockatong Formation can be estimated by multiplying the specific conductance by 0.63, the median ratio of 12 samples. The TDS concentration of water samples from diabase and the Brunswick Group can be estimated by multiplying the specific conductance by 0.65, the median ratio of 10 and 23 samples, respectively. The TDS concentration of a water sample from the Stockton Formation can be estimated by multiplying the specific conductance by 0.69, the median ratio of 11 samples.

The alkalinity of water is the capacity for solutes it contains to react with and neutralize acid (Hem, 1985, p. 106). Alkalinity is produced by dissolved carbon dioxide, bicarbonate, and carbonate and is expressed in terms of an equivalent amount of calcium carbonate. Water from wells in crystalline rocks has the lowest median alkalinity of the hydrogeologic units (16 mg/L as $CaCO_3$) because the crystalline rocks contain few minerals that contribute to alkalinity. Water from wells in the carbonate rocks has the highest median alkalinity of the hydrogeologic units (195 mg/L as $CaCO_3$) because calcium and magnesium carbonate dissolved from carbonate rocks contribute to high alkalinity.

The median concentration of dissolved oxygen of water from wells in all hydrogeologic units, except for the Lockatong Formation, ranges from 4.4 (Brunswick Group) to 9.0 mg/L (crystalline rocks). The median concentration of dissolved oxygen of water from wells in the Lockatong Formation is only 0.8 mg/L. The high median concentration of dissolved oxygen of water from wells in the crystalline rocks is because of the lack of oxidizable minerals. The low median concentration of dissolved oxygen of water from wells in the Lockatong Formation is because of abundant oxidizable minerals, such as pyrite, which deplete the available oxygen.

The median temperature of ground-water samples from 110 wells, 13.5°C, is approximately the mean annual air temperature in northern Bucks County.

Table 16. *Physical properties of ground water in northern Bucks County*

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; °C, degrees Celsius; <, less than; –, too few data to compute statistic]

Constituent or property	Number of wells sampled	Tenth percentile	Median	Ninetieth percentile
pH (units)				
Diabase	14	6.4	7.5	8.8
Quartzite conglomerate	5	–	7.1	–
Brunswick Group	36	7.3	7.7	8.1
Lockatong Formation	16	6.6	7.6	8.5
Stockton Formation	14	5.5	6.6	7.7
Carbonate rocks	15	7.0	7.8	7.9
Crystalline rocks	9	5.1	5.8	7.6
Specific conductance (µS/cm)				
Diabase	14	105	292	498
Quartzite conglomerate	5	–	230	–
Brunswick Group	35	221	404	622
Lockatong Formation	16	250	428	695
Stockton Formation	14	166	235	325
Carbonate rocks	15	242	410	592
Crystalline rocks	8	–	139	–
Alkalinity (mg/L as $CaCO_3$)				
Diabase	10	48	102	192
Quartzite conglomerate	4	–	68	–
Brunswick Group	26	102	138	216
Lockatong Formation	14	54	180	222
Stockton Formation	11	11	68	103
Carbonate rocks	14	98	195	280
Crystalline rocks	8	–	16	–
Dissolved oxygen (mg/L)				
Diabase	10	.2	5.4	8.2
Quartzite conglomerate	3	–	7.8	–
Brunswick Group	20	.5	4.4	7.8
Lockatong Formation	11	<.1	.8	5.9
Stockton Formation	11	3.4	6.6	8.2
Carbonate rocks	10	.9	7.1	8.4
Crystalline rocks	6	–	9.0	–
Temperature (°C)				
Diabase	14	11.8	13.0	14.0
Quartzite conglomerate	5	–	14.0	–
Brunswick Group	37	12.0	13.5	14.0
Lockatong Formation	18	11.4	13.5	16.1
Stockton Formation	14	12.8	13.5	15.0
Carbonate rocks	14	12.0	13.8	15.2
Crystalline rocks	8	–	13.2	–

Inorganic Compounds

Common ions analyzed and reported are calcium, chloride, fluoride, magnesium, potassium, silica, sodium, and sulfate. Nutrient species analyzed and reported are nitrate, nitrite, ammonia, phosphorus, and orthophosphate. Trace constituents analyzed and reported are arsenic, iron, lead, and manganese.

Common Ions

Common ions dissolved from soil and rock constitute most of the dissolved solutes in ground water; some solutes are dissolved in precipitation. Common ions, in order of decreasing concentration, in the ground water of northern Bucks County are calcium, sulfate, silica, chloride, magnesium, sodium, nitrate, potassium, and fluoride. Median concentrations for each hydrogeologic group are summarized in table 17. Nitrate is discussed in the following section.

The classification of water types, which are categorized by the predominant cations and anions in the water (expressed in milliequivalents per liter), is common practice in investigations of water quality. According to Hem (1985, p. 166), a water in which no one cation or anion constitutes as much as 50 percent of the totals should be recognized as a mixed water type and identified by the names of all the important cations and anions. Most of the ground water in northern Bucks County is classified as calcium bicarbonate water. A few of the water samples from diabase and carbonate rocks are of a mixed cation water type. Figure 32 is a piper diagram showing median cation-anion percentages of calcium bicarbonate water type (Brunswick Group, Lockatong Formation, and Stockton Formation) and of mixed cation water type (diabase and carbonate rocks). Ground water from diabase and carbonate rock are of the bicarbonate anion water type.

The U.S. Environmental Protection Agency (USEPA) has set maximum contaminant levels (MCL's) and secondary maximum contaminant levels (SMCL's) for some constituents in drinking water (table 18). MCL's usually are set because elevated concentrations of these constituents may cause adverse health effects. SMCL's usually are set for aesthetic reasons; elevated concentrations of these constituents may impart an undesirable taste or odor to water.

TDS is a measurement of the total solutes in water. Water from crystalline rocks, which are resistant to weathering, contains the lowest concentrations of TDS of the hydrogeologic units. Water from the Lockatong Formation contains the highest concentration of TDS of the hydrogeologic units (table 17). The USEPA SMCL for TDS concentration in drinking water is 500 mg/L. Water from 1 of 83 wells sampled (less than 2 percent) in northern Bucks County exceeded the SMCL for TDS; the well is in the Lockatong Formation.

Most chloride in ground water is dissolved from natural sources. Elevated concentrations of chloride also may be caused by anthropogenic sources, such as input from highway deicing salt, fertilizers, and septic systems. The USEPA SMCL of 250 mg/L for chloride concentration was not exceeded in water from 86 wells sampled in northern Bucks County.

Sulfate (SO_4) is the second most prevalent common ion in the ground water of northern Bucks County. The source of sulfur is metallic sulfides, such as pyrite (FeS_2), gypsum ($CaSO_4 \cdot 2H_2O$), or anhydrite ($CaSO_4$), which are common in sedimentary rock. The USEPA SMCL of 250 mg/L for sulfate concentration was not exceeded in water from 87 wells sampled in northern Bucks County. The median concentrations of sulfate in ground water from the Brunswick Group and Lockatong Formation are 37 and 39 mg/L, respectively, which are higher than the concentration of sulfate in water from all other hydrogeologic units. Also, water from these two units contain higher concentrations of calcium (48 and 58 mg/L, respectively), than water from the other hydrogeologic units, which may indicate gypsum or anhydrite in these formations as the source of sulfate. Abundant pyrite in the Lockatong Formation is another source of sulfate.

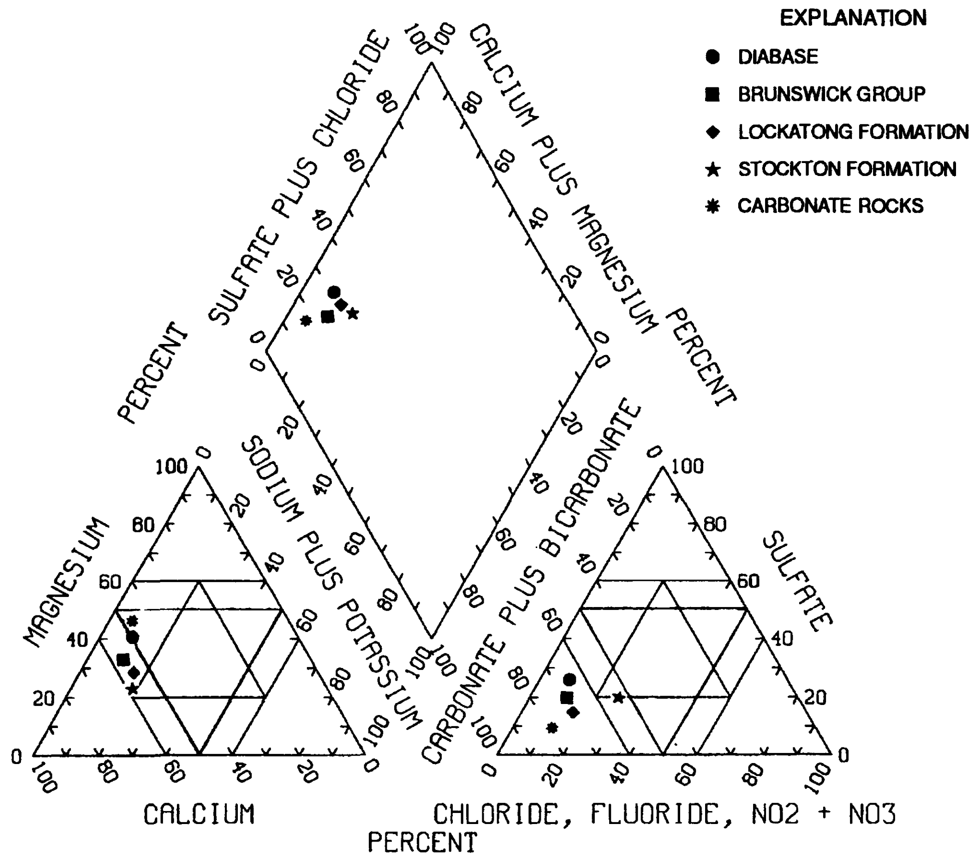


Figure 32. Piper diagram of median cation-anion percentages for ground water from the diabase, Brunswick Group, Lockatong Formation, Stockton Formation, and carbonate rocks, northern Bucks County.

Table 17. Concentrations of common ions in ground water in northern Bucks County

[mg/L, milligrams per liter; <, less than; --, too few data to compute statistic]

Constituent	Number of wells sampled	Concentrations (mg/L)		
		Tenth percentile	Median	Ninetieth percentile
Total dissolved solids				
Diabase	10	124	173	329
Quartzite conglomerate	4	--	148	--
Brunswick Group	26	201	259	374
Lockatong Formation	13	145	292	494
Stockton Formation	11	110	148	193
Carbonate rocks	11	152	238	433
Crystalline rocks	8	--	100	--
Calcium				
Diabase	9	14	28	63
Quartzite conglomerate	4	--	32	--
Brunswick Group	25	28	48	67
Lockatong Formation	14	14	58	112
Stockton Formation	11	12	29	36
Carbonate rocks	11	25	54	78
Crystalline rocks	7	--	8.7	--

Table 17. Concentrations of common ions in ground water in northern Bucks County--Continued

[mg/L, milligrams per liter; <, less than; --, too few data to compute statistic]

Constituent	Number of wells sampled	Concentrations (mg/L) Tenth percentile	Median	Ninetieth percentile
Chloride				
Diabase	10	3.0	5.0	70
Quartzite conglomerate	4	--	6.6	--
Brunswick Group	26	4.2	11	36
Lockatong Formation	13	5.3	26	42
Stockton Formation	11	7.4	11	23
Carbonate rocks	14	4.6	8.7	42
Crystalline rocks	8	--	4.6	--
Fluoride				
Diabase	10	<.1	<.1	.4
Quartzite conglomerate	4	--	<.1	--
Brunswick Group	23	<.1	.1	.5
Lockatong Formation	11	<.1	.2	1
Stockton Formation	11	<.1	<.1	.1
Carbonate rocks	10	<.1	<.1	.2
Crystalline rocks	7	--	<.1	--
Magnesium				
Diabase	10	3.8	14	34
Quartzite conglomerate	4	--	5.7	--
Brunswick Group	25	6.6	16	24
Lockatong Formation	14	4.6	20	34
Stockton Formation	11	2.7	6.8	11
Carbonate rocks	11	12	34	39
Crystalline rocks	7	--	3.8	--
Potassium				
Diabase	10	0.2	0.6	7.2
Quartzite conglomerate	4	--	1.4	--
Brunswick Group	25	.6	1.0	3.6
Lockatong Formation	14	.6	2.0	8.0
Stockton Formation	11	.6	1.1	3.3
Carbonate rocks	11	.6	1.6	5.0
Crystalline rocks	7	--	2.2	--
Silica				
Diabase	10	23	40	58
Quartzite conglomerate	4	--	13	--
Brunswick Group	25	15	19	31
Lockatong Formation	14	14	18	28
Stockton Formation	11	11	24	28
Carbonate rocks	13	3.0	10	18
Crystalline rocks	7	--	18	--
Sodium				
Diabase	10	3.1	6.4	12
Quartzite conglomerate	4	--	4.8	--
Brunswick Group	25	7.8	11	34
Lockatong Formation	14	7.3	16	145
Stockton Formation	11	4.5	9.5	14
Carbonate rocks	11	2.8	5.3	18
Crystalline rocks	7	--	6.9	--
Sulfate				
Diabase	10	9.1	28	50
Quartzite conglomerate	4	--	2.2	--
Brunswick Group	26	16	37	97
Lockatong Formation	14	25	39	145
Stockton Formation	11	8.2	19	36
Carbonate rocks	14	5.6	15	57
Crystalline rocks	8	--	20	--

***Table 18.** 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 (1991 and 1992); 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	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.

Nutrients

Essential nutrients for plant and animal growth include species of nitrogen and phosphorus. Nitrogen is found in water principally as nitrate (NO_3), nitrite (NO_2), and ammonia (NH_4). Phosphorus is found in water principally as a form of the orthophosphate ion species. The orthophosphate species are the most thermodynamically stable of the P^{5+} forms likely to occur in natural waters (Hem, 1985, p. 127). The presence of elevated concentrations of nutrients is usually an indicator of ground-water contamination. Nutrient sources include fertilizers, animal wastes, and effluent from sewage treatment or on-site septic systems. Median concentrations of nutrients for each hydrogeologic unit are summarized in table 19.

Nitrate is the most prevalent nitrogen species in ground water (table 18). The concentrations of nitrate given in table 19 were computed by subtracting the concentration of nitrite from nitrate plus nitrite; when nitrite was below the detection limit, zero was used in the computation. The median concentration of nitrate for all hydrogeologic units is 2.3 mg/L. Of 71 water samples from wells in northern Bucks County, no concentrations of nitrate exceed the USEPA MCL; however, the concentration of nitrate in water from well BK-1977 in the Stockton Formation was equal to the USEPA MCL of 10 mg/L nitrate as nitrogen. Nitrite, ammonia, and phosphorus species are present in concentrations less than 0.50 mg/L; median concentrations of these constituents for all hydrogeologic units are equal to or less than 0.01 mg/L (table 19).

Metals and Other Trace Constituents

Metals such as iron, lead, and manganese and other trace constituents, such as arsenic, typically are present in low concentrations in water samples from wells in northern Bucks County. Most of the metals and other trace constituents in natural ground water are leached from the soil or dissolved from the underlying bedrock in minute quantities by circulating ground water. Some are present in precipitation. Lead in tap water may be leached from household plumbing systems.

Table 20 is a summary of concentrations of lead, arsenic, iron, and manganese in ground water. These constituents generally do not pose a water-quality problem in northern Bucks County. The median concentrations of constituents in table 20 represent natural background concentrations. The USEPA has established MCL's and SMCL's for these constituents, except for lead, in drinking water (table 18). For lead, an action level of 15 μg/L has been established by the USEPA (U.S. Environmental Protection Agency, 1991). The action level, as defined by the USEPA, means that a public water purveyor must take corrective action if the concentration of lead is above 15 μg/L in more than 10 percent of tap water samples collected during any monitoring period. The USEPA action level of 15 μg/L for lead was not exceeded in water from 71 wells sampled. The USEPA MCL of 50 μg/L for arsenic was not exceeded in water from 36 wells sampled.

Elevated concentrations of iron and manganese in water may impart a bitter taste and stain laundry and plumbing fixtures. Of the water samples analyzed, 5 of 86 samples (6 percent) and 6 of 75 samples (8 percent) exceed the USEPA SMCL's for iron and manganese, respectively. A water sample collected from well BK-789 in quartzite conglomerate had an iron concentration two orders of magnitude higher than the median iron concentration for all hydrogeologic units; the iron concentrations of three other samples from quartzite conglomerate are all less than or equal to 10 μg/L. Sources of iron in well water include minerals in the bedrock, such as hematite and pyrite. Bacterial activity may elevate iron concentrations. Sources of manganese in ground water include minerals in the bedrock.

Volatile Organic Compounds

VOC's are extensively used in industrial, commercial, and household applications. Their presence in ground water presents a serious problem for public water suppliers, industries, and domestic well owners that rely on ground water. Many of the VOC's are confirmed or suspected human or animal carcinogens (Council on Environmental Quality, 1981, p. 64). VOC's generally enter the ground-water system by spills, leakage from storage tanks, discharge from septic systems, and from lagoons and disposal sites. Once in the ground-water system, VOC's are difficult to remove, and treatment generally is expensive.

Table 19. *Concentration of nutrients in ground water in Northern Bucks County*
[<, less than; --, too few data to compute statistic]

Constituent	Number of wells sampled	Concentration (milligrams per liter)		
		Tenth percentile	Median	Ninetieth percentile
Nitrate as nitrogen				
Diabase	10	<0.05	0.44	3.2
Quartzite conglomerate	3	--	2.0	--
Brunswick Group	20	.13	2.5	4.1
Lockatong Formation	11	<.05	.23	3.9
Stockton Formation	11	2.7	4.4	9.6
Carbonate rocks	10	.81	2.5	7.8
Crystalline rocks	6	--	3.2	--
Nitrite as nitrogen				
Diabase	10	<.01	<.01	<.01
Quartzite conglomerate	3	--	<.01	--
Brunswick Group	20	<.01	<.01	<.01
Lockatong Formation	11	<.01	<.01	.02
Stockton Formation	11	<.01	<.01	<.01
Carbonate rocks	10	<.01	<.01	<.01
Crystalline rocks	6	--	<.01	--
Ammonia as nitrogen				
Diabase	10	<.01	<.01	.02
Quartzite conglomerate	3	--	.02	--
Brunswick Group	20	<.01	.01	.02
Lockatong Formation	11	<.01	.04	.12
Stockton Formation	11	<.01	.02	.03
Carbonate rocks	10	<.01	.02	.03
Crystalline rocks	6	--	.02	--
Phosphorus				
Diabase	10	<.01	<.01	.03
Quartzite conglomerate	3	--	.04	--
Brunswick Group	20	<.01	.02	.03
Lockatong Formation	11	<.01	<.01	.02
Stockton Formation	11	<.01	.06	.10
Carbonate rocks	10	<.01	<.01	.02
Crystalline rocks	6	--	<.01	--
Orthophosphate as phosphorus				
Diabase	10	<.01	<.01	.03
Quartzite conglomerate	3	--	.01	--
Brunswick Group	21	<.01	.02	.05
Lockatong Formation	11	<.01	<.01	.03
Stockton Formation	11	<.01	.06	.11
Carbonate rocks	10	<.01	<.01	<.01
Crystalline rocks	7	--	.01	--

Table 20. *Concentrations of arsenic, iron, lead, and manganese in ground water in Northern Bucks County*
[Concentrations in micrograms per liter; <, less than]

Constituent	Number of wells sampled	Detection limit	Number of samples below detection limit	Maximum concentration	Median concentration
Arsenic	36	1	19	28	<1.0
Iron	86	3	31	1,900	6.0
Lead	71	1	59	14	<1.0
Manganese	75	1	35	530	2.0

VOC's have been in use for many years. The length of time VOC's have been present in the ground water is unknown. Trichloroethylene (TCE), a commercial solvent and industrial metal degreaser, became a common degreasing agent in the 1920's, and its use in the dry cleaning industry began in the 1930's. Awareness of its presence in ground water began in the late 1970's.

Water samples for analysis of VOC's were collected from 34 wells. The choice of wells for sampling was biased toward wells where the potential existed for the presence of VOC's in ground water, such as near landfills and industrial sites. Compounds detected, maximum concentrations detected, and frequency of detection and number of samples exceeding the USEPA MCL are summarized in table 21. Complete chemical analyses are given by Schreffler and others (1994). MCL's are set for only a few VOC's (table 18).

Table 21. *Volatile organic compounds detected in ground water in northern Bucks County*

[Concentrations given in micrograms per liter; USEPA MCL, U.S. Environmental Protection Agency Maximum Contaminant level; --, no set maximum contaminant level]

Compound	Number of wells in which compound was detected	Maximum concentration detected	Number of wells exceeding USEPA MCL
Chloroform	2	9.0	0
Dichlorobromomethane	1	.2	--
1,1-Dichloroethane	1	.6	--
1,2-Dichloroethane	1	9.0	1
1,1-Dichloroethylene	1	4.7	0
trans-1,2,-Dichloroethylene	1	17	0
Methylchloride	1	1.2	--
Methylene chloride	1	22	1
Tetrachloroethylene	1	80	1
1,1,1-Trichloroethane	1	4	0
1,1,2-Trichloroethane	1	.7	0
Trichloroethylene	4	46	3

VOC's were detected in water from 23 percent of the 34 wells sampled. Out of 35 compounds analyzed, 12 were detected (table 21). The most commonly detected compound was TCE (13 percent of sampled wells). Total concentrations of VOC's were as high as 153 μg/L; concentrations of a single compound (tetrachloroethylene or PCE) were as high as 80 μg/L. However, the concentrations of most compounds detected were less than 10 μg/L.

Many of the VOC's detected in the ground water are industrial solvents. TCE, PCE, and 1,1,1-trichloroethane are commonly used as degreasers in the metals, electronics, and plastics industries. TCE also has been used as a septic tank cleaner and a solvent for paints and varnishes and has been used extensively in the dry cleaning, chemical, and pharmaceutical industries. PCE commonly is used in dry cleaning.

Some of the VOC's present in the water samples were never used in the study area and are the result of anaerobic degradation by microorganisms in the subsurface. Some compounds, such as trans-1,2-dichloroethylene (DCE), and 1,1-dichloroethane (DCA) are degradation products of other VOC's. Under anaerobic conditions, PCE successively degrades by reductive dechlorination to TCE, cis-DCE or trans-DCE, 1,1-dichloroethene, and vinyl chloride (Parsons and others, 1984; Vogel and McCarty, 1985; Freedman and Gossett, 1988). 1,1,1-trichloroethane anaerobically degrades to DCA.

Radon

Although radionuclides occur naturally in the ground water of northern Bucks County, elevated activities may present a health problem. Radioactivity is the release of energy and energetic particles by changes in the structure of certain unstable elements as they break down to form more stable arrangements. The most commonly used unit for radioactivity in water is picoCuries per liter. One Curie is the activity of 1 gram of radium, which is equal to 3.7×10^{10} atomic disintegrations per second. Activity refers to the number of particles emitted by a radionuclide. The rate of decay is proportional to the number of atoms present and inversely proportional to half-life.

Naturally occurring radioactivity in ground water is produced primarily by the radioactive decay of uranium-238 and thorium-232. They disintegrate in steps, forming a series of radioactive nuclide "daughter" products, mostly short lived, until a stable lead isotope is produced.

The uranium-238 decay series produces the greatest amount of radioactivity in natural ground water. Uranium-238 has a half-life of 4.5×10^9 years. Its daughter products include radium-226 (half-life 1,620 years) and radon-222 (half-life 3.8 days). Radon-222 is a decay product of radium-226 and is a colorless, odorless, inert, alpha-particle-emitting gas, which is water soluble. The end product of the decay series is the stable isotope lead-206.

Ground-water samples for analysis for dissolved radon-222 were collected from 71 wells. The data are summarized in table 22. Complete analytical results are given by Schreffler and others (1994). The median radon-222 activity was 1,300 pCi/L. Median radon-222 activity was highest for water samples from wells in crystalline rock (3,600 pCi/L), the Stockton Formation (2,300 pCi/L), and the Brunswick Group (2,100 pCi/L). Median radon-222 activities were lowest for water samples from wells in the Lockatong Formation (340 pCi/L) and diabase (350 pCi/L).

Table 22. *Radon-222 activities in ground water in northern Bucks County*

Hydrogeologic unit	Number of samples	Radon-222 activity (picoCuries per liter)		
		Minimum	Maximum	Median
Diabase	10	88	6,400	350
Quartzite conglomerate	3	980	1,200	–
Brunswick Group	20	1,000	5,600	2,100
Lockatong Formation	11	120	5,500	340
Stockton Formation	11	1,100	7,300	2,300
Carbonate rock	10	120	1,700	710
Crystalline rock	6	530	14,000	3,600

The highest radon-222 activity, 14,000 pCi/L, was measured in a water sample from well BK-1288 in the Hardyston Quartzite. This well also was sampled in 1988 as part of a study of radionuclides in quartzite in southeastern Pennsylvania (Senior and Vogel, in press). In 1988, the radon-222 activity was 12,000 pCi/L. In 1988, the well also was sampled for radium-226 and radium-228. The combined activities of radon-226 (1.7 pCi/L) and radium-228 (3.6 pCi/L) exceeded the USEPA MCL of 5 pCi/L for combined radium-226 and radium-228. Senior and Vogel (in press) found that pH is the strongest control on radium mobility, and that dissolved organic carbon may enhance radium mobility in low pH waters. These factors may favor radium mobility by promoting a decrease in adsorption and an increase in solubility. Low pH decreases adsorption of radium and other ions by silica, kaolinite, and other mineral surfaces, such as iron and manganese hydroxides. Radon-222 activities vary temporally and do not correlate with and are not supported by the activity of its parent, radium-226, in solution.

SUMMARY

The 187-mi^2 study area in northern Bucks County includes New Hope Borough and Bridgeton, Buckingham, Nockamixon, Plumstead, Solebury, Springfield, Tinicum, and Wrightstown Townships. Approximately 90 percent of residents in the study area rely on domestic wells for their source of water supply.

Most of the area lies in the Triassic Lowlands Section of the Piedmont Physiographic Province. This area is chiefly underlain by sedimentary rocks of Upper Triassic age and intrusive diabase. Two southwest-northeast trending valleys, the Durham and Buckingham Valleys, are underlain by carbonate and crystalline rock. The extreme northern part of the study area lies in the Reading Prong Section of the Appalachian Highlands Physiographic Province.

All hydrogeologic units in northern Bucks County are considered to be aquifers. A less-permeable overlying hydrogeologic unit or bed within a hydrogeologic unit may be considered locally as a confining unit. The hydrogeologic units of northern Bucks County are combined into five general groups on the basis of a similarity in ground-water-flow systems: (1) unconsolidated sediments, (2) diabase, (3) Triassic sedimentary rocks (sandstone, shale, and conglomerate), (4) carbonate rocks (limestone and dolomite), and (5) crystalline and metamorphosed sedimentary rocks (quartzite, phyllite, schist, and gneiss). Characteristics of the ground-water-flow system, as well as aquifer hydraulic properties, are related to geology. Flow systems of each group differ from each other.

Twelve percent of the study area is underlain by diabase of early Jurassic age. The thickness of the Coffman Hill diabase sheet determined by natural-gamma geophysical logs ranged from 81 to 568 ft. Diabase has no primary porosity, and the depth of fracturing rarely exceeds 100 to 150 ft. Therefore, all ground-water flow is through fractures, and nearly all ground-water storage is in the upper weathered zone. Where the weathered zone is absent, little ground-water storage is available. Many wells drilled into diabase penetrate underlying hydrogeologic units, and these wells may derive some or all of their water from the underlying units.

Triassic sedimentary rocks cover 74 percent of northern Bucks County. The principal formations are the Brunswick Group, the Lockatong Formation, and the Stockton Formation. Ground water in the unweathered zone moves primarily through a network of interconnecting secondary openings—fractures, bedding planes, and joints. The ground-water-flow system in Triassic sedimentary rocks is highly anisotropic with the predominant direction of flow in the direction of strike. The network of interconnected water-bearing openings is more or less continuous along strike, but the continuity of individual beds downdip is limited because fractures are closed by compression or absent with depth. Because of anisotropy, interference from pumping generally is greater for wells aligned parallel to strike than for wells aligned perpendicular to strike.

The ground-water system in Triassic sedimentary rocks can be visualized as a series of beds with a relatively high transmissivity separated by beds with a relatively low transmissivity. The beds, a few inches to a few feet thick, act as a series of alternating aquifers and confining or semiconfining units that form a leaky, multiaquifer system. Ground water is unconfined in the shallower part of the aquifer and confined or semiconfined in the deeper part of the aquifer. Beds within a formation are hydraulically connected by vertical joints that intersect each other at various angles throughout the beds. Each bed generally has different hydraulic properties, and permeability commonly differs from one bed to another.

Most deep wells are open to several water-bearing zones and are multiaquifer wells. Each water-bearing zone usually has a different hydraulic head. The hydraulic head in a deep well is the composite of the heads in the several water-bearing zones it penetrates. If the hydraulic head is above the land surface, the well will flow. If the hydraulic head is below the uppermost water-bearing zone or zones, water from these zones will drain into the well and cascade down the borehole to the water surface. Where differences in hydraulic head exist between water-bearing zones, water in the well bore flows under nonpumping conditions in the direction of decreasing head. This can cause water levels in some wells to differ from water levels in adjacent wells of different depths.

Rocks of the Brunswick Group underlie 39 percent of the study area. Because the rocks of the Brunswick Group are fine grained, primary porosity and permeability are small. The Brunswick is highly fractured and has many closely spaced joints, which accounts for the relatively high well yields from a shale and siltstone formation. Rocks of the Lockatong Formation underlie 17 percent of the study area. The Lockatong Formation has no primary porosity or permeability. All ground water moves through fractures and joints that generally are widely spaced, relatively tight, and poorly interconnected, which accounts for the relatively low well yields in the Lockatong. The Lockatong weathers to a dense, clayey soil that plugs fractures and joints in the weathered zone, commonly causes ground water to be confined, and impedes recharge. Rocks of the Stockton Formation underlie 15 percent of the study area. The arkosic sandstones and conglomerates of the lower part of the Stockton are poorly cemented and easily fractured, resulting in high transmissivity and high well yields. Some wells in the Stockton Formation north of Buckingham Valley may penetrate the underlying carbonate-rock formations.

Four percent of the study area is underlain by carbonate rocks of Cambrian and Ordovician age that crop out in parts of Buckingham and Durham Valleys. The principal formations are the Rickenbach Dolomite, Limeport Formation, Allentown Dolomite, and Leithsville Formation. Most ground water in carbonate rock flows through a network of secondary openings—fractures, joints, and bedding planes—that have been enlarged by solution. Where solution has been active, permeability may be high; elsewhere, the same unit may be nearly impermeable.

Seven percent of the study area is underlain by crystalline rocks. Crystalline rocks are found in Buckingham and Durham Valleys and in the Reading Prong to the north of Durham Valley. The crystalline rocks in the northern part of the study area are Hardyston Quartzite in Durham Valley and granitic and hornblende gneisses in the Reading Prong. The crystalline rocks of Buckingham Valley are Hardyston Quartzite and phyllite of the Furlong Klippe. In crystalline rocks, ground water moves through a network of interconnecting secondary openings—fractures and joints—in the unweathered rock. A considerable quantity of water may be stored in the weathered zone where it is thick. The ground-water-flow system in crystalline rock is local with streams acting as drains. Flow paths generally are short.

For statistical analysis and description of aquifer and well-construction characteristics, the geologic units mapped in northern Bucks County were grouped into nine hydrogeologic units or rock types: diabase, quartzite conglomerate, Brunswick Group (red beds, lower beds, and hornfels), Lockatong Formation, Stockton Formation, carbonate rocks (Rickenbach Dolomite, Limeport Formation, Allentown Dolomite, and Leithsville Formation), and crystalline rocks (Hardyston Quartzite, phyllite, and gneiss). The unconsolidated sediments along the Delaware River and the limestone conglomerate were not used in statistical analyses because too few data were available.

The distribution of 560 water-bearing zones in 217 wells representing 49,552 ft of uncased borehole was analyzed. The frequency of occurrence of water-bearing zones decreases with depth. Sixty-five percent of water-bearing zones for all hydrogeologic units are within 200 ft of land surface, and 85 percent are within 300 ft of land surface. The Stockton Formation had the most water-bearing zones per 100 ft of uncased borehole (1.60) of all the hydrogeologic units, and the Lockatong Formation and diabase had the fewest water-bearing zones per 100 ft of uncased borehole (0.82 and 0.84, respectively).

On the basis of the median specific capacity of nondomestic wells, carbonate rocks, the Brunswick Group, and the Stockton Formation are the most productive hydrogeologic units or rock types, followed by crystalline rocks and the Lockatong Formation in descending order. Carbonate rocks and the Stockton Formation have the highest median nondomestic well yields (156 and 120 gal/min, respectively) among the hydrogeologic units and rock types; the Lockatong Formation has the lowest median nondomestic well yield (22 gal/min). No nondomestic wells were reported in diabase and quartzite conglomerate. The Stockton Formation has the highest median domestic well yields among the hydrogeologic units and rock types. Ten percent of all domestic wells drilled in northern Bucks County, except for wells drilled in the Stockton Formation, yield less than 5 gal/min, which is considered an adequate supply for domestic use. Thirty-four percent of domestic wells drilled in diabase, 30 percent in the Lockatong Formation, and 21 percent in carbonate rock yield less than 5 gal/min.

Aquifer transmissivities, which are based on the analysis of five aquifer tests in the Brunswick Group, ranged from 94 to 2,200 ft^2/d; the median was 190 ft^2/d. Aquifer transmissivities, which are based on the analysis of three aquifer tests in the Lockatong Formation, ranged from 250 to 1,500 ft^2/d; the median was 820 ft^2/d. Aquifer transmissivities, which are based on the analysis of seven aquifer tests in the Stockton Formation, ranged from 260 to 1,800 ft^2/d; the median was 410 ft^2/d. Although specific-capacity and yield data show the Lockatong Formation to be a relatively low-yielding aquifer, the aquifer-test data show that high-yielding production wells can be successfully located in the Lockatong.

Water levels fluctuate in response to recharge to the ground-water system from precipitation and discharge from the ground-water system to pumped wells and quarries, ground-water evapotranspiration, and streams. Water levels generally rise during the late fall, winter, and early spring when ground-water evapotranspiration and soil-moisture evapotranspiration is at a minimum and recharge is at a maximum. Water levels generally decline during the late spring, summer, and early fall when ground-water evapotranspiration and soil-moisture evapotranspiration are at a maximum and recharge is at a minimum. Some anthropogenic activities, such as pumping of nondomestic wells or dewatering of a quarry, may lower water levels and create a cone of depression around the pumped well or quarry.

The median depth to water for both domestic and nondomestic wells is greatest for the Brunswick Group (101 and 81 ft, respectively). The median depth to water for both domestic and nondomestic wells is least for the Lockatong Formation (18 and 10 ft, respectively).

Water budgets were calculated for the Cooks, Tinicum, Paunnacussing, and Mill Creek Basins for 1991-92. Precipitation in the four basins for 1991 and 1992 ranged from 39.8 to 43.9 in. The water budgets represent years of below normal precipitation.

The average annual precipitation in the Cooks Creek Basin for 1991-92 was 42.5 in. Average annual ET and other losses were 23.8 in., average annual streamflow was 19 in., and the average annual change in ground-water storage was a decrease of 0.2 in. The Cooks Creek Basin had the lowest average annual ET and the highest average annual streamflow of the four basins.

The average annual precipitation in the Tinicum Creek Basin for 1991-92 was 41.5 in. Average annual ET and other losses were 27.9 in., average annual streamflow was 13.9 in., and the average annual change in ground-water storage was a decrease of 0.2 in.

The average annual precipitation in the Paunnacussing Creek Basin for 1991-92 was 41.7 in. Average annual ET and other losses were 24.7 in., average annual streamflow was 17.2 in., and the average annual change in ground-water storage was a decrease of 0.1 in.

The average annual precipitation in the Mill Creek Basin for 1991-92 was 40.2 in. Average annual ET and other losses was 30.3 in., average annual streamflow was 10.8 in., and the average annual change in ground-water storage was a decrease of 0.9 in. The Mill Creek Basin had the highest average annual ET and the lowest average annual streamflow of the four basins.

Average water-budget components for 1991-92, weighted by drainage area, were calculated for the four basins. Average annual precipitation was 41.7 in., average annual ET and other losses were 26.2 in., average annual streamflow was 15.9 in., and the average annual change in ground-water storage was a decrease of 0.3 in.

Although most of the Tohickon Creek Basin lies outside the study area, Tohickon Creek drains the same hydrogeologic units that are found in the study area. Water budgets for the Tohickon Creek Basin were calculated for 1968-91 (prior to regulation of the stream by Lake Nockamixon). The average annual precipitation was 47.2 in., average annual ET and other losses were 24.3 in., and average annual streamflow was 22.6 in.

All recharge to the ground-water system is derived from local precipitation. Generally, recharge occurs on hilltops and hillsides; topographically low areas commonly are discharge areas. For 1991, estimated recharge ranged from 8.2 in. in the Tinicum and Mill Creek Basins to 12.4 in. in the Cooks and Paunnacussing Creek Basins. Estimated recharge for the four basins for 1991 weighted by drainage area was 10.5 in. [0.504 $(Mgal/d)/mi^2$]. For 1992, estimated recharge ranged from 8.2 in. in the Mill Creek Basin to 12.1 in. in the Paunnacussing Creek Basin. Estimated recharge for the four basins for 1992 weighted by drainage area was 9.5 in. [0.456 (Mgal/d)/mi^2]. Average estimated recharge for the four basins for 1991-92 weighted by drainage area was 10.1 in. [0.485 (Mgal/d)/mi^2]; this is equal to a recharge rate of 758 gal/d per acre.

The ground-water and surface-water systems are well connected in northern Bucks County. In most areas, streams act as drains for the shallow ground-water system and gain water. In some places, stream reaches may lose water and recharge the ground-water system. Discharge data for Paunnacussing Creek show that all reaches measured were gaining reaches. Discharge data for Tohickon Creek below Lake Nockamixon dam show a streamflow gain between some sites and a streamflow loss between other sites, indicating that some reaches of Tohickon Creek are losing reaches.

Flow-duration curves show that the flow of Cooks Creek is better sustained by ground-water discharge at the low end of the discharge range than the flow in other basins. The flow of Tinicum Creek is poorly sustained by ground-water discharge at the low end of the discharge range. On the basis of discharge ratios taken from the flow-duration curves, the largest storage capacity is in the Cooks Creek Basin. The smallest storage capacity is in the Tinicum Creek Basin, largely because 54 percent of the basin is underlain by diabase.

Streamflow is composed of ground-water discharge (base flow) and surface runoff. Streamflow hydrographs for 1991-92 for Cooks, Tinicum, Paunnacussing, and Mill Creeks were separated into base-flow and runoff components. In the Cooks Creek Basin, average annual ground-water discharge to streams was 9.4 in., which was 49 percent of the average annual streamflow. Average annual surface runoff was 9.6 in. The percentage of precipitation as surface runoff (23 percent) of the four basins was highest in the Cooks Creek Basin.

In the Tinicum Creek Basin, average annual ground-water discharge to streams for 1991-92 was 6.7 in., which was 48 percent of the average annual streamflow. Average annual surface runoff was 7.2 in. The lowest percentage of streamflow as base flow (48 percent) of the four basins was calculated for the Tinicum Creek Basin. The highest percentage of streamflow as surface runoff (52 percent) of the four basins was calculated for the Tinicum Creek Basin. The higher ratio of surface runoff to base flow is because 54 percent of the basin is underlain by diabase.

In the Paunnacussing Creek Basin, average annual ground-water discharge to streams for 1991-92 was 10.5 in., which was 61 percent of the average annual streamflow. Average annual surface runoff was 6.8 in. The highest percentage of precipitation as base flow of the four basins was calculated for the Paunnacussing Creek Basin; the basin is underlain by the relatively more permeable Stockton Formation.

In the Mill Creek Basin, average annual ground-water discharge to streams for 1991-92 was 7.1 in., which was 66 percent of the average annual streamflow. Average annual surface runoff was 3.6 in. The highest percentage of streamflow as base flow and the lowest percentage of streamflow as surface runoff of all four basins was calculated for the Mill Creek Basin.

Average annual ground-water discharge to streams for the four basins for 1991-92 weighted by drainage area was 8.4 in. [0.403 (Mgal/d)/mi^2], which was 53 percent of the average annual streamflow. Average annual surface runoff for the four basins for 1991-92 weighted by drainage area was 7.4 in.

Separation of the streamflow hydrograph from the streamflow-measurement station on Tohickon Creek into base-flow and surface-runoff components was done for 1936-71 (the period of record for the station prior to regulation by Lake Nockamixon). Annual base flow ranged from 2.5 in. [0.12 (Mgal/d)/mi^2] in 1965 to 8.4 in. [0.403 (Mgal/d)/mi^2] in 1945. The median base flow was 5.3 in. [0.25 (Mgal/d)/mi^2].

The median pH of water from wells in the Stockton Formation and crystalline rocks is acidic; the median pH of water from wells in quartzite conglomerate is near neutral; and the median pH of water from wells in the diabase, Brunswick Group, Lockatong Formation, and carbonate rocks is basic. Water from wells in the crystalline rocks (median pH of 5.8) has the lowest (most acidic) median pH of the hydrogeologic units. Water from wells in carbonate rocks (median pH of 7.8) has the highest (most basic) median pH of the hydrogeologic units.

Water from wells in crystalline rocks has the lowest median specific conductance of the hydrogeologic units (139 µS/cm). Water from wells in the Lockatong Formation has the highest median specific conductance of the hydrogeologic units (428 µS/cm).

Water from wells in crystalline rocks has the lowest median alkalinity of the hydrogeologic units (16 mg/L as $CaCO_3$) because the crystalline rocks contain few minerals that contribute to alkalinity. Water from wells in the carbonate rocks has the highest median alkalinity of the hydrogeologic units (195 mg/L as $CaCO_3$) because calcium and magnesium carbonate dissolved from carbonate rocks contribute to high alkalinity.

The median dissolved oxygen concentration of water from wells in all hydrogeologic units, except for the Lockatong Formation, ranges from 4.4 mg/L (Brunswick Group) to 9.0 mg/L (crystalline rocks). The median dissolved oxygen concentration of water from wells in the Lockatong Formation is only 0.8 mg/L. The high median dissolved oxygen concentration of water from wells in the crystalline rocks is because of the lack of oxidizable minerals. The low median dissolved oxygen concentration of water from wells in the Lockatong Formation is because of abundant oxidizable minerals, such as pyrite, which deplete the available oxygen.

Common ions dissolved from soil and rock constitute most of the dissolved solutes in ground water; some solutes are dissolved in precipitation. Common ions, in order of decreasing concentration, in the ground water of northern Bucks County are calcium, sulfate, silica, chloride, magnesium, sodium, nitrate, potassium, and fluoride. Five of 86 samples (6 percent) and 6 of 75 samples (8 percent) exceed the USEPA SMCL's for iron and manganese, respectively.

Water from crystalline rocks contains the lowest concentrations of TDS of the hydrogeologic units. Water from the Lockatong Formation contains the highest concentration of TDS of the hydrogeologic units. Water from 1 of 83 wells sampled (less than 2 percent) in northern Bucks County exceeded the USEPA SMCL of 500 mg/L for TDS; the well is in the Lockatong Formation.

Nitrate is the most prevalent nitrogen species in ground water. The median concentration of nitrate for all hydrogeologic units is 2.3 mg/L. Of 71 water samples from wells in northern Bucks County, no concentrations of nitrate exceed the USEPA MCL, but in a water sample from one well, the concentration of nitrate was equal to the USEPA MCL of 10 mg/L nitrate as nitrogen. Median concentrations of nitrite, ammonia, and phosphorus species are equal to or less than 0.01 mg/L.

Water samples for analysis for VOC's were collected from 34 wells. The choice of wells for sampling was biased towards wells where the potential existed for the presence of VOC's in ground water. VOC's were detected in 23 percent of the 34 wells sampled. Three samples exceeded the USEPA MCL for TCE, and one sample each exceeded the USEPA MCL for methylene chloride and PCE. The most commonly detected compound was TCE (13 percent of sampled wells). Total concentrations of VOC's were as high as 153 µg/L; concentrations of a single compound (PCE) were as high as 80 µg/L. However, the concentrations of most compounds detected were less than 10 µg/L.

Samples for analysis for dissolved radon-222 were collected from 71 wells. The median radon-222 activity was highest for water samples from wells in crystalline rock (3,600 pCi/L) and lowest for water samples from wells in the Lockatong Formation (340 pCi/L) and diabase (350 pCi/L).

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