Geohydrology and Ground-Water Resources of Philadelphia, Pennsylvania

By GARY N. PAULACHOK

Prepared in cooperation with the City of
Philadelphia Water Department

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GLOSSARY

[After Heath, 1982]

Aquifer. A rock unit that will yield water in a usable quantity to a well or spring.

Bedrock. A general term for the consolidated (solid) rock that underlies soils or other unconsolidated surficial material.

Cone of depression. The reduction of ground-water heads around a pumping well caused by the withdrawal of water.

Confining bed. A rock unit having very low hydraulic conductivity that restricts the movement of water into and out of adjacent aquifers.

Datum plane. An arbitrary surface (or plane) used in the measurement of ground-water heads. The datum plane most commonly used is the National Geodetic Vertical Datum of 1929, which closely approximates sea level.

Drawdown. The reduction in head at a point caused by the withdrawal of water from an aquifer.

Equipotential line. A line on a map or cross section along which total head is equivalent.

Ground water. Water in the saturated zone that is under pressure equal to or greater than atmospheric pressure.

Hydraulic conductivity. A measure of the capacity of a rock to transmit water. It is expressed as the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit cross-sectional area measured at right angles to the direction of flow.

Hydraulic gradient. The change in head per unit of distance measured in the direction of greatest change.

Leakage. Vertical flow of water through confining beds and into an aquifer.

Porosity. A measure of void space in a rock. Porosity may be expressed quantitatively as the ratio of the volume of voids in a rock to the total volume of the rock.

Potentiometric surface. A surface that represents the total head in an aquifer, that is, it represents the height above a datum plane at which the water level stands in tightly cased wells that penetrate the aquifer.

Rock. Any naturally formed, consolidated or unconsolidated material (but not soil) consisting of two or more minerals.

Saprolite. Thoroughly decomposed but untransported rock.

Saturated zone. The subsurface zone in which all pores are full of water.

Soil. The layer of material at the land surface that supports plant growth.

Specific capacity. The yield of a well per unit of drawdown in the well.

Specific yield. The ratio of the volume of water that will drain under the influence of gravity to the volume of saturated rock.

Storage coefficient. The volume of water that an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

Total head. The height above a datum plane of a column of water. In a ground-water system, it consists chiefly of elevation head and pressure head.

Transmissivity. The rate at which water at the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient. It equals the hydraulic conductivity multiplied by the aquifer saturated thickness.

Unsaturated zone. The subsurface zone, usually beginning at the land surface, that contains water and air in the pore spaces.

Water table. The surface in the saturated zone along which the water pressure is equal to atmospheric pressure.

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Abstract

The aquifers underlying the 134.6-square-mile city of Philadelphia are divided by the Fall Line into the unconsolidated aquifers (chiefly sand and gravel) of the Coastal Plain and the consolidated-rock aquifers (chiefly schist of the Wissahickon Formation) of the Piedmont. Ground water is present under confined and unconfined conditions. The principal units of the confined-aquifer system are the lower and middle sands of the Potomac-Raritan-Magothy aquifer system. The lower sand unit is the most productive aquifer in Philadelphia. The median yield of wells screened in the lower sand unit is 275 gal/min (gallons per minute), and yields of some wells are as high as 1,350 gal/min. The median specific capacity is 16 (gal/min)/ft (gallons per minute per foot of drawdown). The principal units of the unconsolidated unconfined-aquifer system are the upper sand unit of the Potomac-Raritan-Magothy aquifer system and the informally named Trenton gravel. The median yield of wells tapping these two undifferentiated units is 90 gal/min, and yields of some wells are as high as 1,370 gal/min. The median specific capacity is 12 (gal/min)/ft. The consolidated unconfined-aquifer system consists mainly of the Wissahickon Formation. The median yield of nondomestic wells that tap the Wissahickon Formation is 45 gal/min, and yields are as high as 350 gal/min. The median specific capacity is 0.5 (gal/min)/ft.

Urbanization has considerably modified the hydrologic cycle in Philadelphia. Impervious surfaces have reduced recharge areas and evapotranspiration and have increased direct runoff. Leakage from the water-distribution system, which is supplied from the Delaware and Schuylkill Rivers, was about 60 to 72 Mgal/d (million gallons per day) in 1980. Ground-water infiltration to sewers is estimated to be as much as 135 Mgal/d when the water table is high. The potentiometric surface of the lower sand unit has been lowered substantially by pumping. By 1954, cones of depression were more than 50 ft (feet) below sea level at the U.S. Naval Base and more than 70 ft below sea level along the Delaware River northeast of the naval base. As a result of withdrawals, declining heads in the lower sand unit caused water to flow downward from the overlying unconsolidated deposits and the water table to decline below sea level along the Delaware River. Beginning in the mid-1960's, ground-water withdrawals from the lower sand unit decreased, and, by 1979, water levels had risen 25 ft at the U.S. Naval Base and 45 ft farther north along the Delaware River. As of 1985, water levels in the lower sand unit were controlled largely by pumping in nearby parts of New Jersey.

Urbanization also has caused substantial degradation of the quality of ground water in Philadelphia. By 1945, the quality of water in the unconfined aquifer system began to deteriorate as contaminants present at the land surface migrated downward. Withdrawal of water from the deeper confined aquifers caused a head decline that resulted in downward movement of contaminated water from the overlying unconfined aquifer system. Consequently, water in the confined aquifers deteriorated progressively in chemical quality so it resembles water in the unconfined aquifer system.

The concentration of dissolved solids in water samples collected during 1979–80 ranged from 90 to 4,480 mg/L (milligrams per liter). The average concentration of 778 mg/L was 45 percent higher than that of samples collected during 1945–58. Water from the unconfined unconsolidated aquifers generally had the highest dissolved-solids concentration. The concentration of dissolved iron in water samples collected during 1979–80 ranged from 0 to 220 mg/L and exceeded 0.30 mg/L in 71 percent of the samples. The average concentration of 17 mg/L was nearly 30 percent higher than that of samples collected during 1945–58. Many wells have been abandoned because of elevated iron concentrations. The concentration of dissolved manganese in water samples collected during 1979–80 ranged from 0 to 31,000 μg/L (micrograms per liter) and exceeded 50 μg/L in 78 percent of the samples. The average concentration of 1,700 μg/L was about nine times higher than that of samples collected during 1945–58. The concentration of dissolved sulfate in water samples collected during 1979–80 ranged from 0.9 to 2,200 mg/L and exceeded 250 mg/L in 11 percent of the samples. The average concentration of 161 mg/L was nearly 9 percent higher than

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that of samples collected during 1945–58. From 1958 to 1979, the extent of ground water containing sulfate concentrations exceeding 250 mg/L was reduced significantly because of the discharge of contaminated water from the aquifer and its replacement by less mineralized recharge.

Except in a few localized areas, ground water contains undetectable or low concentrations of trace elements. However, mercury concentrations in 17 percent of the water samples exceeded the drinking water standard. During 1979–80, 68 ground-water samples were analyzed for selected volatile organic compounds. The most commonly detected compounds were 1,1,1-trichloroethane (74 percent of samples), chloroform (72 percent), 1,1,2-tetrachloroethylene (68 percent), trichloroethylene (63 percent), 1,2-dichloroethane (60 percent), and 1,2-dichloropropane (51 percent).

Anthropogenic heat production has caused elevated ground-water temperatures in many parts of Philadelphia. Most ground-water temperatures were higher than the local mean annual air temperature of 12.6 °C (degrees Celsius), and many well logs show cooling trends with increasing depth or anomalous temperature gradients. Water temperatures in densely urbanized areas commonly are highest directly beneath the land surface and decrease with depth. Temperatures in less developed areas generally increase downward at about 1 °C per 100 ft, which is the natural rate of increase of temperature with depth.

The first aquifer to be developed for water supply was the Trenton gravel. From 1900 through 1969, an average of 580 Mgal (million gallons) of water was withdrawn annually from this aquifer; from 1970 through 1979, an average of 420 Mgal was withdrawn annually. The principal source of ground water is the lower sand unit. From 1900 through 1969, an average of 2,700 Mgal of water was withdrawn annually from the lower sand unit; from 1970 through 1979, an average of 1,800 Mgal was withdrawn annually. Annual withdrawal from the crystalline rocks peaked 2 decades earlier than annual withdrawal from the unconsolidated sediments. From 1900 through 1969, an average of 1,000 Mgal of water was withdrawn annually from the Wissahickon Formation; from 1970 through 1979, an average of 150 Mgal was withdrawn annually. Pumpage of ground water from 16 sumps draining the subway system and the sump draining Veterans Stadium averaged about 1,300 Mgal per year in the early 1980's. Most of the water entering the sumps comes from the Trenton gravel; the remainder comes from the Wissahickon Formation.

INTRODUCTION

Purpose and Scope

The purpose of this report is to summarize information on the occurrence, availability, and quality of ground water in Philadelphia, Pa. The study on which the report is based was conducted during 1978–82 by the U.S. Geological Survey, in cooperation with the city of Philadelphia Water Department. The objectives of the study were to evaluate ground-water conditions and to determine the suitability of ground water as a source of emergency public supply. Ground-water conditions in Philadelphia had not been evaluated in detail since the late 1950's (Greenman and others, 1961); hence, it was necessary to collect new data to assess present availability and quality.

This report contains information on geology and hydrology, including ground-water occurrence, water-level fluctuations, aquifer hydraulic properties, and ground-water quality. Information on geology, including lithology and stratigraphy, was obtained chiefly from driller's and geologist's logs of samples from boreholes. Geophysical logs, including gamma ray, temperature, neutron, caliper, fluid conductivity, fluid velocity, single-point resistance, and spontaneous potential, were run in 48 wells to complement the geologic logs and to provide hydrologic information. Geohydrologic units also were inspected in the outcrop area and in excavations.

Data on water levels, well yields, water use, construction methods, and other details were updated or newly collected for 244 wells and three drainage sumps.

Water levels were measured in 163 wells. Additional water-level data for 358 cased test boreholes were obtained from the city of Philadelphia Water Department (1975). Water levels in 21 observation wells were measured periodically for information on fluctuations. Four of these wells were equipped with continuous water-level recorders, and monthly measurements were made in the rest.

Single-well pumping tests, generally of 1 to 3 hours duration, were conducted on unconsolidated aquifers at 20 sites to obtain estimates of aquifer coefficients.

Eighty-nine water samples collected during 1978–81 from 77 wells and three sumps were analyzed for major ions, nutrients, trace elements, gross organic measures, and volatile organic compounds. Samples generally were collected only once; however, six sites were sampled several times to evaluate short-term changes in water quality.

Description of Area

Location

The city of Philadelphia, which is coincident with Philadelphia County, is an area of 134.6 mi^2 (square miles) in southeastern Pennsylvania. Philadelphia is bordered on the south and east by the Delaware River, which separates Pennsylvania from New Jersey, and on the north and west by Bucks, Montgomery, and Delaware Counties (fig. 1).

Population and Land Use

Philadelphia is densely populated and extensively urbanized. According to the Federal Census of 1980 (U.S. Department of Commerce, 1982), the population was 1.7

Figure 1. Location of study area.

Table 1. Land use in Philadelphia, 1975

Land use	Percentage of total
Commercial and industrial	43.8
Residential	30.1
Undeveloped	15.0
Recreation and resource production	11.1
Total	100.0

million, or about 12,600 persons per square mile. The part of Philadelphia along the Delaware and lower Schuylkill Rivers is one of the Nation's major commercial and industrial centers. Land use in 1975 (table 1) was 44 percent commercial and industrial, 30 percent residential, 15 percent undeveloped, and 11 percent recreation and resource production (David Segal, Philadelphia City Planning Commission, oral commun., 1982).

Physiography

Philadelphia occupies parts of the Coastal Plain and Piedmont physiographic provinces (fig. 2). The Fall Line, or landward edge of the Coastal Plain, traverses Philadelphia from southwest to northeast. It divides the city into two areas of significantly different topographic, geologic, and hydrologic characteristics.

The Coastal Plain lies southeast of the Fall Line and in Philadelphia is a 35-mi^2 narrow band along the Delaware River. The soft, unconsolidated deposits of gravel, sand, silt, and clay that make up the Coastal Plain form broad areas of low relief. Land-surface elevations range from 0 to about 40 ft (feet).

The Piedmont in Philadelphia is a 100-mi^2 upland area that lies northwest of the Fall Line. In the Piedmont, land-surface elevations range from about 40 ft at the Fall Line to more than 400 ft in northwestern Philadelphia. This area stands well above the level of the bordering Coastal Plain and is characterized by ridges, hills, and deep, narrow valleys. The crystalline bedrock that underlies the Piedmont is hard and dense and generally is at or near the land surface. The bedrock surface slopes gently to the southeast and forms the basement beneath the Coastal Plain deposits.

Climate and Precipitation

Philadelphia's climate is classified as a humid-continental type. It is influenced by the Appalachian Mountains to the west and the Atlantic Ocean to the east and is characterized by a large annual temperature range, cold winters dominated by low-humidity airmasses, hot summers dominated by medium- to high-humidity airmasses, and ample precipitation.

Generally, temperatures are moderate and extreme temperatures seldom prevail longer than a few days. During 1979–81, the period of data collection for this study, the mean annual air temperature at the National Weather Service station at Philadelphia International Airport was 12.4 °C, or 0.2 °C below the long-term mean. Monthly mean temperatures during 1979–81 ranged from -5.0 °C in February 1979 to 26.7 °C in August 1980 (fig. 3).

Precipitation is moderate throughout the year. The long-term mean annual precipitation at Philadelphia is 39.93 in (inches). During 1979–81, annual precipitation ranged from 37.83 in for 1981, or 2.10 in below the mean, to 52.79 in for 1979, or 12.86 in above the mean (fig. 3). In 1980, precipitation was 1.13 in below the mean. Generally, precipitation is distributed fairly evenly throughout the year, although slightly more falls during the late summer months. Much of the summer rainfall is due to thunderstorms; consequently, amounts throughout the area may vary a great deal.

Drainage

Philadelphia is drained by the Delaware River and its tributaries. At Philadelphia, about 100 mi (miles) from its mouth, the Delaware is estuarine and has a tidal range of about 5.5 ft. The average discharge of the Delaware River at Trenton, N.J., for 1913–84, unadjusted for diversion, was 11,700 ft^3/s (cubic feet per second). In dry years, however, the flow has been as low as 1,180 ft^3/s. During extended periods of low streamflow, the salt line, or location in the estuary where the chloride concentration equals 250 mg/L (milligrams per liter), has moved upstream as far as the Benjamin Franklin Bridge (fig. 4) at Philadelphia (Toffey, 1982, p. 43).

The major streams and locations of six selected streamflow-gaging stations in the Philadelphia area are shown in figure 4. Table 2 summarizes streamflow data for these stations through the 1984 water year. The station-identification numbers are those assigned by the U.S. Geological Survey. Additional descriptive information and streamflow data are given in "Water Resources Data for Pennsylvania, Volume 1, Delaware River Basin," published annually by the U.S. Geological Survey.

The principal tributary to the Delaware River is the Schuylkill River, which enters Philadelphia from the northwest and merges with the Delaware in southern Philadelphia (fig. 4). Downstream from the Fairmount Dam at Philadelphia (fig. 4), the Schuylkill is estuarine. The average discharge of the Schuylkill River at Philadelphia (fig. 4, station 01474500) for 1931–84 was 2,970 ft^3/s. During drought, however, the minimum mean daily flow has been as low as 0.6 ft^3/s.

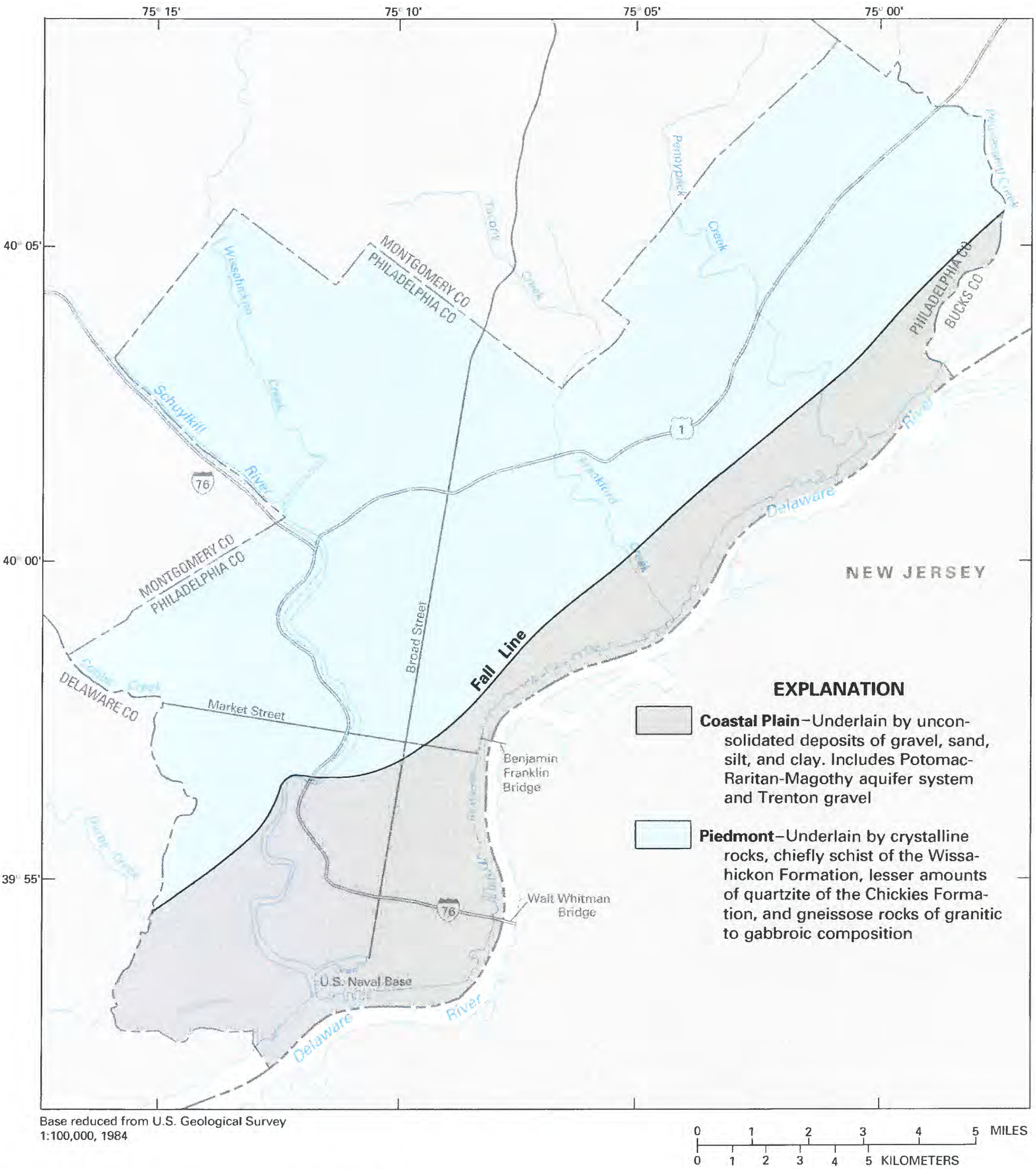

Figure 2. Physiographic provinces in Philadelphia.

Several perennial streams are tributary to the Delaware and Schuylkill Rivers. Upstream from its confluence with the Schuylkill River, the Delaware has several major tributaries in Philadelphia, including Tacony-Frankford, Pennypack, and Poquessing Creeks; downstream from the confluence, Cobbs Creek is the principal tributary (fig. 4). These streams originate in the Piedmont and flow swiftly toward the southeast under moderate to steep gradients.

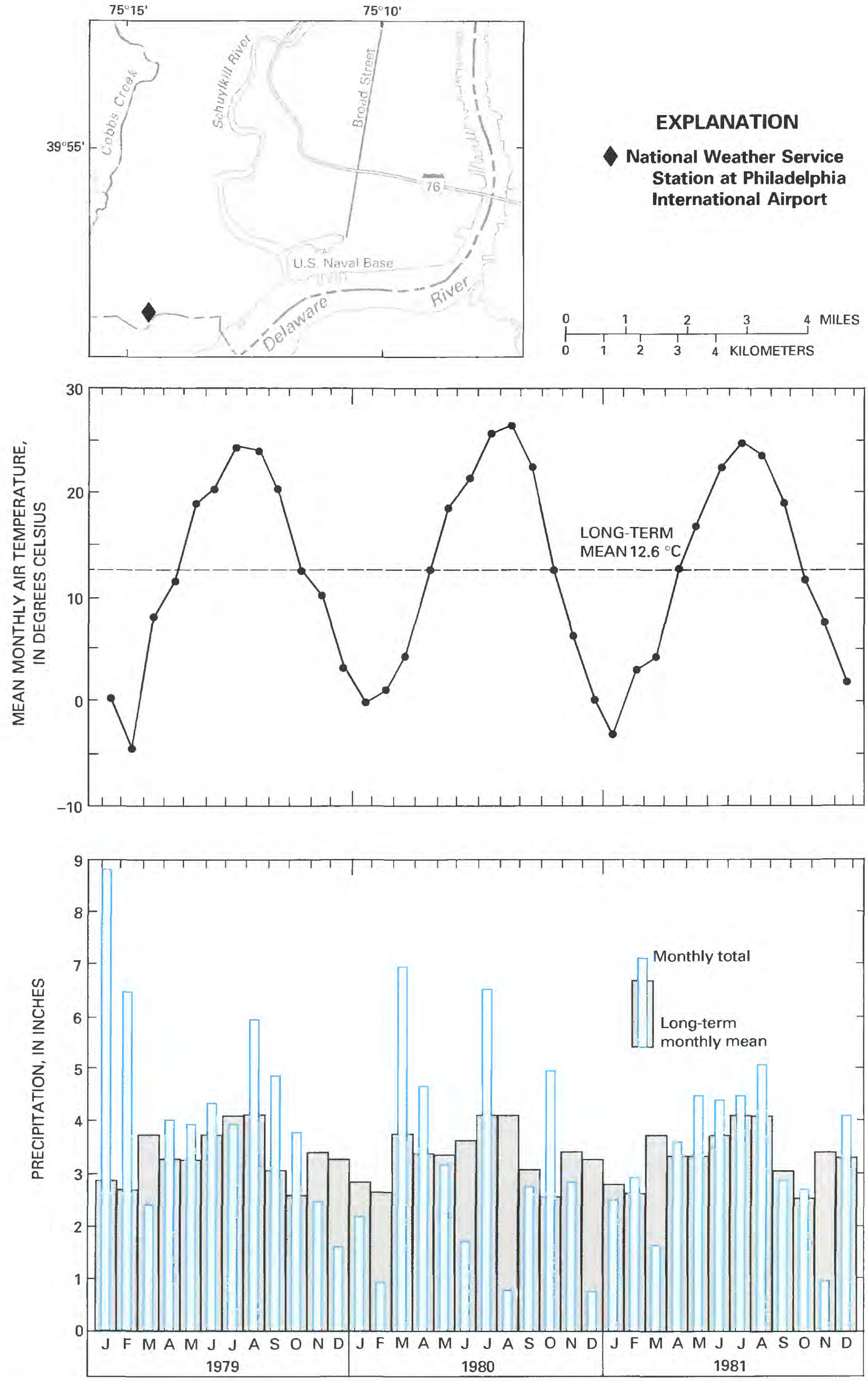

Figure 3. Meteorological data, 1979–81.

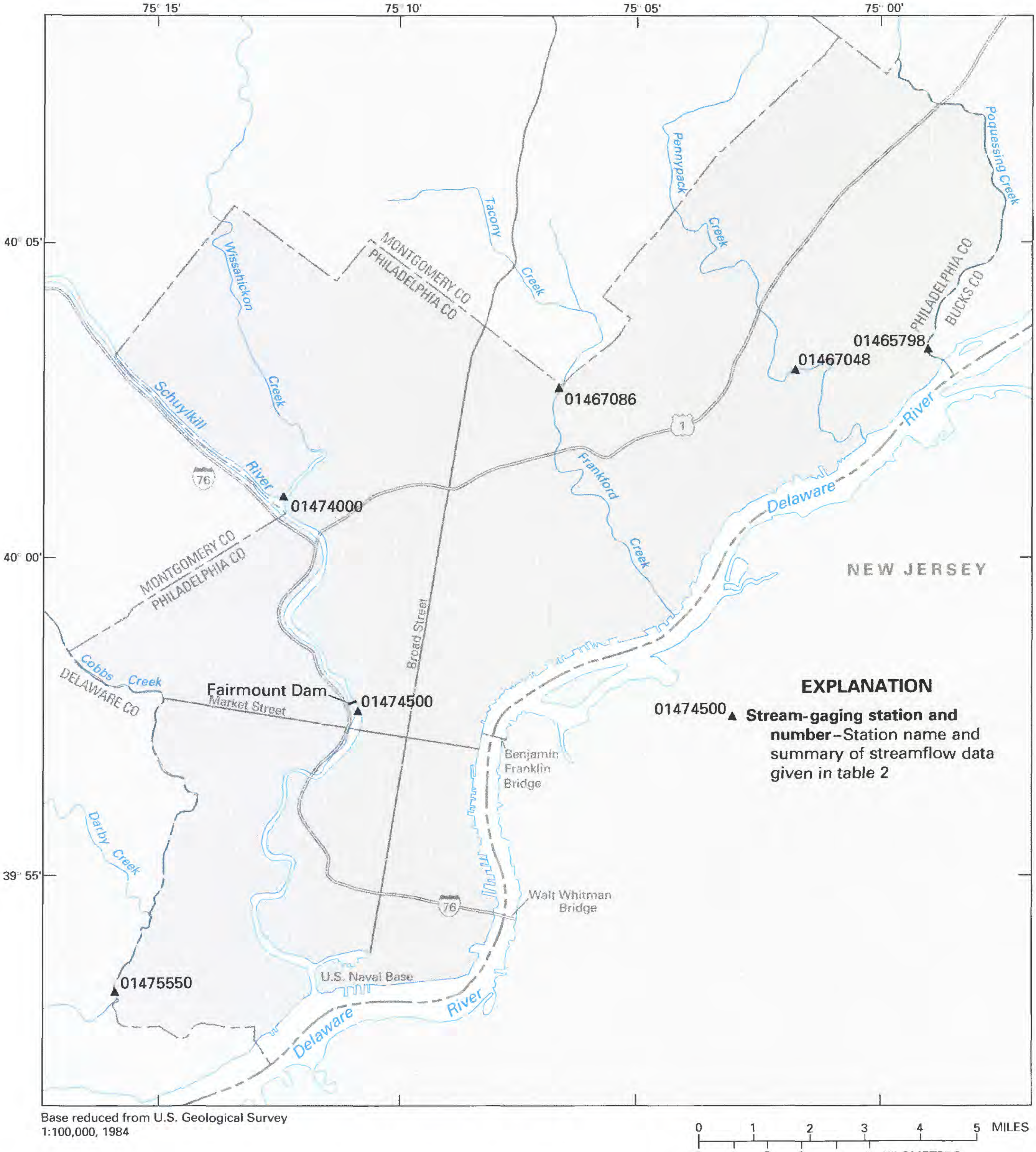

Figure 4. Principal streams and locations of selected gaging stations.

Upon entering the Coastal Plain, however, their gradients are reduced, and generally they meander. The lower reaches of these streams are tidal. Wissahickon Creek lies entirely within the Piedmont and empties into the Schuylkill River.

Water Supply and Wastewater Treatment

Municipal water-supply and wastewater-treatment facilities serve all of Philadelphia. Surface waters are the

Table 2. Summary of streamflow data for selected gaging stations, through water year 1984

[mi^2, square miles; ft^3/s, cubic feet per second]

Station number	Station name	Drainage area (mi^2)	Years of record	Average discharge (ft^3/s)	Maximum discharge (ft^3/s)	Minimum daily discharge (ft^3/s)
01463500	Delaware River at Trenton, NJ	6,780	72	11,700	329,000	1,180
01465798	Poquessing Creek at Grant Avenue, Philadelphia, PA	21.4	19	34.3	9,400	1.1
01467048	Pennypack Creek at Lower Rhawn Street Bridge, Philadelphia, PA	49.8	19	95.2	9,770	6.0
01467086	Tacony Creek above Adams Avenue, Philadelphia, PA	16.7	19	27.7	4,550	1.8
01474000	Wissahickon Creek at Mouth, Philadelphia, PA	64.0	20	105	6,870	2.0
01474500	Schuylkill River at Philadelphia, PA	1,893	53	2,970	103,000	0.6
01475550	Cobbs Creek at Darby, PA	22.0	20	31.4	4,490	0.0

sole source of the municipal supply. An average of 356 Mgal/d (million gallons per day) of water is withdrawn in nearly equal amounts from the Delaware and Schuylkill Rivers. This water is used chiefly for domestic and industrial purposes. The storage capacity of the municipal water system is about 743 Mgal. In addition, nearly 10 Mgal/d of ground water is withdrawn by several municipal agencies and private firms, mainly for site dewatering and industrial use. A 3,000-mi network of sewers transports wastewater to three treatment plants. Ultimately, treated wastewater is discharged into the Delaware River.

Previous Studies

Several descriptive reports on the ground-water resources of the Philadelphia area were published from 1904 to 1968. The earliest report, by Bascom (1904), contains a section on deep and artesian wells; this section describes geologic conditions and water-bearing properties of the crystalline rocks and Coastal Plain deposits. A report by Hall (1934) on southeastern Pennsylvania contains a chapter on ground water in Philadelphia County. It gives a general description of geology and hydrology and includes records of 58 wells and results of two chemical analyses. Graham and Kammerer (1952) discussed ground-water availability and quality in part of the Coastal Plain of southern Philadelphia. Barksdale and others (1958) broadly evaluated the ground-water resources of the greater Philadelphia area. Biesecker and others (1968) described ground-water conditions in those parts of the Piedmont and Coastal Plain that lie within the Schuylkill River basin.

The first report to specifically address the ground-water resources of Philadelphia was by Greenman and others (1961). It describes ground-water occurrence, availability, and quality in the Coastal Plain deposits and crystalline rocks and documents the effects of human activities on water quality. The report contains records of 509 wells in Philadelphia and lists 646 chemical analyses of water samples from some of those wells.

Several reports supplement this report. Paulachok and others (1984) present records of 828 wells and three drainage sumps and give 1,467 chemical analyses of water samples from 205 sites. These analyses include 103 determinations for trace elements and 68 determinations for volatile organic compounds. The report also contains an index of geophysical logs. Paulachok and Wood (1984) present a water-table map of Philadelphia. The effects of heat production on local ground-water temperatures and gradients are described by Paulachok (1984). A report by Sloto (1988) contains a predictive digital computer model of the confined aquifer system in southern Philadelphia.

Site-Identification System

The well-identification numbers used in this report consist of two parts: (1) the prefix "PH," which identifies Philadelphia as the county in which the well is located, and (2) a sequentially assigned number.

Drainage sumps cited in this report are identified by the names of the intersecting streets nearest the site or the name of the structure at which the sump is located.

Acknowledgments

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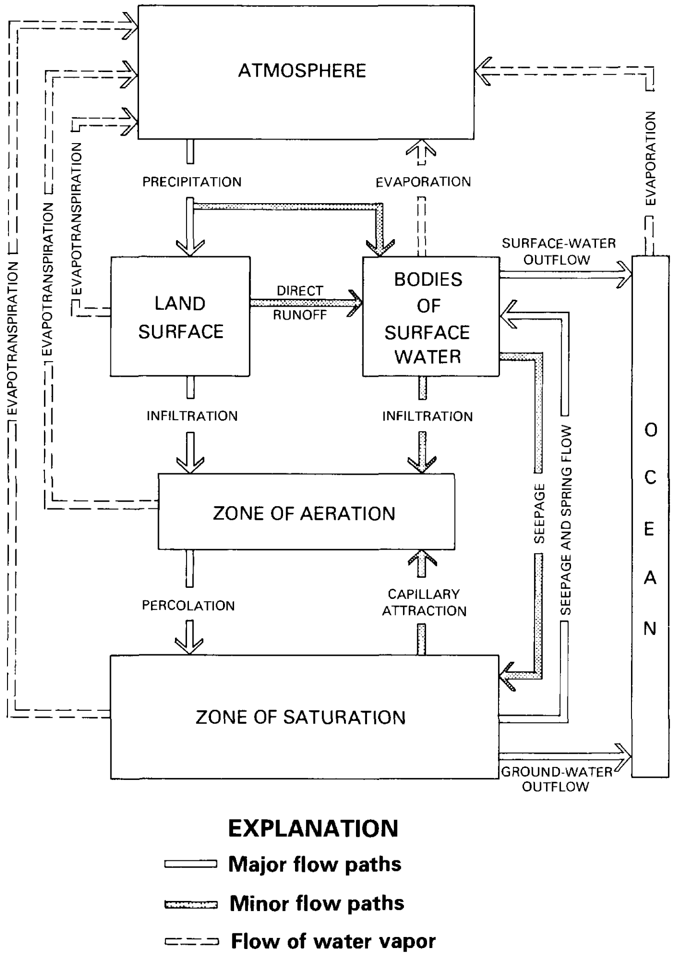


Figure 5. Flow diagram of the hydrologic cycle under natural conditions. (Modified from Franke and McClymonds, 1972, fig. 13.)

GENERAL HYDROLOGY

Natural Hydrologic Cycle

The Earth's water-circulation system is called the hydrologic cycle. The cycle is a dynamic process in which water is transported from the oceans to the atmosphere and, by various pathways, back to the oceans. The flow diagram (fig. 5) shows that, in the natural cycle, precipitation on the land surface may infiltrate downward to the zone of aeration, evaporate or transpire back to the atmosphere, or flow over the land surface as direct runoff. Some precipitation percolates to the water table (the upper surface of the zone of saturation) and recharges the ground-water reservoir. Water in the hydrologic cycle flows at various rates, depending on whether it is in the form of water vapor, surface water, or ground water.

The quantitative relation among the components of the hydrologic cycle can be expressed as an equation called a water budget. A water budget states that, for a given area and interval of time and adjusting for changes in storage, the volume of inflow equals the volume of outflow. Thus, the water-budget equation for a natural system may be expressed as

Inflow=*Outflow* plus *Storage Adjustment*

or

$$P=R+ET+\Delta S,$$

where

P=precipitation,
R=runoff,
ET=evapotranspiration (water loss), and
ΔS=change in water storage.

Runoff is that part of precipitation that appears in stream channels; it usually consists of two components: (1) direct runoff—water that flows over the land surface to channels and (2) ground-water runoff (or base flow)—water that enters stream channels as ground-water inflow. According to Parker and others (1964, p. 111), the mean annual runoff from the Schuylkill River basin above the Fairmount Dam at Philadelphia (fig. 4), adjusted to the base period 1921–50, is 20.5 in, or 46 percent of the concurrent mean annual precipitation. Biesecker and others (1968, p. 71) estimate that runoff from the basin for an average year is 48 percent of the corresponding annual precipitation.

Natural water loss from the area occurs chiefly by evapotranspiration. Evapotranspiration is the discharge of water vapor to the atmosphere and consists of evaporation plus transpiration by vegetation. Direct measurements of evapotranspiration usually are not possible; commonly, it is estimated as a residual in the water-budget equation by subtracting runoff from precipitation. About half the precipitation on southeastern Pennsylvania is lost by evapotranspiration. By using data for the Schuylkill River basin above the Fairmount Dam (fig. 4), Biesecker and others (1968, p. 71) estimate evapotranspiration during an average year as 52 percent of the corresponding annual precipitation.

Storage is the quantity of water in surface and subsurface reservoirs. The natural surface storage includes water in stream channels, ponds, and marshes. The subsurface storage includes water in soils, aquifers, and confining beds. In Philadelphia, surface storage capacity is small compared with subsurface storage capacity, if estuaries are excluded.

Effects of Urbanization on the Natural Hydrologic Cycle

The natural hydrologic cycle in Philadelphia has been altered significantly by urbanization. Several effects of urbanization, including alteration of the occurrence, availability, and quality of water, are described below.

Changes in land use resulting from conversion of rural land to industrial, commercial, and residential areas generally have had detrimental effects on the hydrologic system in Philadelphia. Such effects were recognized about 200 years ago by Benjamin Franklin, as revealed in the following excerpt from his will (Smyth, 1907, p. 506):

> And, having considered that the covering of a groundplot of the city with buildings and pavements, which carry off most of the rain and prevent its soaking into the Earth and renewing and purifying the Springs, whence the water of wells must gradually grow worse, and in time be unfit for use, as I find has happened in all old cities, I recommend that at the end of the first hundred years, if not done before, the corporation of the city...(bring) by pipes, the water of Wissahickon Creek into the town, so as to supply the inhabitants....

The flow diagram (fig. 6) shows the effects of the urbanization of Philadelphia on the hydrologic cycle. Comparison of this diagram with that showing the hydrologic cycle under natural conditions (fig. 5) reveals the addition of several important flow paths. Although water inflow from precipitation varies little with time, its disposition has been modified by the widespread construction of streets, parking lots, buildings, and other impervious surfaces. Because much of the natural vegetative cover has been replaced by impervious surfaces, direct runoff has increased and evapotranspiration and infiltration of precipitation have decreased. Direct conveyance of storm water to streams by streets, gutters, and sewers now causes more frequent floods with higher flows. Owing to reduced infiltration, ground-water levels may have declined during the early stages of urbanization, resulting in a reduction of groundwater storage and base flow of streams. In addition, the accidental and intentional disposal of chemicals and wastes by a large population generally has degraded water quality.

Effects of Urbanization on the Ground-Water System

Infiltration and Exfiltration

Construction of sewers in Philadelphia significantly changed the natural hydrologic cycle. Interchange of water from sewers with the ground-water system now represents a major flow path in the hydrologic cycle (fig. 6).

The sewer-construction program began about 1855; most sewers constructed in the 19th century were made of brick. Commonly, sewers built before 1875 were constructed without mortar between the bricks on the premise that the open joints would admit ground water and lower the water table, thereby reducing foundation-drainage problems. When mortar was used, it generally contained high concentrations of lime that dissolved slowly and formed additional points of leakage. Although brick sewers continued to be built until about 1940, they were largely supplanted by vitrified clay pipes, which were introduced about 1890, and by concrete pipes, which were introduced more recently. A recent study showed that Philadelphia's wastewater-collection system consists of nearly 3,000 mi of sewers, of which about 52 percent are brick (City of Philadelphia Water Department, Water Pollution Control Division, 1975.)

Although brick sewers without mortar joints were designed as ground-water drains, they also can function as a source of ground-water recharge. The processes of infiltration, or flow of ground water into sewers through open joints and cracks in pipes and manholes, and exfiltration, or flow of wastewater into the ground-water system from leaky sewers, depend chiefly on the physical condition of the sewers and the position of the water table relative to wastewater levels (fig. 7).

If the water table is above the wastewater level in leaky sewers, ground water flows into the sewers. The average rate of infiltration into sewers was estimated to be 135 Mgal/d when the water table is elevated (City of Philadelphia Water Department, Water Pollution Control Division, 1975). When the water table is below the wastewater level in the sewers, leaking wastewater augments

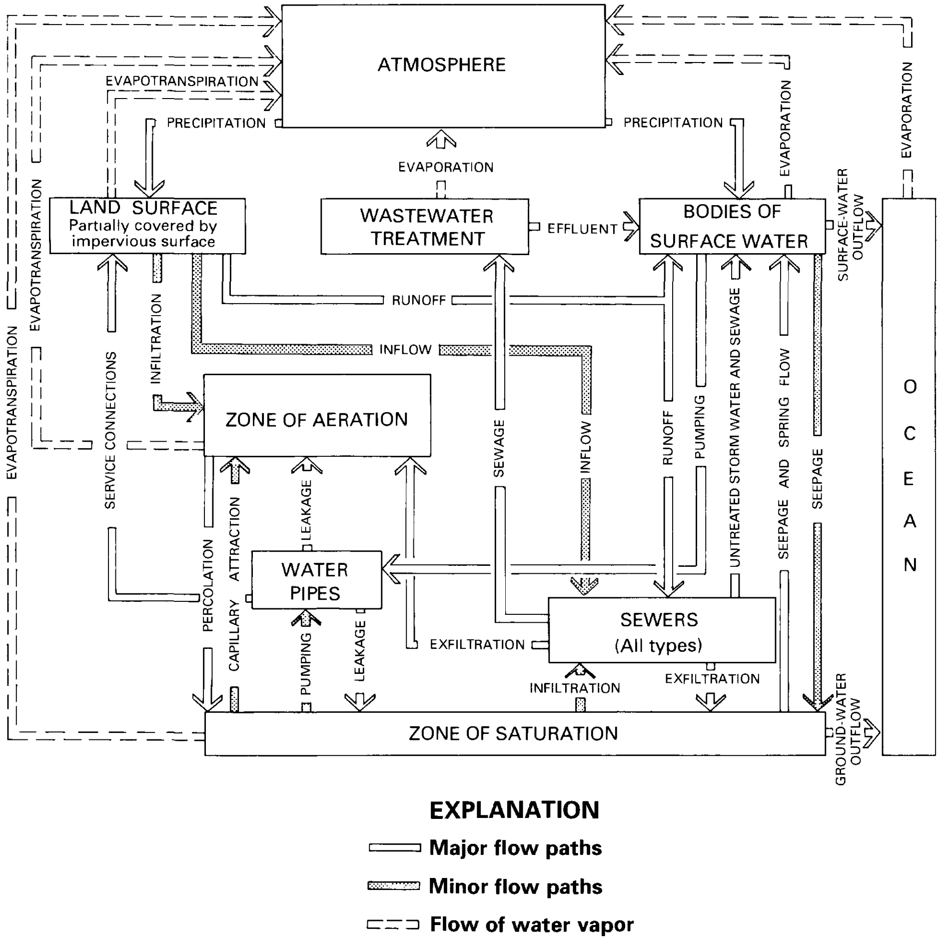


Figure 6. Flow diagram of the hydrologic cycle following urbanization and development of water supply and wastewater disposal. (Modified from Franke and McClymonds, 1972, fig. 33.)

ground-water recharge from precipitation. The quantity of wastewater that exfiltrates from sewers has not been established, however. Some specific effects of sewers on the water table are discussed in the section "Water-Level Fluctuations."

Leakage from Water-Distribution Pipes

Except in localities of elevated water table, water-distribution pipes in Philadelphia generally are above the water table. Breaks in these pipes are common. Although most breaks quickly become evident and are repaired, many small leaks and probably a few large leaks remain undetected. Water that leaks from distribution pipes may percolate to the water table; however, most leakage probably is intercepted by sewers that lie beneath the water pipes. Estimates of the amount of water lost in 1980 through leaks in the distribution system ranged from 60 to 72 Mgal/d, or about 17 to 20 percent of the finished supply (Roy Romano, City of Philadelphia Water Department, oral commun., 1987).

GEOHYDROLOGY

Occurrence of Ground Water

Each of the major geohydrologic units in Philadelphia has a different physical character, each differs in its ability to transmit and store water, and each generally yields native water of somewhat different quality. It is necessary to know the distribution of the different units if the quantity and quality of ground water available at a given location are to be estimated. Photographs of exposures of selected geologic units are shown in figure 8, and a generalized map of surficial geology is presented in figure 2. The generalized sections of south-central Philadelphia show the geology in the west-east (fig. 9), south-north (fig. 10), and northwest-southeast (fig. 11) directions.

Table 3 gives the age and stratigraphic relations of the geohydrologic units and correlates the nomenclature used in this report with that of Greenman and others (1961) for the Coastal Plain of southeastern Pennsylvania. Table 4 summarizes important characteristics of the units.

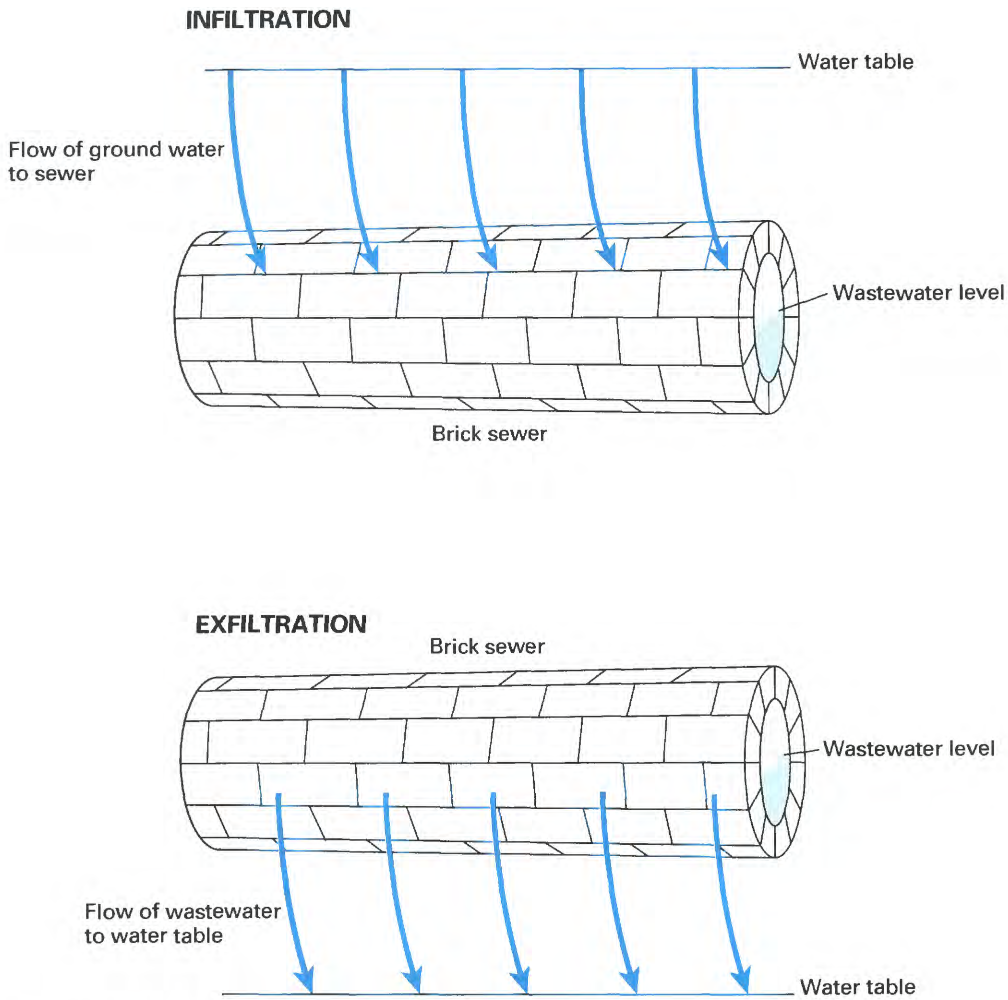


Figure 7. Processes of infiltration and exfiltration.

Philadelphia is underlain by unconsolidated sediments of the Coastal Plain and by older crystalline rocks of the Piedmont; both contain water. In unconsolidated sediments, water is present in voids between mineral grains (fig. 12). Most of the gravels and sands of the Coastal Plain yield large supplies of water that are used chiefly for industrial and other nondomestic purposes. These sediments form the principal aquifers in Philadelphia. Crystalline rocks are so named because they are composed of interlocking mineral grains or crystals. In crystalline rocks, water is present in fractures and openings along planes of bedding and schistosity (fig. 13). Because fractures and planar structures account for only a small part of the volume of these rocks, the crystalline rocks commonly yield small amounts of water that are used mainly for domestic purposes. Accordingly, the crystalline rocks form aquifers of local importance.

The lower and middle sand units of the Potomac-Raritan-Magothy aquifer system form the major unconsolidated part of the confined aquifer system. The lower sand unit is confined where it is overlain by the lower clay unit, the middle clay unit, or both. It is the most important confined aquifer in the area. The upper sand unit is confined where it is overlain by the upper clay unit.

Water is under confined conditions in the crystalline rocks where they are overlain by confining units of unconsolidated sediments. Figure 14 shows the approximate extent of the confined aquifer system.

The unconfined, or water-table, aquifer system includes all geohydrologic units that receive direct recharge from precipitation and surface sources. The major sources of recharge to the unconfined aquifer system are precipitation on areas of the aquifers exposed at the land surface, water from surface sources, and leakage from sewers and water pipes. The lower and upper sand units are unconfined where the overlying clay units are absent and the sands are in direct hydraulic contact with overlying unconsolidated deposits. The other unconsolidated units of the unconfined aquifer system are the Bridgeton Formation, Trenton gravel (informal usage), and alluvium. Water in the crystalline

Table 3. Geohydrologic units

SYSTEM	SERIES	GEOHYDROLOGIC UNIT: This report		GEOHYDROLOGIC UNIT: Greenman and others (1961)	
Quaternary	Holocene	Alluvium		Alluvium	
Quaternary	Pleistocene	"Trenton gravel" (informal usage)		Cape May Formation	
				Pensauken Formation[1]	
Tertiary	Miocene	Bridgeton Formation			
Cretaceous	Upper Cretaceous	Potomac-Raritan-Magothy aquifer system	Upper clay unit	Magothy Formation[1]	
				Upper Clay member[1]	
			Upper sand unit	Raritan Formation	Old Bridge Sand Member[1]
			Middle clay unit		Middle clay member
			Middle sand unit		Sayreville Sand Member
			Lower clay unit		Lower clay member
	Lower Cretaceous		Lower sand unit		Farrington Sand Member
Pre-Cretaceous		Crystalline rocks, includes Chickies Formation and Wissahickon Formation of Glenarm Group		Crystalline rocks of Glenarm Series (former usage)	

[1] Present usage of the U.S. Geological Survey: the Pensauken Formation is of Miocene age. The Old Bridge Sand Member and Upper Clay member belong to the Magothy Formation.

rocks is unconfined where the rocks crop out or where they are overlain directly by unconfined unconsolidated sediments.

Unconsolidated Aquifers

In Pennsylvania and adjacent parts of New Jersey, the deepest Coastal Plain sediments, from oldest to youngest, are the Potomac Formation, Raritan Formation, and Magothy Formation. These sediments of Cretaceous age form the Potomac-Raritan-Magothy aquifer system. This aquifer-system name has been used extensively in New Jersey, and it has been adopted for use in Pennsylvania to conform with the New Jersey usage. However, in Pennsylvania, the Cretaceous sediments belong chiefly to the Raritan Formation; the Magothy Formation has not been identified, although some sediments of the Potomac Group may be present (G.M. Farlekas, U.S. Geological Survey, oral commun., 1983). The Potomac-Raritan-Magothy aquifer system consists of interbedded gravel, sand, silt, and clay units that are at or near the land surface in southeastern Pennsylvania and parts of New Jersey. Deposits of the Potomac-Raritan-Magothy aquifer system represent three

Figure 8. Exposures of geologic units: *A*, Subsurface exposure of Trenton gravel (informal usage) in central Philadelphia showing wide range of grain sizes and indistinct bedding.

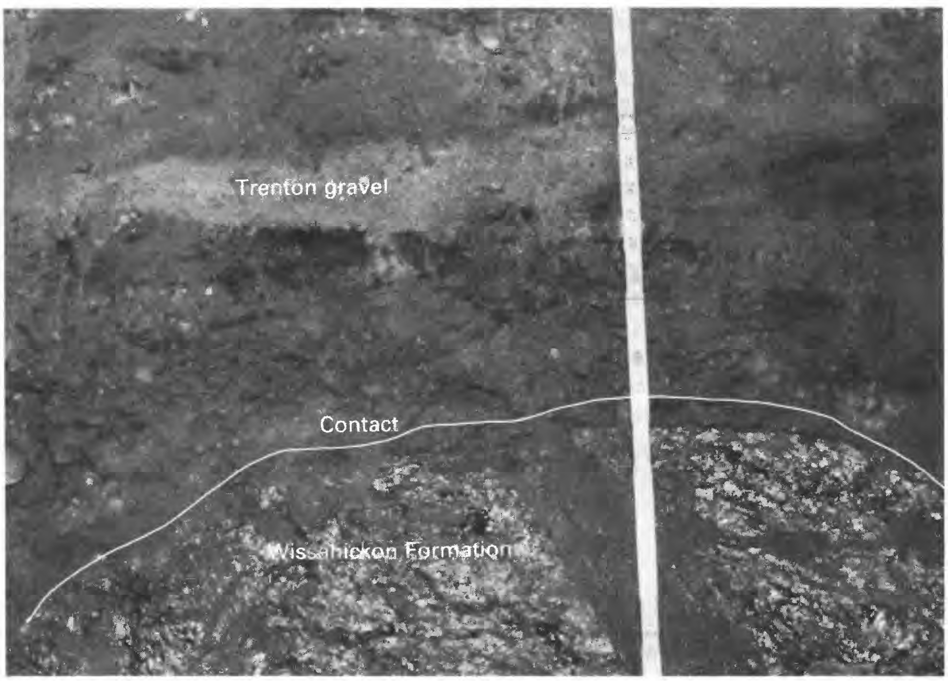


Figure 8. Continued. *B*, Subsurface exposure of Trenton gravel in central Philadelphia showing unconformable contact with the Wissahickon Formation.

Figure 8. Continued. C, Exposure of Wissahickon Formation in roadcut west of Philadelphia showing schistosity planes.

cycles of sedimentation. Each cycle began with the deposition of a gravel and sand unit and ended with the deposition of a clay unit. However, one or more of these units may be absent locally. The three gravel and sand units, referred to as the lower, middle, and upper sand units, form the highest yielding aquifers in Philadelphia. However, these individual units may not be continuous or correlative with similar units in adjacent States. Although the clay units are low-permeability confining beds that yield little water to wells, they may store considerable water. In Philadelphia, the maximum thickness of the Potomac-Raritan-Magothy aquifer system is about 190 ft. Table 3 shows that the Potomac-Raritan-Magothy aquifer system is equivalent to the Raritan and Magothy Formations of Greenman and others (1961).

The Cretaceous sediments may be overlain locally by Miocene deposits of the Bridgeton Formation. The Bridgeton Formation consists chiefly of gravel and sand deposits that crop out in the Piedmont. These sediments commonly are very thin and lie above the water table and thus do not form an important aquifer there. In the Coastal Plain, however, the Bridgeton Formation constitutes a minor part of the unconfined aquifer system where it is connected hydraulically to the underlying upper sand unit of the Potomac-Raritan-Magothy aquifer system or the overlying Trenton gravel.

The informally named Trenton gravel (Owens and Minard, 1979) overlies the Bridgeton Formation where it is present, although generally it rests directly on the Cretaceous sediments. The Trenton gravel forms an important aquifer where it is thick. It is equivalent to the Pleistocene sediments of Wisconsin age described by Greenman and others (1961).

Near the mouth of the Schuylkill River and at a few other localities, the Trenton gravel is overlain by a veneer of alluvium of Holocene age. Generally, deposits of alluvium are fine grained and thin; consequently, they do not form an important aquifer. In Philadelphia, the Coastal Plain sediments attain a maximum thickness of about 280 ft.

Alluvium

The alluvium consists of fine sand, silt, and mud (Greenman and others, 1961, p. 48). These deposits are nearly 80 ft thick in southern Philadelphia where the Delaware and Schuylkill Rivers merge, but the thickness rarely exceeds 30 ft half a mile or more from that area. Because the alluvial deposits are very fine grained, they have very low permeability and do not yield much water to wells. Therefore, the alluvium is not an important aquifer.

Trenton Gravel

Description

The Trenton gravel consists of gravel, sand, and minor amounts of clay (Owens and Minard, 1979). The size of the mineral grains that constitute this unit varies greatly from place to place; the water-bearing properties of the

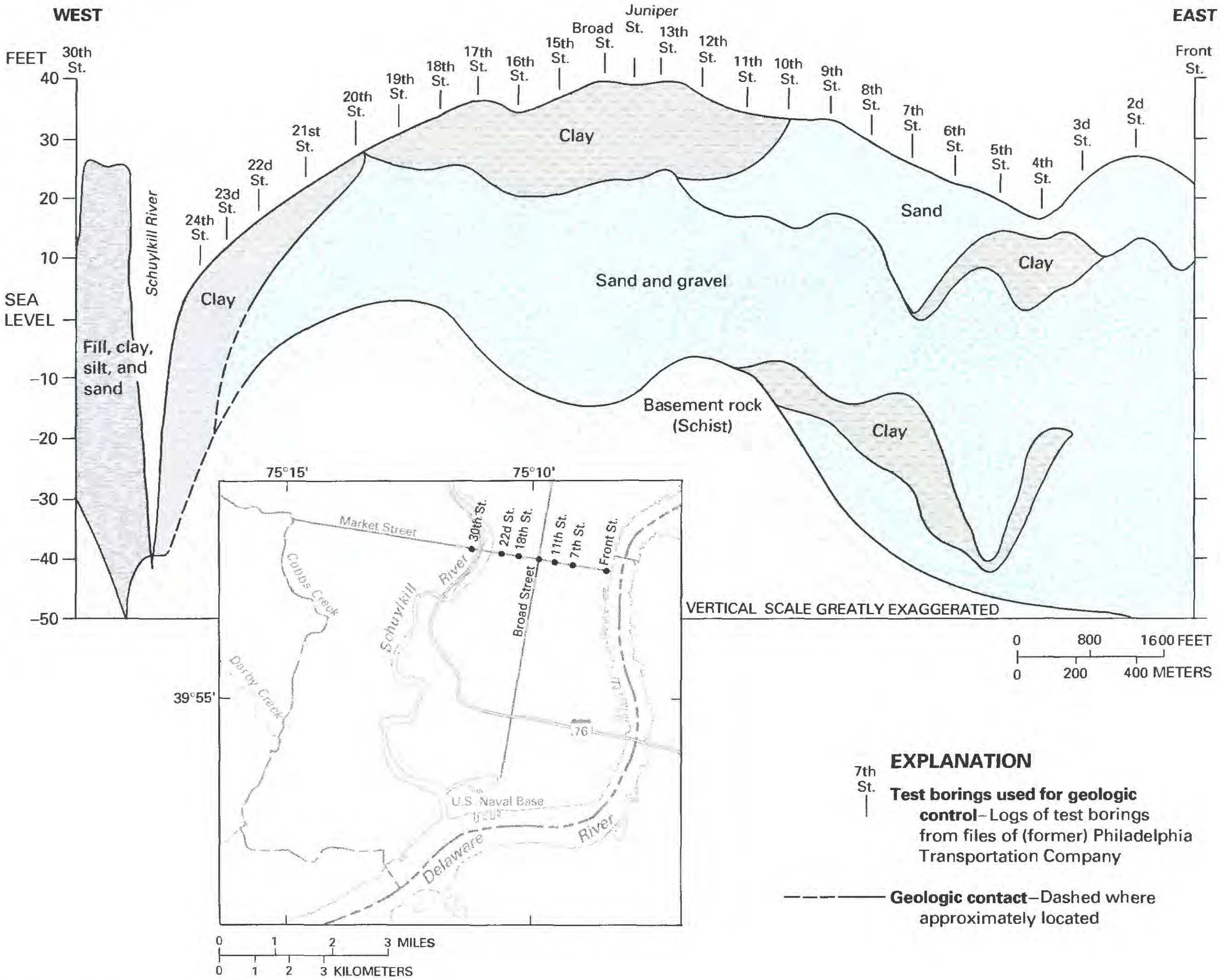


Figure 9. Generalized west-east geologic section.

Trenton gravel differ widely according to the grain size, sorting, and thickness of the sediments. The Trenton gravel occupies lowland areas along the Delaware River (fig. 15), and the upper surface of these deposits generally has an altitude of 40 ft or less above sea level. The thickness of the Trenton gravel averages about 40 ft and locally is as much as 80 ft. Most of the unconfined aquifer system consists of the Trenton gravel.

Well Yield and Specific Capacity

Commonly, it is difficult to differentiate between the upper sand unit and the Trenton gravel and to determine the principal source of water from wells completed in the unconsolidated unconfined aquifer. Therefore, yield and specific-capacity data for these two units are combined. Most of the data, however, probably are for the Trenton gravel. Both the upper sand unit of the Potomac-Raritan-Magothy aquifer system and the Trenton gravel are permeable enough to yield moderate amounts of water to wells. The mean and median reported yields of 122 wells open to either the upper sand unit or the Trenton gravel are 170 and 90 gal/min (gallons per minute), respectively. These values of yield are considerably lower than those for the unconsolidated part of the confined aquifer system. Some wells in the upper sand unit or the Trenton gravel yield as much as 1,370 gal/min, whereas some low-capacity wells yield less than 1 gal/min. The cumulative frequency distribution (fig. 16) shows that 88 percent of the yields exceed 1 gal/min and that 10 percent exceed 510 gal/min. Figure 17 shows the variation in yield of wells in the Trenton gravel. Commonly, yields are highest where the aquifer has greatest saturated thickness. Because the physical properties and saturated thickness of the Trenton gravel differ greatly from place to place, the map cannot be used to predict the precise yield of a well at a particular site.

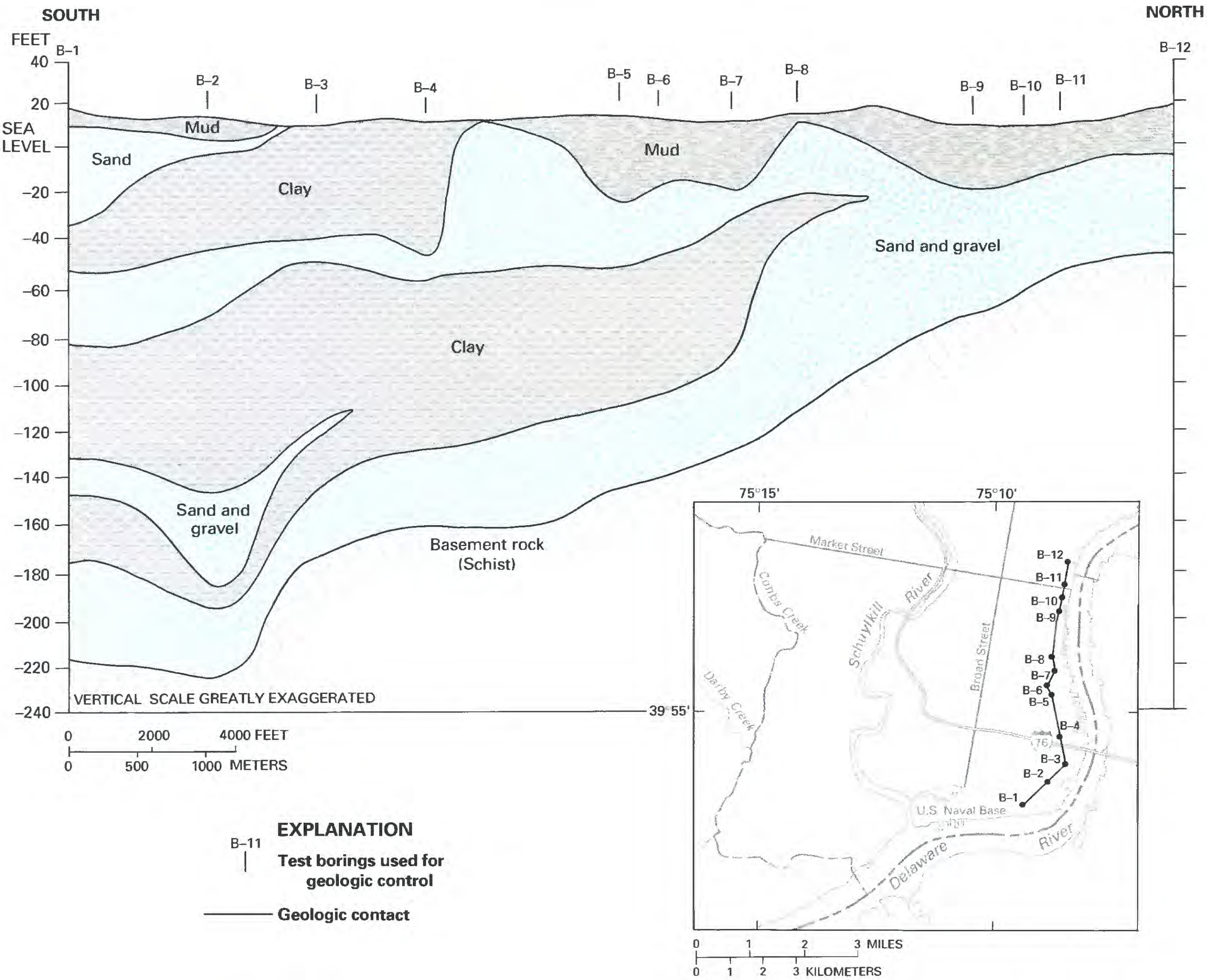


Figure 10. Generalized south-north geologic section.

Although well yields provide some measure of the water-yielding capability of aquifers, the various well-construction methods and testing procedures make the yield values subject to differences that usually cannot be related directly to aquifer characteristics. Specific capacity, or the rate of discharge of water from a well divided by the drawdown of water level in the well, is, therefore, a better indicator of water-yielding capability.

The mean and median specific capacities of 40 wells open to either the upper sand unit or the Trenton gravel are 16 and 12 (gal/min)/ft (gallons per minute per foot), respectively. These values are about equal to the average of values for the confined lower and middle sand units. Some wells open to deposits that are thick have specific capacities as high as 68 (gal/min)/ft, whereas some wells in deposits that are thin have specific capacities of essentially zero. Most wells in the important unconfined aquifers have moderate specific capacities. The cumulative-frequency distribution (fig. 18) shows that 90 percent of the specific capacities exceed 0.5 (gal/min)/ft and that 10 percent exceed 40 (gal/min)/ft.

The ability of a geohydrologic unit to transmit and store water usually is evaluated by means of an aquifer test. Such tests generally involve the withdrawal of water from a well and concurrent measurement of the drawdown of water level in the pumped well or observation wells near it. The resulting data are analyzed to provide values of aquifer hydraulic properties such as hydraulic conductivity, transmissivity, and storage coefficient. Aquifer coefficients thus obtained represent the integrated properties of that part of the aquifer influenced by pumping of the test well.

Ten short-duration (less than 3-hour), single-well tests of unconfined aquifers were conducted for the present study, two of the upper sand unit at two sites and eight of

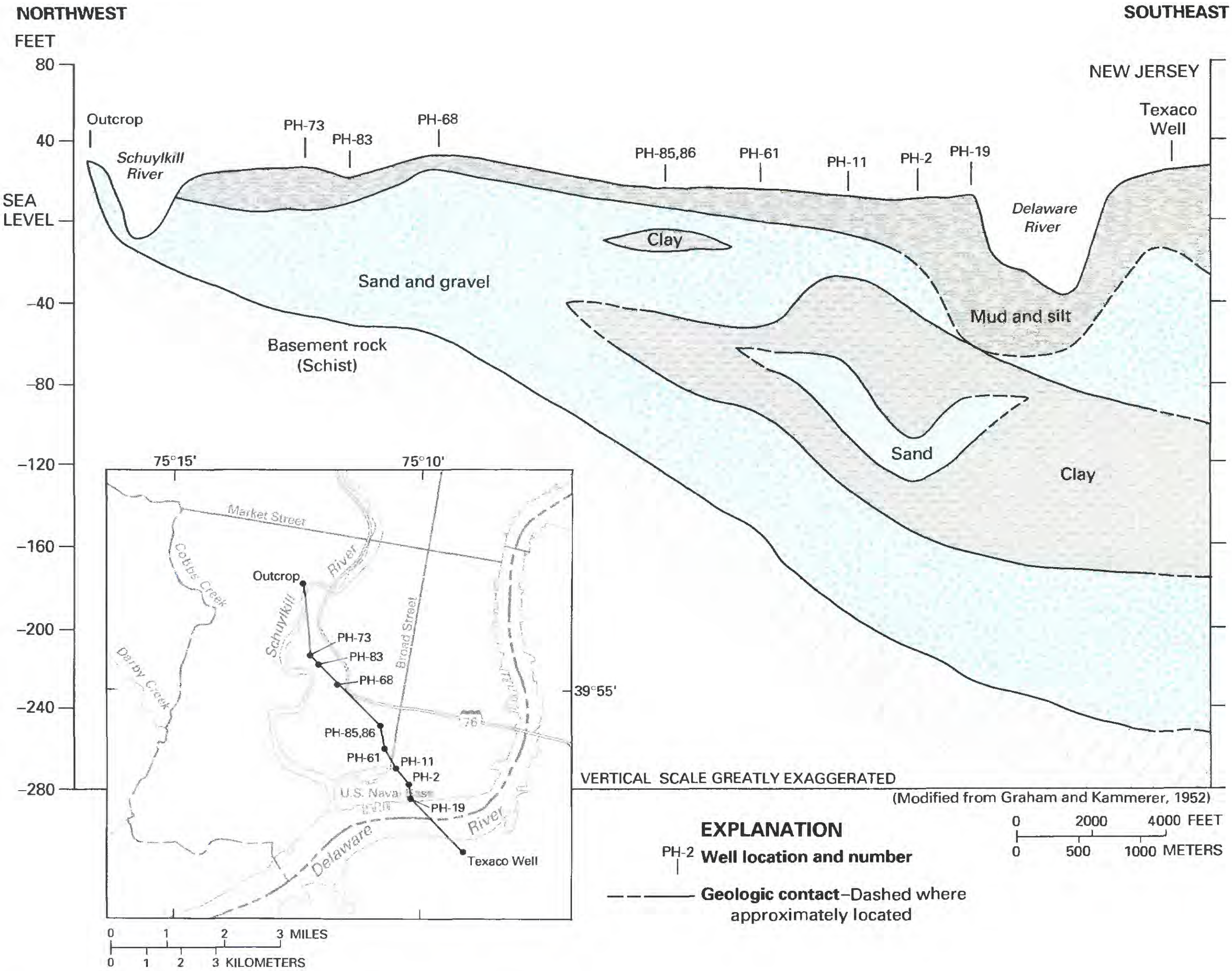


Figure 11. Generalized northwest-southeast geologic section.

the Trenton gravel at seven sites. However, only the results of two of the short-term tests of the Trenton gravel could be interpreted reliably. Analysis of the test data provided estimates of transmissivity and supplemented data from a previous long-duration test of well PH-412 (Greenman and others, 1961, p. 47). Figure 19 shows the locations of the pumped wells and aquifer coefficients compiled from the three reliable tests. The test results characterize the Trenton gravel as a moderately permeable aquifer that is confined locally by overlying alluvium.

The hydraulic conductivity (permeability) of an aquifer provides a measure of the ease of flow of water through the aquifer. The average hydraulic conductivity of the Trenton gravel, computed from the test data on pumped well PH-412 and associated observation wells, is 142 ft/d (feet per day). The transmissivity of an aquifer is another measure of the ease of flow of water through the aquifer and is equal to the hydraulic conductivity multiplied by the saturated thickness of the aquifer. Therefore, in an aquifer having uniform hydraulic conductivity, the thickest part will have the greatest transmissivity. Transmissivity values calculated from the three reliable tests range from 3,800 to 5,000 ft^2/d (feet squared per day). The highest value was computed from the test involving well PH-412. The data for this test suggest that the Trenton gravel may be in direct hydraulic contact with the Delaware River about 0.5 mi north of the pumped well.

Bridgeton Formation

The Bridgeton Formation is composed of gravel and very coarse to fine sand (Owens and Minard, 1979). Commonly, this unit is present on topographic highs as isolated deposits less than 10 ft thick. It generally is too thin to be an important aquifer. Where the Bridgeton Formation is present between the upper sand unit of the Potomac-

Raritan-Magothy aquifer system and the Trenton gravel, it forms a component of the unconfined aquifer system.

Upper Sand Unit of the Potomac-Raritan-Magothy Aquifer System

The upper sand unit of the Potomac-Raritan-Magothy aquifer system consists of coarse to medium sand and minor amounts of fine to very fine sand (Greenman and others, 1961, p. 42). This geohydrologic unit is present in southern Philadelphia, where it occupies channels in the surface of the middle clay unit. The thickness of the upper sand unit commonly is about 35 ft, although locally it exceeds 50 ft. In areas near the Delaware River, the upper sand unit is overlain by the relatively thin upper clay unit of the Potomac-Raritan-Magothy aquifer system. In most other areas, the upper clay unit is absent. The upper sand unit is a confined aquifer where it is overlain by the upper clay unit. In most places where the upper clay unit is absent, the upper sand unit is connected hydraulically to overlying aquifers, and together they form a single unconfined aquifer whose properties are described with those of the Trenton gravel.

Middle Sand Unit of the Potomac-Raritan-Magothy Aquifer System

Description

The middle sand unit of the Potomac-Raritan-Magothy aquifer system is composed of coarse to very fine sand and a few thin layers of clay (Greenman and others, 1961, p. 39). This geohydrologic unit is present in southern Philadelphia, where it occupies channels in the surface of the lower clay unit, and generally is present in an area within about 1.5 mi of the Delaware River (fig. 20). The thickness of the middle sand unit in Philadelphia commonly is less than 20 ft, although locally it exceeds 40 ft. In most areas, the middle sand unit is overlain by the middle clay unit of the Potomac-Raritan-Magothy aquifer system, which in places attains a thickness of 60 ft.

Recharge

The relative importance of the various sources of recharge to the middle sand unit is known poorly. Nevertheless, because the hydrologic setting of the middle and lower sand units of the Potomac-Raritan-Magothy aquifer system is similar, it is likely that water induced from surface sources and leakage through confining layers from overlying aquifers, sewers, and water pipes provides much of the recharge to the middle sand unit. These sources are described in the subsequent section on the lower sand unit.

Well Yield and Specific Capacity

The middle sand unit in Philadelphia is tapped by few wells. However, these wells commonly yield large amounts of water. Data on the water-bearing characteristics and hydraulic properties of the middle sand unit from six wells in Philadelphia and nine wells in adjoining Bucks County, Pa., are summarized below. Although this information is inadequate to fully describe the characteristics and properties, it provides a basis for estimating them.

The mean and median reported yields of 15 wells are 355 and 300 gal/min, respectively. High-capacity wells in the middle sand unit yield as much as 870 gal/min, and less productive wells yield as little as 50 gal/min. The cumulative-frequency distribution (fig. 21) shows that 90 percent of the yields exceed 15 gal/min and that 10 percent exceed 900 gal/min.

The mean and median specific capacities of nine wells open to the middle sand unit are 14 and 10 (gal/min)/ft, respectively. Wells that tap thick sand deposits have specific capacities as high as 36 (gal/min)/ft, whereas wells open to thin deposits have specific capacities of less than 5 (gal/min)/ft. Most wells in the middle sand unit have moderate specific capacities. The cumulative-frequency distribution (fig. 22) shows that 90 percent of the specific capacities exceed 4.7 (gal/min)/ft and that 10 percent exceed 36 (gal/min)/ft.

Hydraulic Properties

One short-duration, single-well aquifer test of the middle sand unit was conducted for the present study. Hydraulic properties of the middle sand unit are thought to be of about the same magnitude as those of the lower sand unit as these units have similar physical properties and hydrologic settings.

Lower Sand Unit of the Potomac-Raritan-Magothy Aquifer System

Description

The lower sand unit of the Potomac-Raritan-Magothy aquifer system consists of fine gravel and coarse sand that grades upward into medium to fine sand and a few layers of clay (Greenman and others, 1961, p. 31). This geohydrologic unit may rest directly on the surface of the crystalline bedrock, or it may be separated from the bedrock surface by a layer of saprolite. The thickness of the lower sand unit differs from place to place, chiefly because of the slope and irregularity of the bedrock surface. In Philadelphia, the sediments of the lower sand unit form a wedge-shaped mass that thickens from a featheredge at the Fall Line to about 90 ft to the southeast, where the sediments have been deposited in channels carved into the bedrock surface by the ancestral Delaware and Schuylkill Rivers (fig. 23). The volume of sediment in the lower sand unit in Philadelphia is about 0.17 mi^3 (cubic mile). The lower sand unit commonly is overlain by the lower clay unit of the

Table 4. Summary of characteristics of geohydrologic units

[mg/L, milligrams per liter]

Geohydrologic unit and lithology	Approximate range of thickness, in feet	Water-bearing properties	Chemical quality of water
Alluvium - Flood plain and channel deposits of mud, silt, fine sand, and some gravel.	0-78	Permeability too low to be important as an aquifer.	Unknown.
Trenton gravel (informal usage) - Sand and gravel	0-80	The water-bearing properties vary greatly from place to place according to the thickness and physical character of the sediments; consequently, wells yield from 1 to 1,370 gallons per minute.	Aquifer subject to contamination from activities at the land surface. Median concentration of dissolved solids is 700 mg/L, median concentration of iron is 7.6 mg/L, and median concentration of manganese is 1.4 mg/L. Locally, volatile organic compounds may be present.
Bridgeton Formation - Sand and gravel; some clay and silt.	0-10	Generally lies above the water table and is not an important aquifer. Where it underlies the Trenton gravel, these two geohydrologic units commonly form a single aquifer	Unknown.
Potomac-Raritan-Magothy Aquifer System: Upper clay unit - Variegated clay; silty, sandy, and gravelly in places.	0-35	Acts chiefly as a confining bed. Present only in southern Philadelphia near the Delaware River.	Unknown.
Potomac-Raritan-Magothy Aquifer System: Upper sand unit - Medium to coarse sand and minor amounts of very fine to fine sand. Beds of gravel are common, particularly at the base of the unit.	0-50	Locally forms an important unconfined aquifer hydraulically connected to the Trenton gravel and other overlying geohydrologic units. Generally not tapped by wells in areas where it is overlain by the upper clay unit.	Water quality similar to that of the Trenton gravel.
Potomac-Raritan-Magothy Aquifer System: Middle clay unit - Red and white clay and some variegated clay; sandy in places.	0-60	An extensive confining bed.	Unknown.
Potomac-Raritan-Magothy Aquifer System: Middle sand unit - Fine to coarse sand and some clay.	0-40	Generally yields large to very large supplies of water to wells. Present only near the Delaware River in southern Philadelphia.	Water quality similar to that of the lower sand unit.
Potomac-Raritan-Magothy Aquifer System: Lower clay unit - Red clay and some variegated clay. Sandy in places.	0-61	An extensive confining bed.	Unknown.
Potomac-Raritan-Magothy Aquifer System: Lower sand unit - Coarse sand and fine gravel, grades upward to fine to medium sand containing some silt and clay.	0-90	The principal source of ground water in Philadelphia. Commonly yields from 500 to 1,000 gallons per minute to wells.	Aquifer subject to contamination from leakage from overlying units. Median concentration of dissolved solids is 510 mg/L, median concentration of iron is 18 mg/L, and median concentration of manganese is 1.5 mg/L.

Table 4. Summary of characteristics of geohydrologic units—Continued

Geohydrologic unit and lithology	Approximate range of thickness, in feet	Water-bearing properties	Chemical quality of water
Crystalline rocks - Chiefly schist of Wissahickon Formation. Also includes Chickies Formation and gneissose rocks of granitic to gabbroic composition.	Unknown	Locally, the Wissahickon Formation is an important aquifer in its outcrop area. Only 2 percent of the wells in this unit fail to obtain sufficient water for domestic supplies; median well yield about 45 gallons per minute.	Median concentration of dissolved solids is 500 mg/L, median concentration of iron is 0.7 mg/L, and 21 percent of the wells yield water with iron concentrations in excess of 10 mg/L. Median concentration of manganese is 0.34 mg/L. Locally, volatile organic compounds may be present.

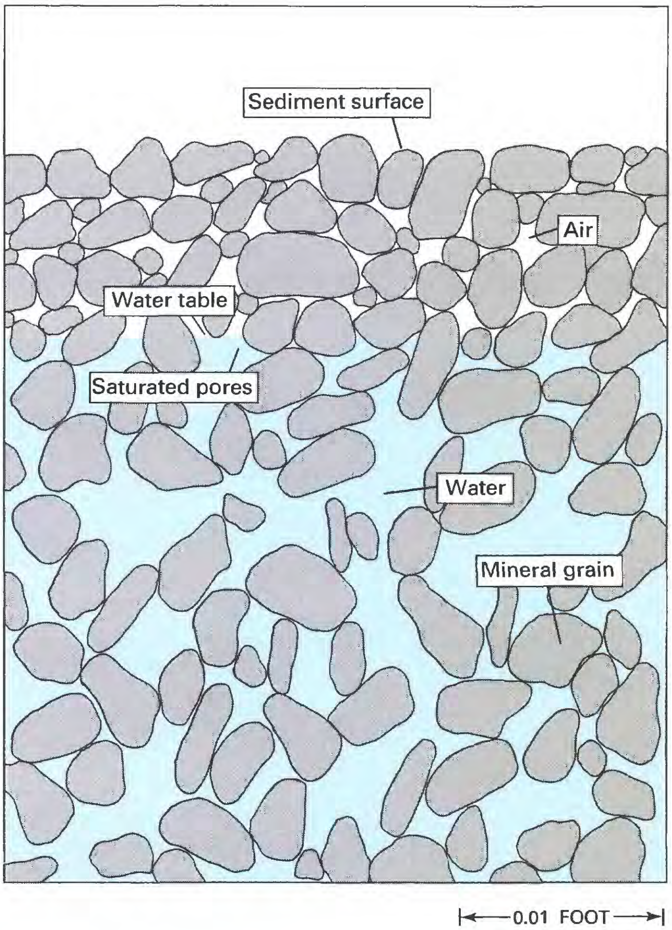


Figure 12. Ground water in unconsolidated sediments.

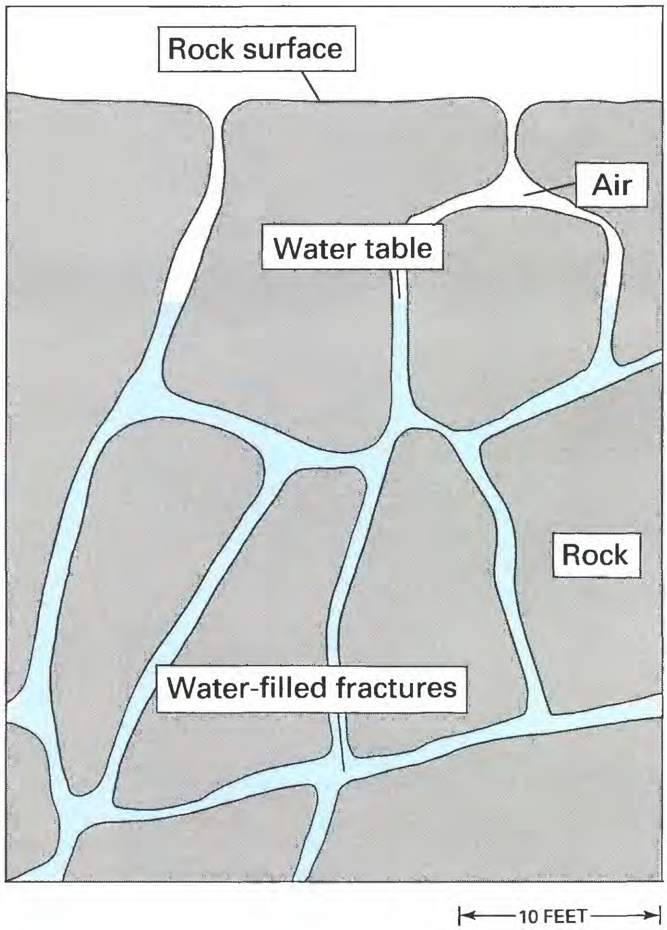


Figure 13. Ground water in fractured rock.

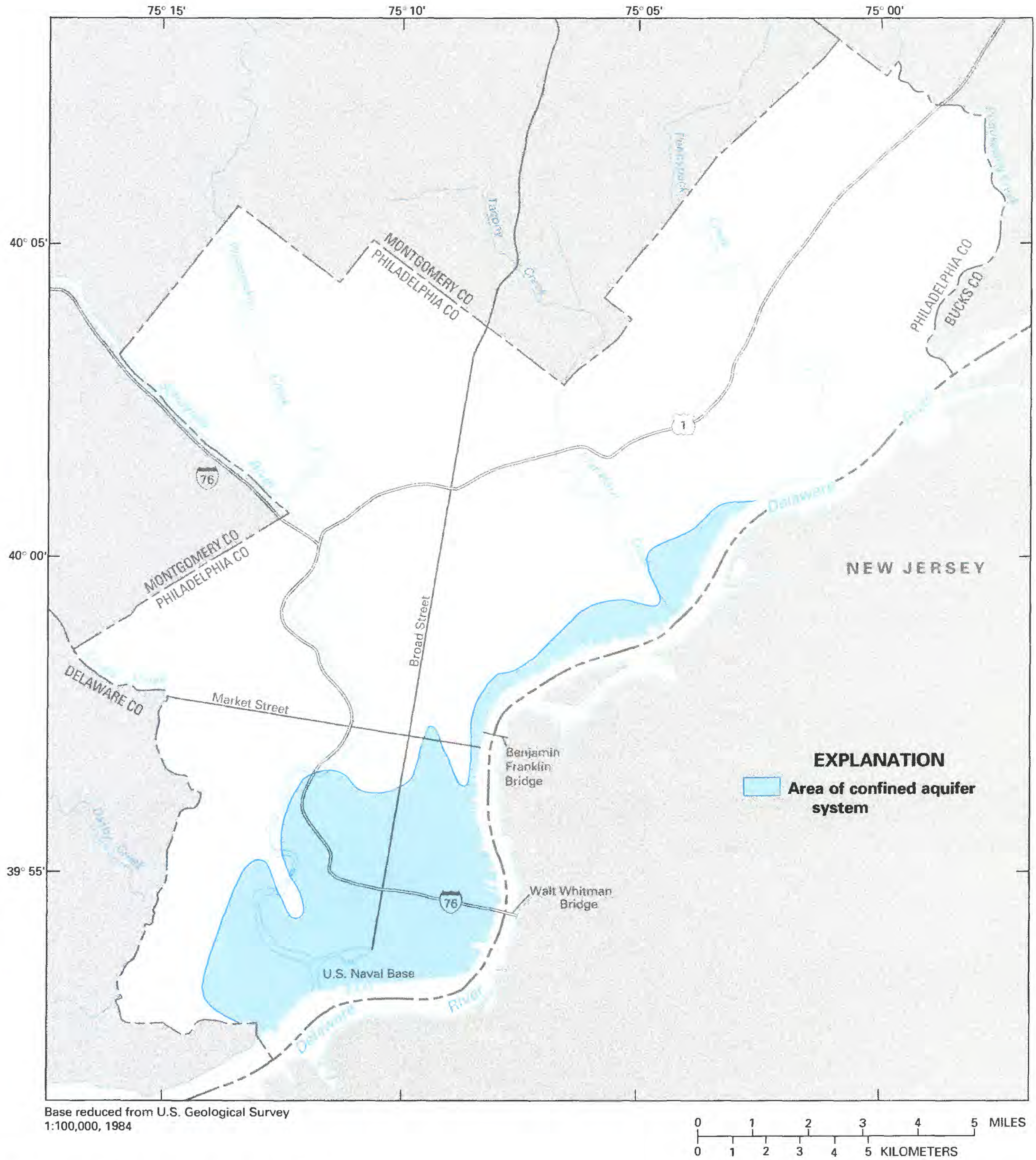


Figure 14. Extent of confined aquifer system.

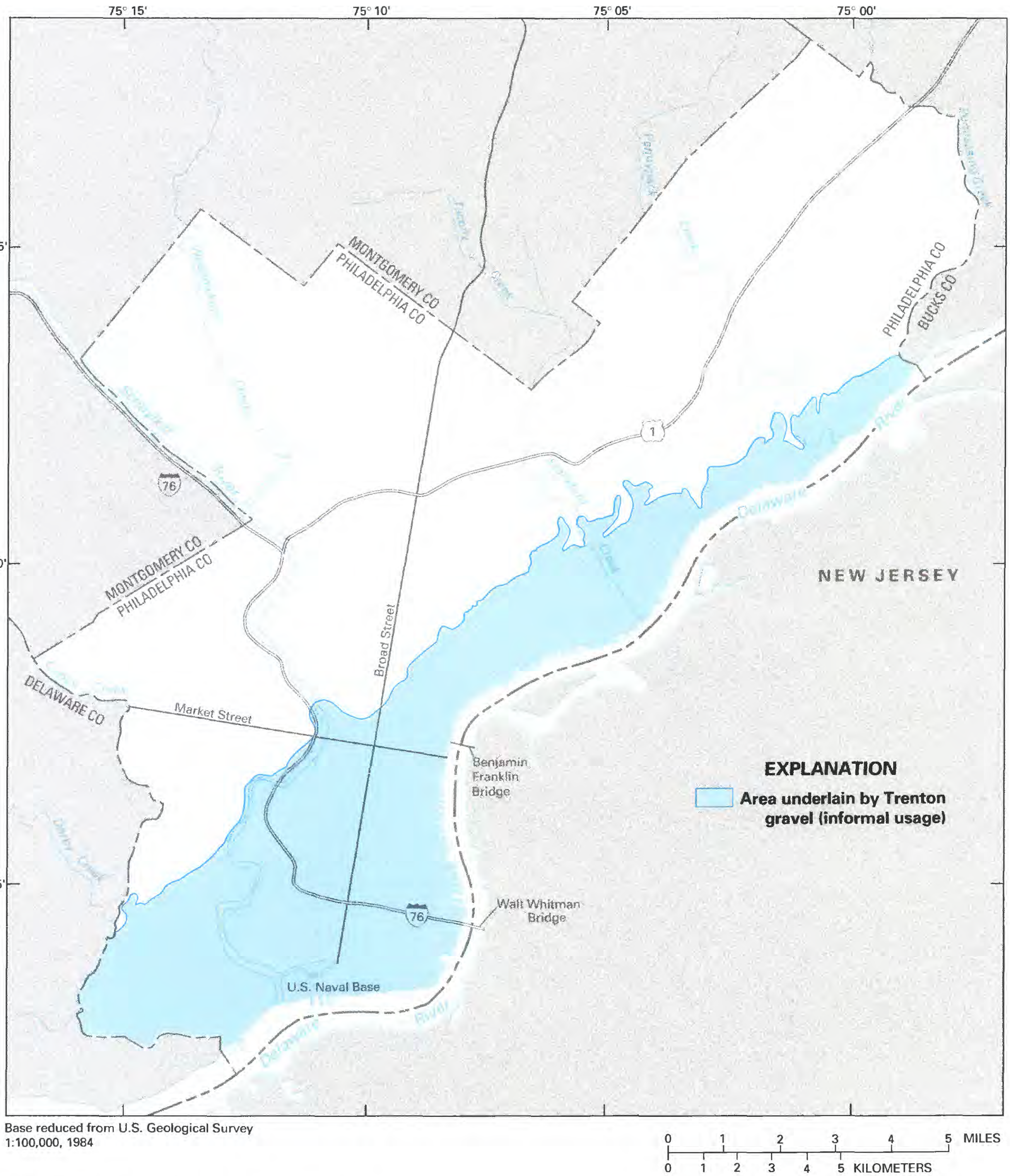


Figure 15. Area underlain by the Trenton gravel.

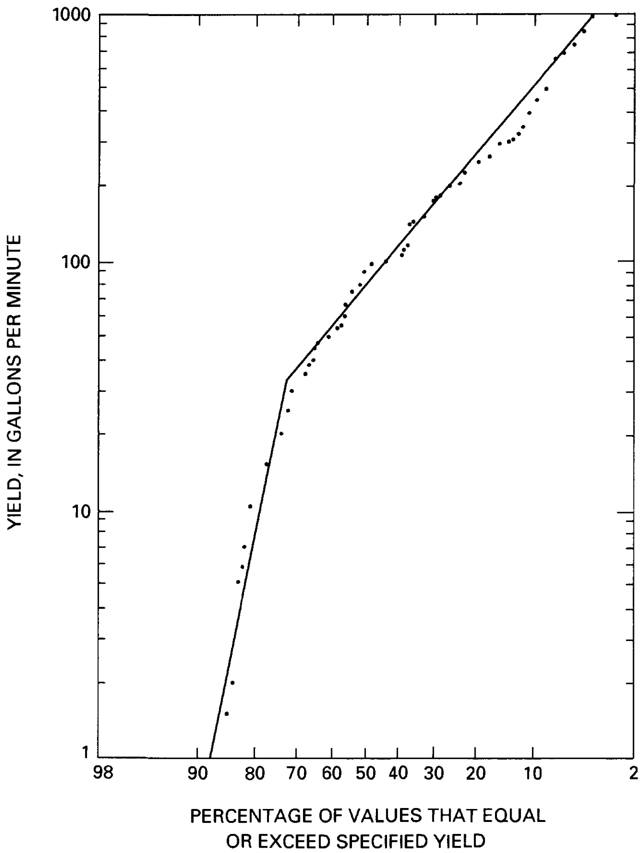


Figure 16. Cumulative-frequency distribution of yields of wells in the unconfined aquifer system.

Potomac-Raritan-Magothy aquifer system, which, in places, attains a thickness of 61 ft (Greenman and others, 1961, p. 38).

Recharge and Discharge

In Philadelphia, the lower sand unit receives substantial recharge, most of which probably comes from sources other than precipitation (Graham and Kammerer, 1952). Interception of precipitation by surface drains and sewers and the covering of the aquifer outcrop area with impervious surfaces have reduced recharge from precipitation. Therefore, important sources of recharge to the lower sand unit are infiltration induced from the Delaware and Schuylkill Rivers and leakage from overlying confining units, aquifers, sewers, and water pipes.

In parts of southern Philadelphia near the confluence of the Delaware and Schuylkill Rivers, infiltration induced from the rivers into the lower sand unit is impeded by a relatively thick and continuous clay layer (figs. 10, 11). However, the lower sand unit crops out farther to the northwest near the lower Schuylkill River (fig. 11). In this outcrop area, water from the Schuylkill River may flow directly into the lower sand unit. Where pumping from wells has lowered ground-water levels below the average stage of the Delaware and Schuylkill Rivers (about 1 ft above sea level), water from the rivers is thought to flow directly into the lower sand unit where the unit and the river bed are in contact and indirectly by downward leakage where they are separated by low-permeability layers. Most surface-water recharge probably comes from the Delaware River because (1) it flows over a much larger potential recharge area than its tributary streams and (2) water levels in the lower sand unit in the parts of New Jersey adjacent to the Delaware River at Philadelphia are substantially below the level of the river.

A computer model developed by Sloto (1988) was used to simulate ground-water flow and to quantify the components of the water budget for the lower sand unit (table 5). The 133-mi^2 modeled area (fig. 24) included parts of Philadelphia and adjacent New Jersey. Recharge on the outcrop area was assumed to be constant at 0.6 billion gallons per year.

Pumpage in the modeled area during 1904–45 was estimated to be 133 billion gallons (3.2 billion gallons per year). It accounted for 66 percent of the discharge from the lower sand unit. Downward leakage was 110 billion gallons (2.6 billion gallons per year) and was the largest source of inflow to the lower sand unit during 1904–45.

Pumpage from the lower sand unit during 1946–56 was 117 billion gallons (11 billion gallons per year). This increase in pumpage caused a large change in the water budget. During 1946–56, pumpage accounted for 90 percent of the discharge from the lower sand unit; downward leakage was 91 billion gallons (8.3 billion gallons per year) and accounted for 70 percent of the inflow to the lower sand unit. During 1946–56, recharge induced from the Delaware and Schuylkill Rivers was 1.0 billion gallons per year. This is greater than that during 1904–45 (0.8 billion gallons per year) as a result of the increased size of cones of depression caused by increased pumping.

Pumpage during 1957–78 was 266 billion gallons (12 billion gallons per year). It accounted for 93 percent of the discharge from the lower sand unit. This is slightly more than that during 1946–56. The major source of water for this pumpage was downward leakage, which also increased. During 1957–78, downward leakage was 221 billion gallons (10 billion gallons per year) and accounted for 77 percent of the inflow to the lower sand unit. Recharge induced from the Delaware and Schuylkill Rivers declined to 0.5 billion gallons per year during 1957–78 as a result of the large decrease in pumping in Philadelphia and the recovery of ground-water levels.

Leakage is the most important source of recharge to the lower sand unit. Because of large withdrawals from the lower sand unit in Philadelphia from 1943 to 1960, ground-water levels were lowered progressively and hydraulic gradients were established that caused greater downward movement of water from overlying geohydrologic units to

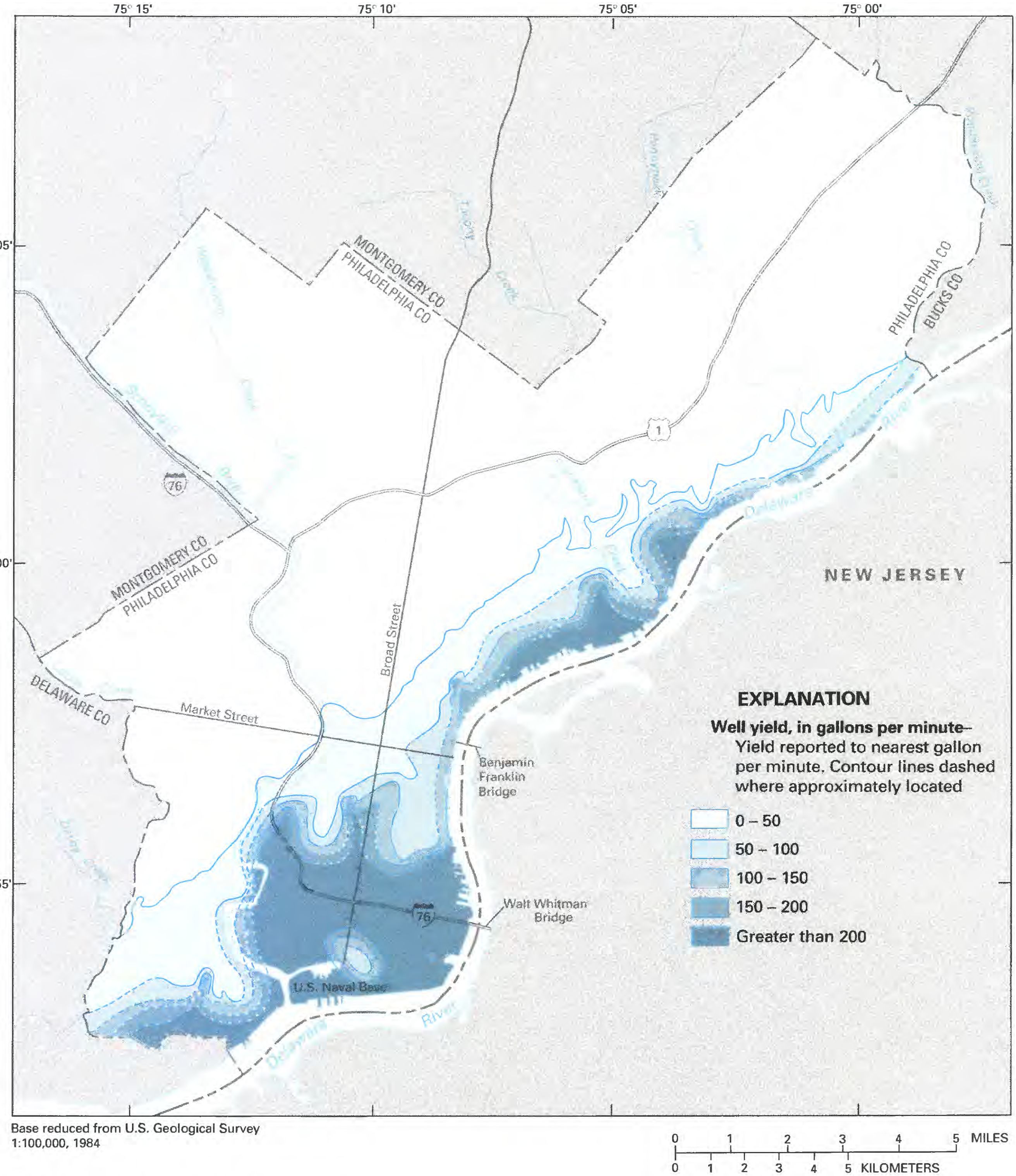


Figure 17. Yields of wells in the Trenton gravel.

the lower sand unit. Although the large withdrawals in Philadelphia were curtailed, pumping in nearby parts of New Jersey presently maintains the hydraulic gradients necessary to sustain downward leakage (fig. 25). Simulations for 1957–78 show that leakage from geohydrologic units overlying the Potomac-Raritan-Magothy aquifer system was equivalent to about 83 percent of concurrent ground-water pumpage in the modeled area.

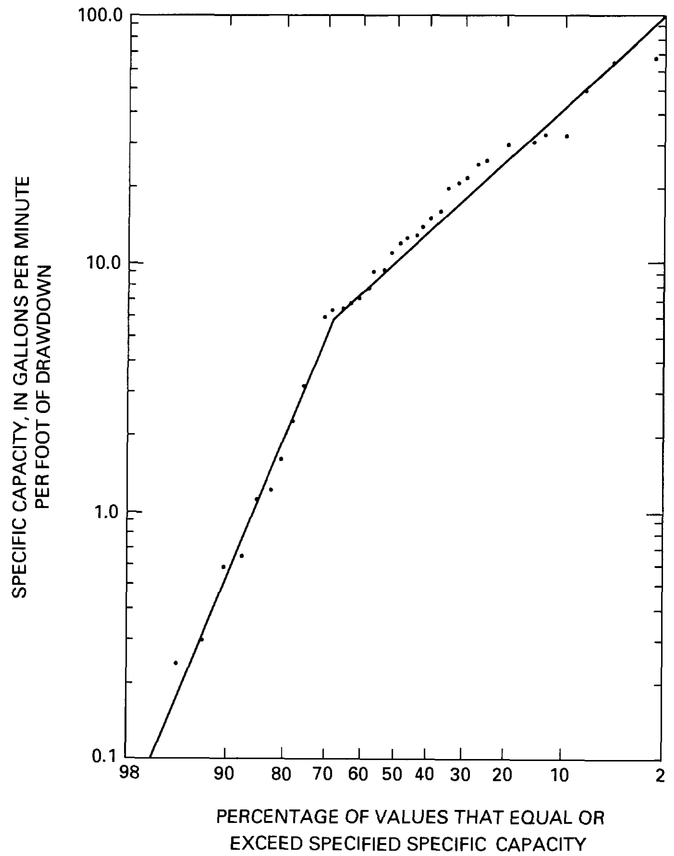


Figure 18. Cumulative-frequency distribution of specific capacities of wells in the unconfined aquifer system.

Where the lower sand unit is near the land surface, it may be recharged locally by the considerable amounts of water that leak from sewers and distribution pipes. Although the volume of such recharge cannot be estimated reliably, it probably constitutes a significant amount of recharge to the lower sand unit.

Well Yield and Specific Capacity

The lower sand unit yields large amounts of water to wells. The mean and median reported yields of 155 wells open to the lower sand are 360 and 275 gal/min, respectively. High-capacity wells yield as much as 1,350 gal/min, whereas low-capacity wells furnish as little as 3.3 gal/min. It is likely, however, that several of the reported well yields are too low to be representative of the water-yielding ability of the lower sand unit. Such low values probably were obtained from pumping tests that failed to produce sufficient drawdown of water level in the wells pumped. The cumulative-frequency distribution (fig. 26) shows that 90 percent of the yields exceed 53 gal/min and that 10 percent exceed 830 gal/min. Figure 27 shows the indistinct relation between thickness of the lower sand unit and reported well yield. Figure 28 shows the spatial variation of well yields in the lower sand unit and may be used to estimate yield in a particular area.

The mean and median specific capacities of 80 wells open to the lower sand unit are 18 and 16 (gal/min)/ft, respectively. Some wells in deposits that are thick have specific capacities as high as 71 (gal/min)/ft, whereas some open to thin deposits have specific capacities as low as 0.5

Table 5. Model-simulated water budget for the lower sand unit of the Potomac-Raritan-Magothy aquifer system, 1904–78
[<, less than; Mgal/yr, million gallons per year. Data from Sloto, 1988]

Discharge

Simulation period	Pumpage (Mgal/yr)	Pumpage (percent)	Upward leakage through confining unit (Mgal/yr)	Upward leakage through confining unit (percent)	Direct discharge to Delaware and Schuylkill Rivers (Mgal/yr)	Direct discharge to Delaware and Schuylkill Rivers (percent)	Flow across boundaries and out of modeled area (Mgal/yr)	Flow across boundaries and out of modeled area (percent)
1904-45	3,200	66	1,300	27	200	4	100	3
1946-56	11,000	90	700	6	300	2	200	2
1957-78	12,000	93	100	4	400	3	500	1

Recharge

Simulation period	Downward leakage through confining unit (Mgal/yr)	Downward leakage through confining unit (percent)	Recharge induced from Delaware and Schuylkill Rivers (Mgal/yr)	Recharge induced from Delaware and Schuylkill Rivers (percent)	Flow across boundaries into modeled area (Mgal/yr)	Flow across boundaries into modeled area (percent)	Recharge on outcrop area (Mgal/yr)	Recharge on outcrop area (percent)	Water released from storage (Mgal/yr)	Water released from storage (percent)
1904-45	2,600	55	800	17	700	15	600	13	2	<1
1946-56	8,300	70	1,000	16	1,900	9	600	5	3	<1
1957-78	10,000	77	500	14	600	5	600	4	3	<1

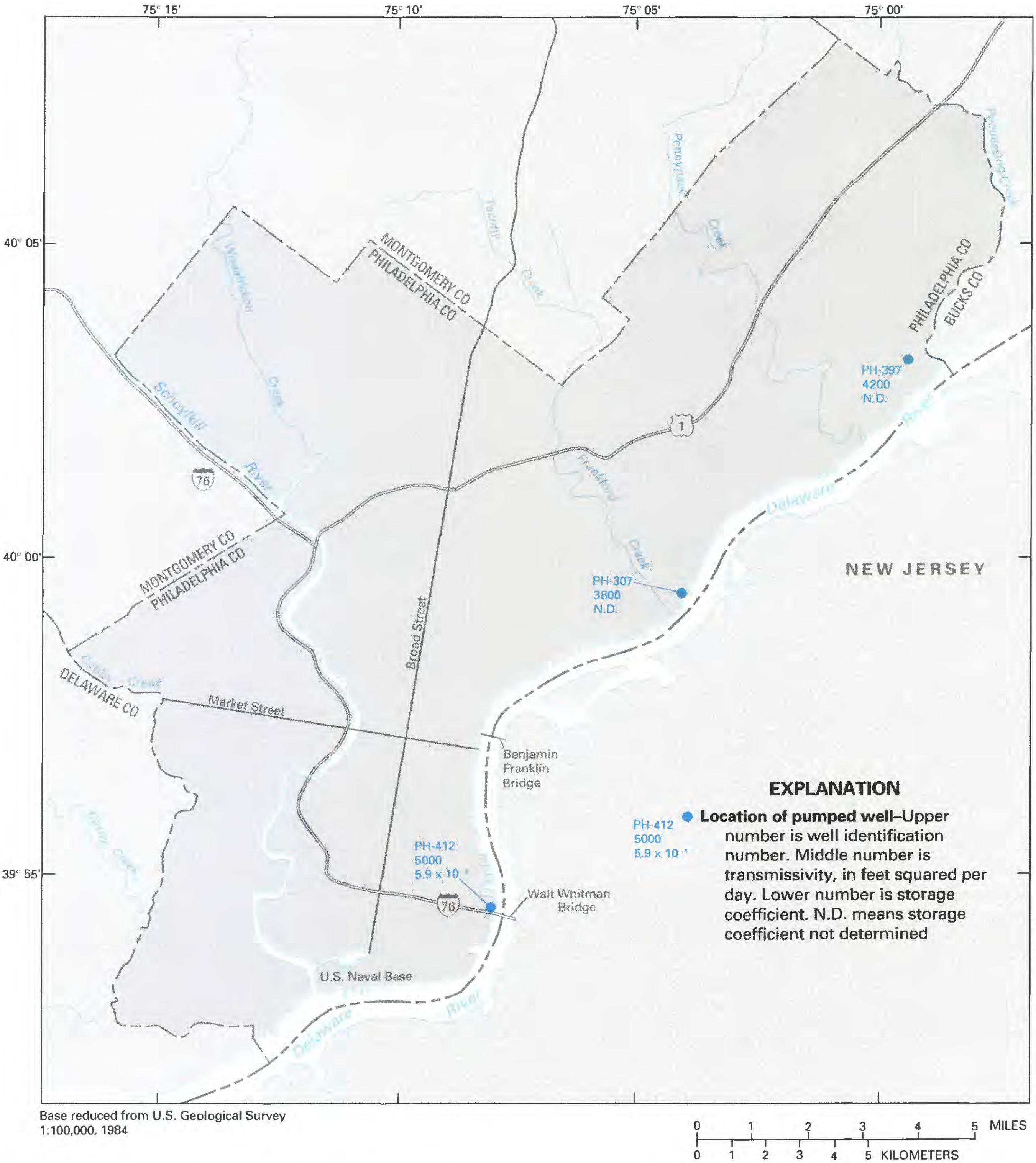


Figure 19. Aquifer coefficients for the Trenton gravel.

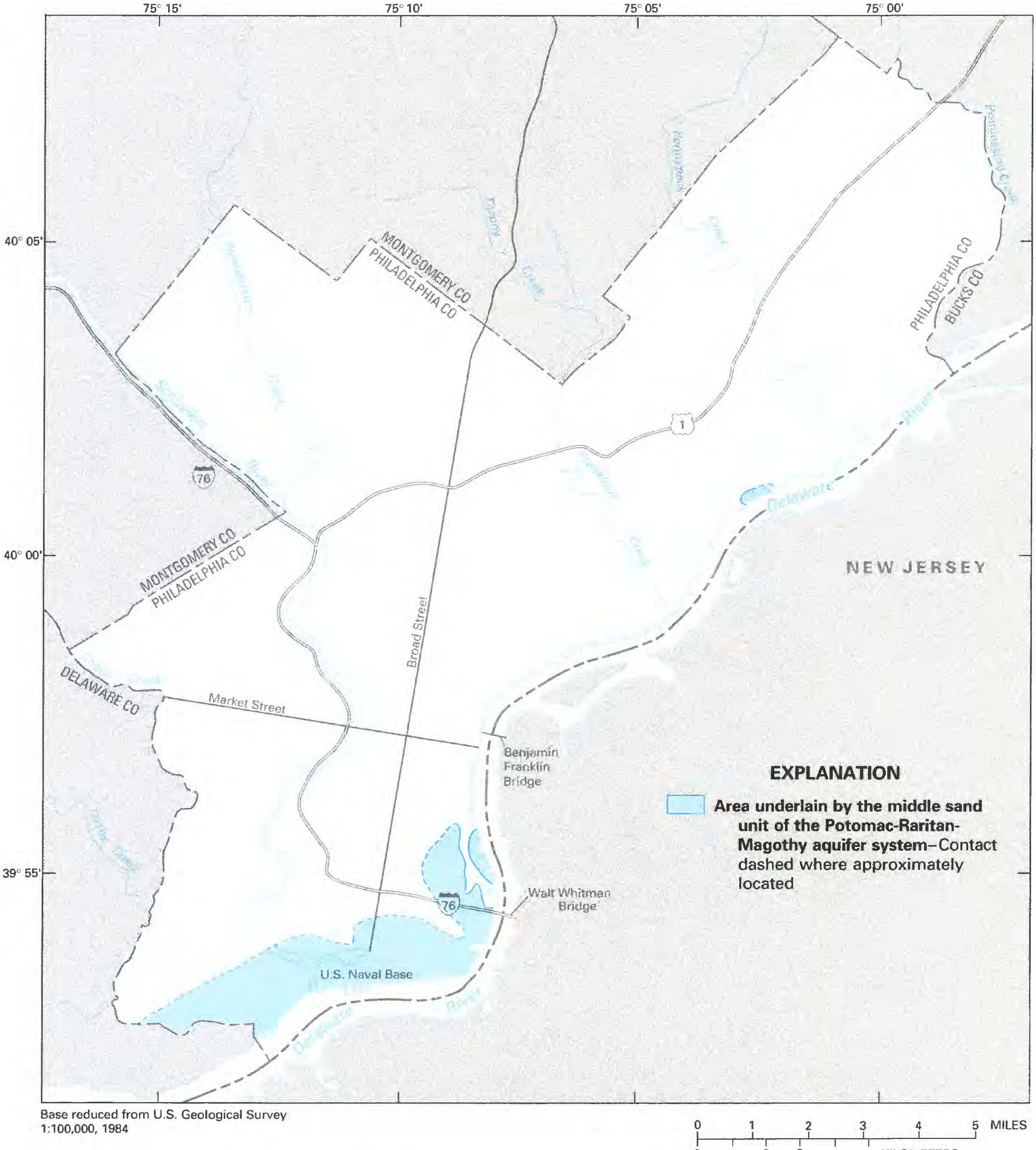


Figure 20. Area underlain by the middle sand unit of the Potomac-Raritan-Magothy aquifer system.

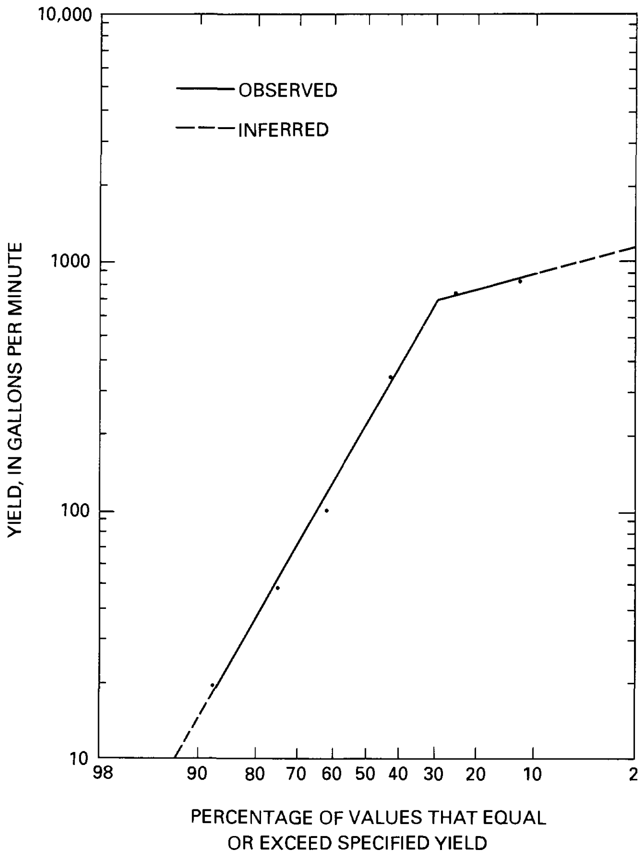


Figure 21. Cumulative-frequency distribution of well yields from the middle sand unit of the Potomac-Raritan-Magothy aquifer system.

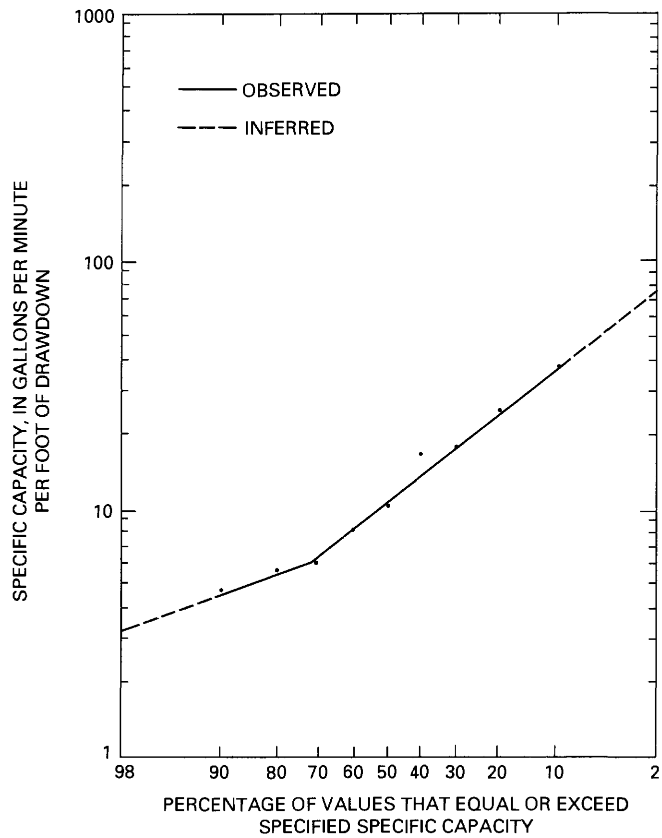


Figure 22. Cumulative-frequency distribution of specific capacities of wells in the middle sand unit of the Potomac-Raritan-Magothy aquifer system.

(gal/min)/ft. Most wells in the lower sand unit have moderate specific capacities. The cumulative-frequency distribution (fig. 29) shows that 90 percent of the specific capacities exceed 3.5 (gal/min)/ft and that 10 percent exceed 34 (gal/min)/ft. Figure 30 shows the generalized relation between thickness of the lower sand unit and specific capacity.

Hydraulic Properties

For the present study, short-duration (1- to 3-hour), single-well aquifer tests of the lower sand unit were conducted at 10 sites; however, only the results of the test of well PH-124 could be interpreted reliably. Analysis of the test data provided estimates of hydraulic conductivity and transmissivity. These estimates supplemented data on aquifer hydraulic properties, including storage coefficient, determined by seven previous long-duration (up to several days), multiple-well tests at six sites (Greenman and others, 1961, p. 34). Figure 31 shows the locations of the test sites and aquifer coefficients compiled from all reliable tests. These results characterize the lower sand unit as a moderately permeable confined aquifer.

Values of hydraulic conductivity of the lower sand unit, computed from the historical test data, range from 123 to 152 ft/d and average about 135 ft/d. This small range of values suggests that the physical properties (particularly grain size and sorting) of the sediments of the lower sand unit are fairly uniform. Values of transmissivity of the lower sand unit at the seven test sites shown in figure 31 range from 2,800 to 9,100 ft^2/d. The values are highest along the Delaware River in southern Philadelphia, where the lower sand unit attains its maximum thickness (fig. 23).

The storage coefficient of an aquifer is a measure of the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. Storage coefficients for the lower sand unit, as computed from the historical test data, range from 7×10^{-5} to 8×10^{-4} and average 3.0×10^{-4} (fig. 31). Such low values indicate that the parts of the lower sand affected by the pumping tests are confined effectively between the underlying, relatively impermeable crystalline rocks or saprolite and an overlying clay layer. After prolonged withdrawals from confined aquifers such as this, cones of depression form and may extend several miles from the centers of pumping.

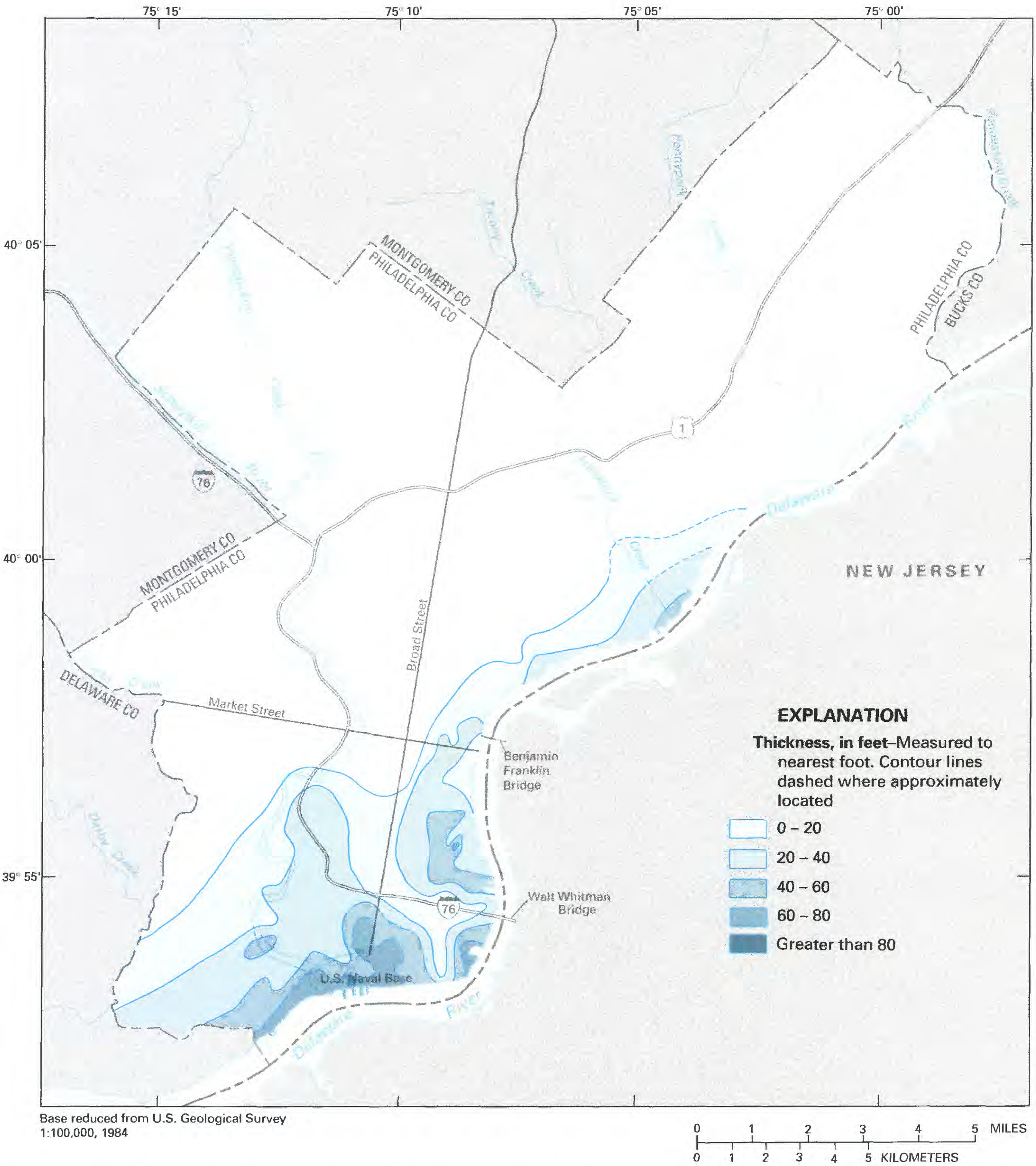


Figure 23. Thickness of the lower sand unit of the Potomac-Raritan-Magothy aquifer system.

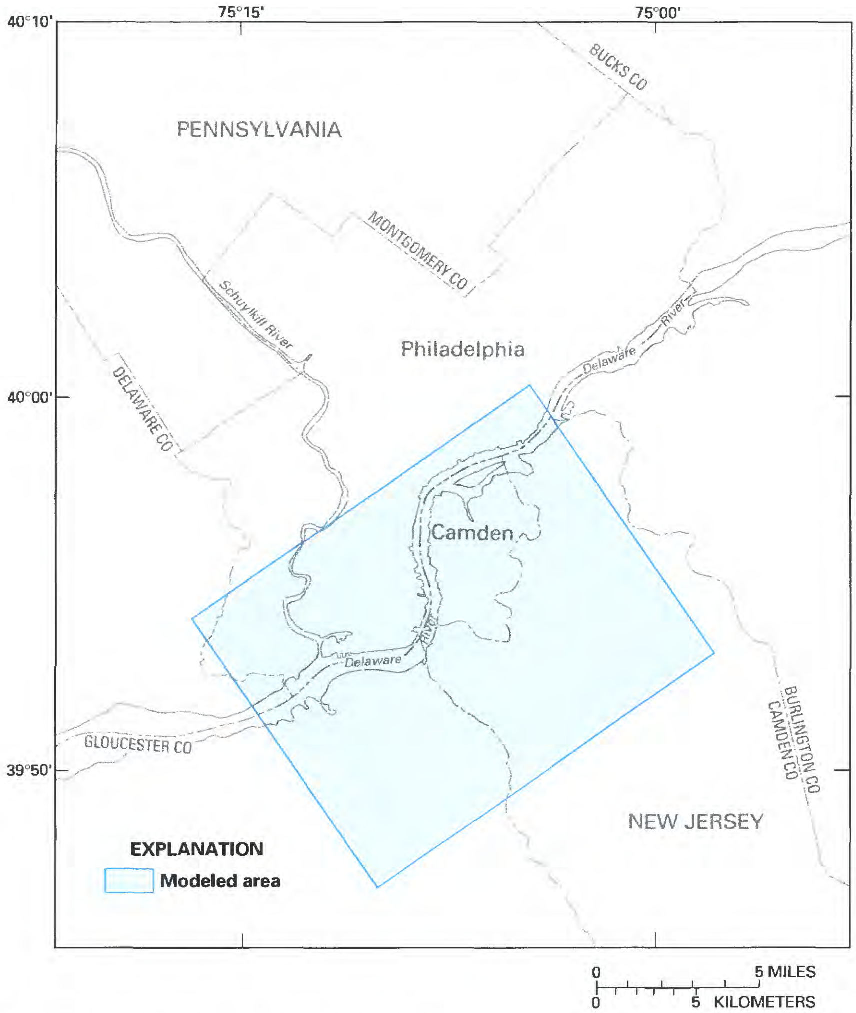


Figure 24. Location of modeled area.

Crystalline Rock Aquifer

Description

The crystalline rocks consist chiefly of schist of the Wissahickon Formation of late Proterozoic and early Paleozoic age, lesser amounts of quartzite of the Chickies Formation of early Cambrian age, and scattered masses of gneissose rocks of uncertain age having granitic to gabbroic composition. The crystalline rocks crop out in the Piedmont, and their surface slopes southeastward, forming the basement beneath the Coastal Plain sediments. The Wissahickon Formation is believed to represent a thick accumulation of sediment that was metamorphosed into hard, dense, foliated rock. It forms the most important crystalline rock aquifer in Philadelphia.

Local precipitation is the chief source of water in the crystalline rocks. Ground water generally is under unconfined conditions in the outcrop area and under confined conditions where the crystalline rocks are overlain by confining units of the Coastal Plain.

The crystalline rocks have little intergranular porosity. The few pores that are present are small and generally are not interconnected; consequently, the crystalline rocks have little primary permeability. However, considerable secondary permeability has been developed by weathering and fracturing. Most of the water in crystalline rocks is stored in and transmitted through the weathered zone near the land surface and in fractures in deeper, less weathered zones. Because of increasing overburden pressure, fractures usually close as depth increases, resulting in a general decrease of permeability with depth.

Well Yield and Specific Capacity

This section discusses the Wissahickon Formation almost exclusively as few wells tap the other crystalline rocks because of their small areal extent. However, the limited data available suggest that the hydraulic properties

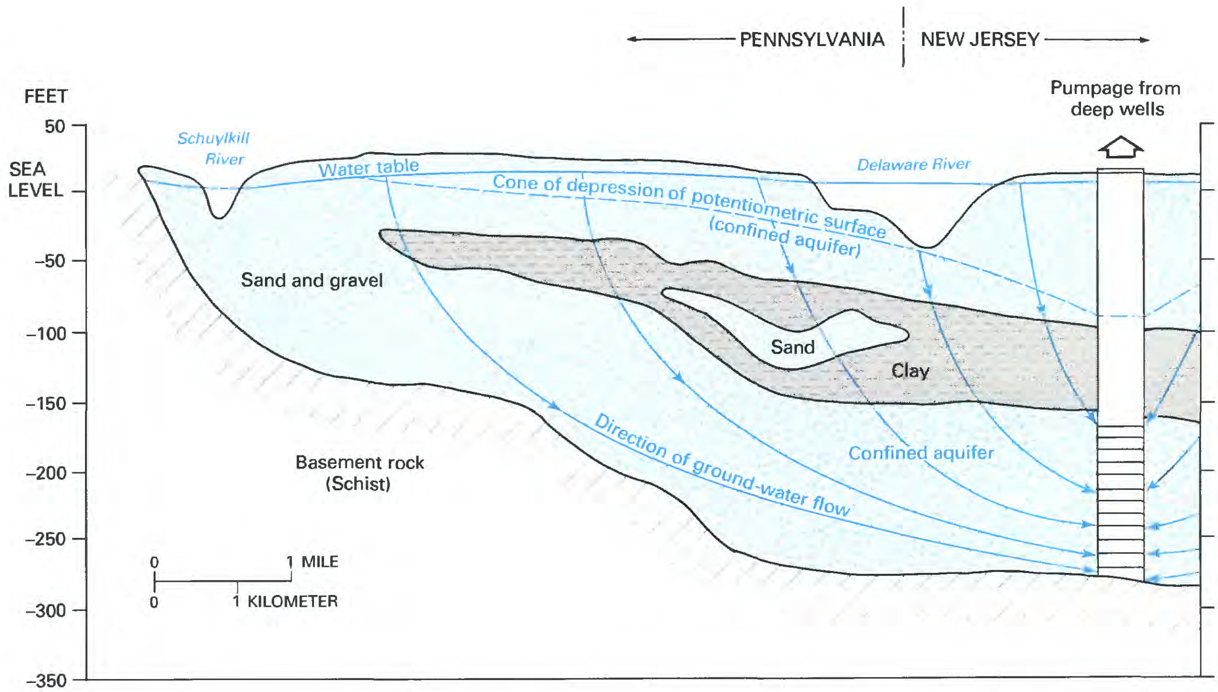


Figure 25. Generalized pattern of ground-water flow caused by pumping in New Jersey following shutdown of Philadelphia wells. (See fig. 11 for location of section.)

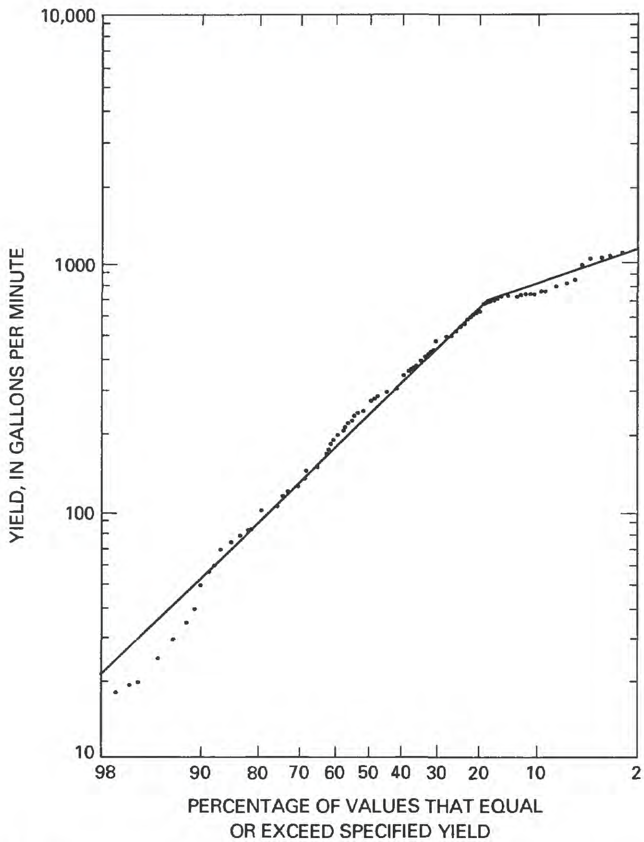


Figure 26. Cumulative-frequency distribution of well yields from the lower sand unit of the Potomac-Raritan-Magothy aquifer system.

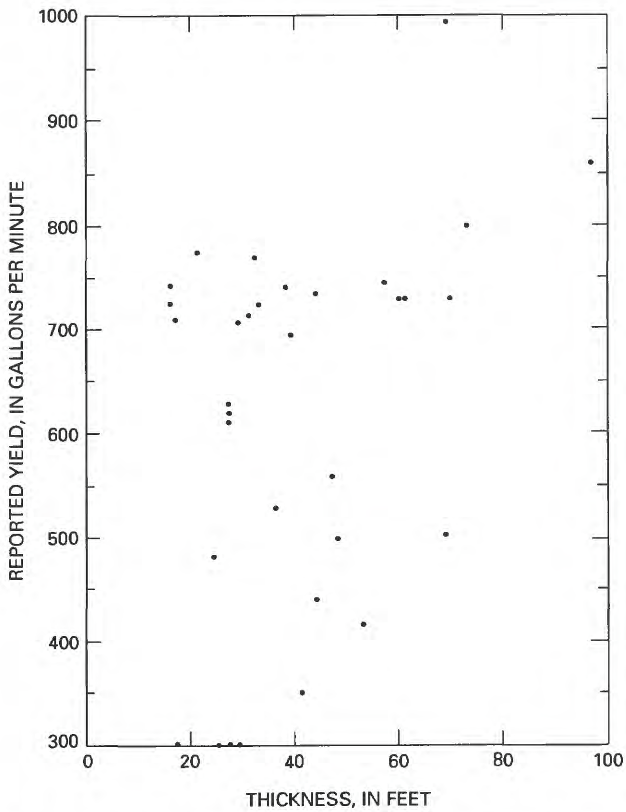


Figure 27. Plot of well yield as a function of thickness of the lower sand unit of the Potomac-Raritan-Magothy aquifer system.

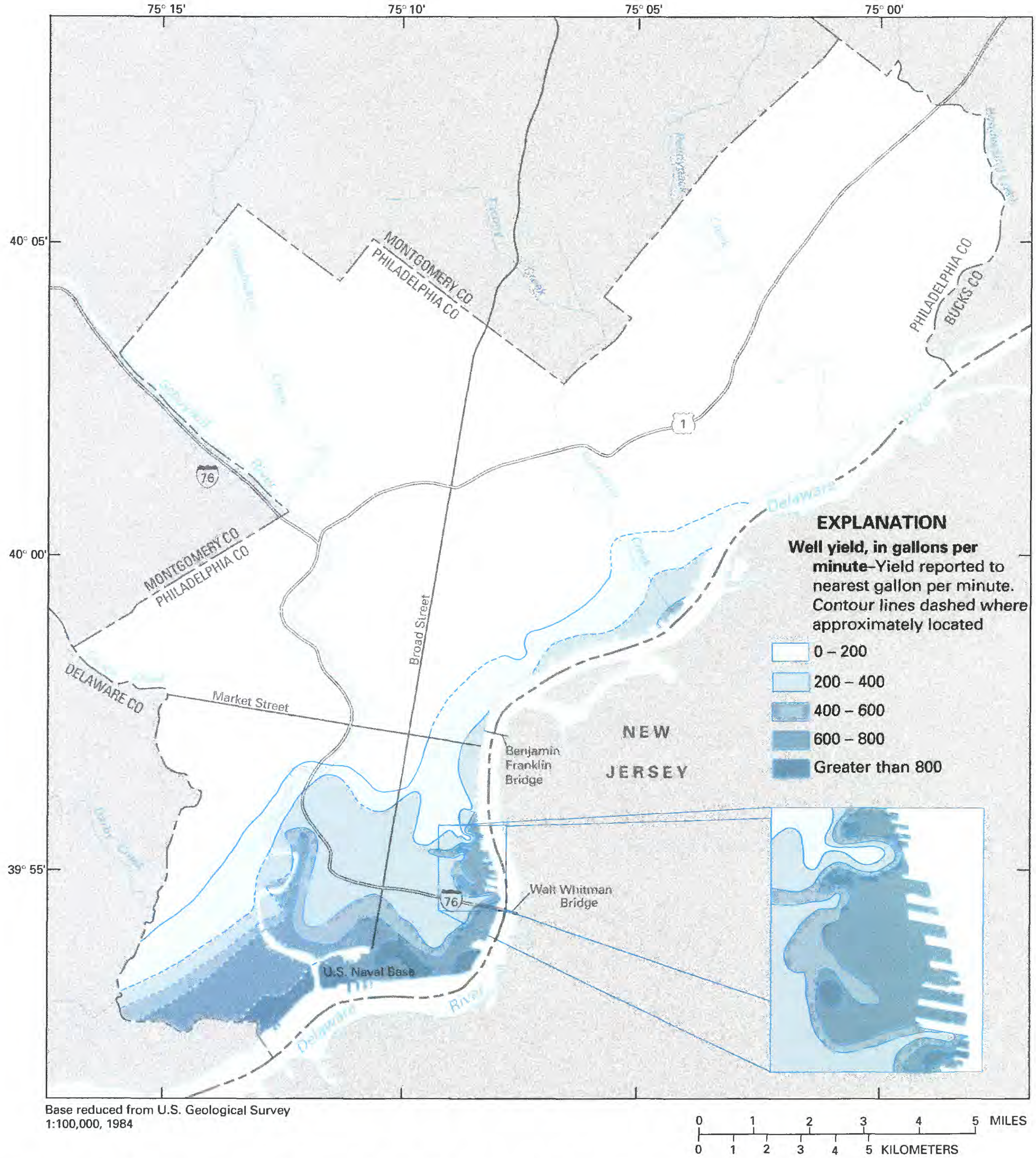


Figure 28. Yields of wells in the lower sand unit of the Potomac-Raritan-Magothy aquifer system.

of the other crystalline rocks are similar to those of the Wissahickon Formation.

Wells in the Wissahickon Formation obtain most of their water within about 125 ft of the land surface (fig. 32). However, some major water-yielding zones are present at depths as great as 300 ft and, locally, minor water-yielding zones are present below that depth. Where the Wissahickon Formation is covered by unconsolidated sediments, most

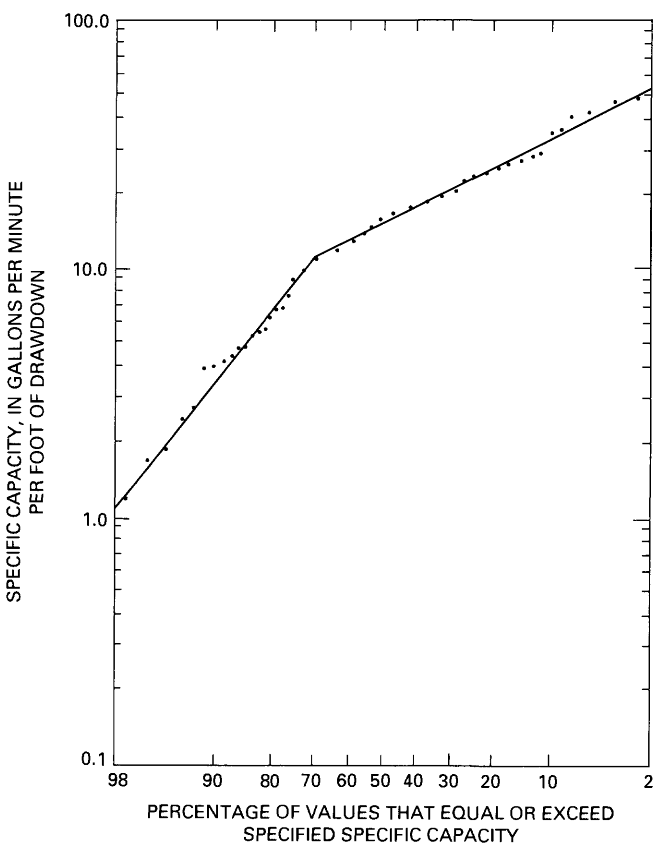


Figure 29. Cumulative-frequency distribution of specific capacities of wells in the lower sand unit of the Potomac-Raritan-Magothy aquifer system.

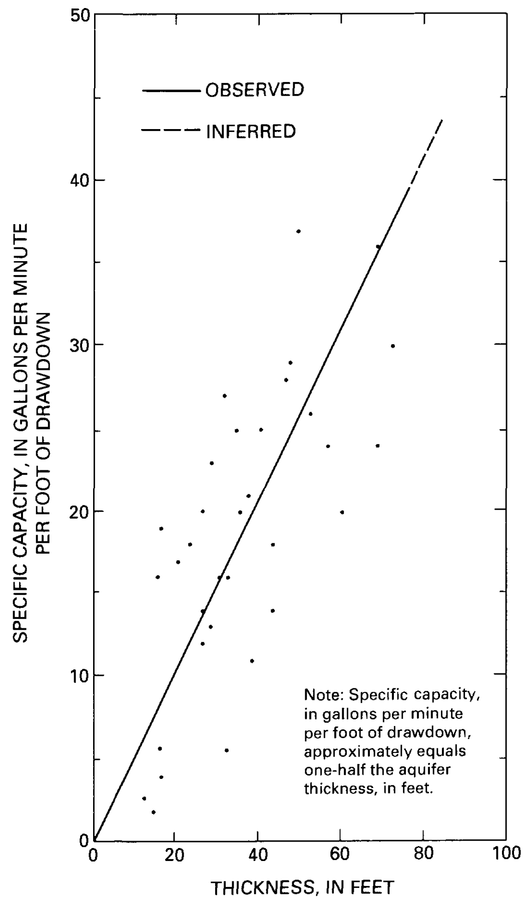


Figure 30. Generalized relation between thickness of the lower sand unit of the Potomac-Raritan-Magothy aquifer system and specific capacity.

major water-yielding zones are less than 300 ft below the surface of the crystalline rock.

Generally, yields of wells in the crystalline rocks are low. The mean reported yields of 392 wells in the Wissahickon Formation and 12 wells in the other crystalline rocks were 64 and 38 gal/min, respectively; the medians of reported yields were 45 and 37 gal/min, respectively. Some high-capacity wells open to fractured or deeply weathered rock yield as much as 350 gal/min, whereas low-capacity wells in fresh rock produce as little as 1 gal/min. Figure 33 shows that most wells in the Wissahickon Formation have low yields. The cumulative-frequency distribution (fig. 34) shows that 90 percent of the yields exceed 7 gal/min and that 10 percent exceed 125 gal/min.

One hundred sixty-six of 436 wells (38 percent) in the Wissahickon Formation had reported yields of more than 50 gal/min, and only 5 percent were reported to yield more than 153 gal/min. Depths of 46 percent of these wells exceed 300 ft.

Figure 35 shows the areal variation of yields of wells in the Wissahickon Formation. Because yields of wells in crystalline rocks depend on the thickness of the weathered zone and on the size, number, and degree of interconnection of fractures intercepted by the well, it is not possible to accurately predict well yield at a particular site. However, three generalizations regarding the effect of location on well yield can be made:

1. Topography has an important effect. Wells in flat lowlands and valleys commonly yield more water than wells in hilly upland areas. The hydrologic section in figure 36 illustrates several reasons for this pattern. The high-yielding well is open to numerous fractures that intersect the weathered zone below the water table. This well can obtain water from the weathered zone or by inducing recharge from the nearby stream. In contrast, the low-yielding well is open to only a few fractures that intersect the weathered zone above the water table. Commonly, the change from fresh to weathered rock is gradational and is not as distinct as shown in figure 36.

2. Almost all wells in the Wissahickon Formation yield enough water for domestic use, although a few yield less than 5 gal/min. Larger supplies can be developed by drilling several test wells in favorable topographic

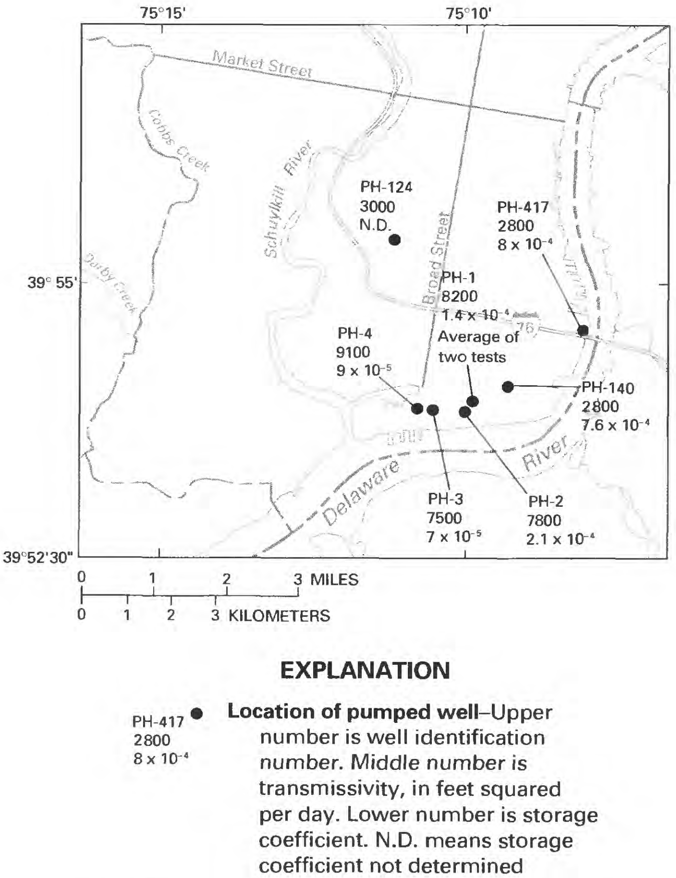


Figure 31. Aquifer coefficients for the lower sand unit of the Potomac-Raritan-Magothy aquifer system.

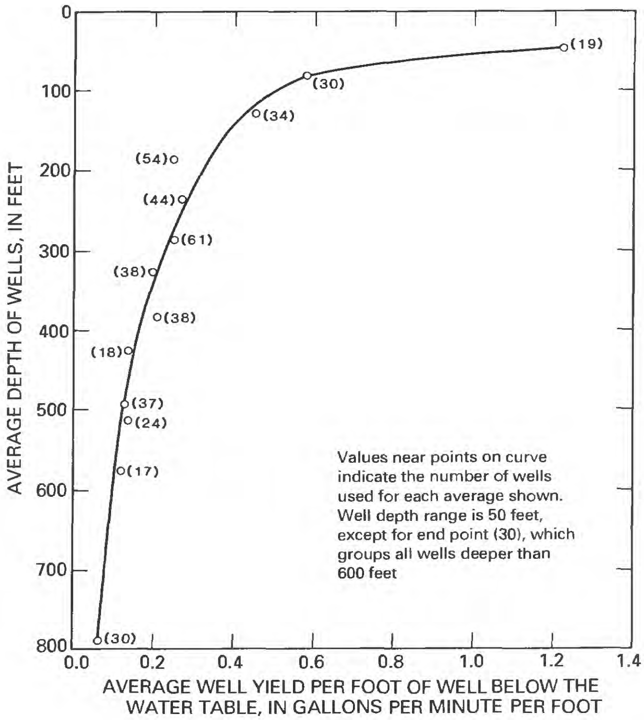


Figure 32. Variation of yield with depth of wells in the Wissahickon Formation.

settings. The cost of development may be high, however, because several low-yielding wells may be drilled before a high-yielding well is obtained.

3. Yields of wells that tap the Wissahickon Formation where it is overlain by saturated unconsolidated sediments are not appreciably higher than yields of wells that penetrate only the Wissahickon Formation (fig. 35). However, water levels in wells in the Wissahickon Formation where it is overlain by the sediments generally fluctuate less than levels in wells that are open to only the crystalline rocks.

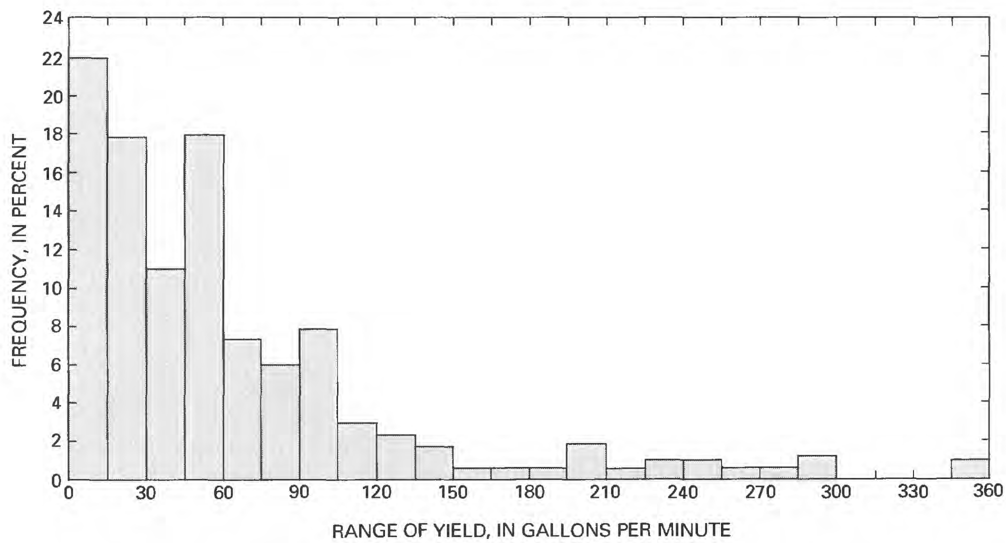


Figure 33. Histogram of well yields from the Wissahickon Formation.

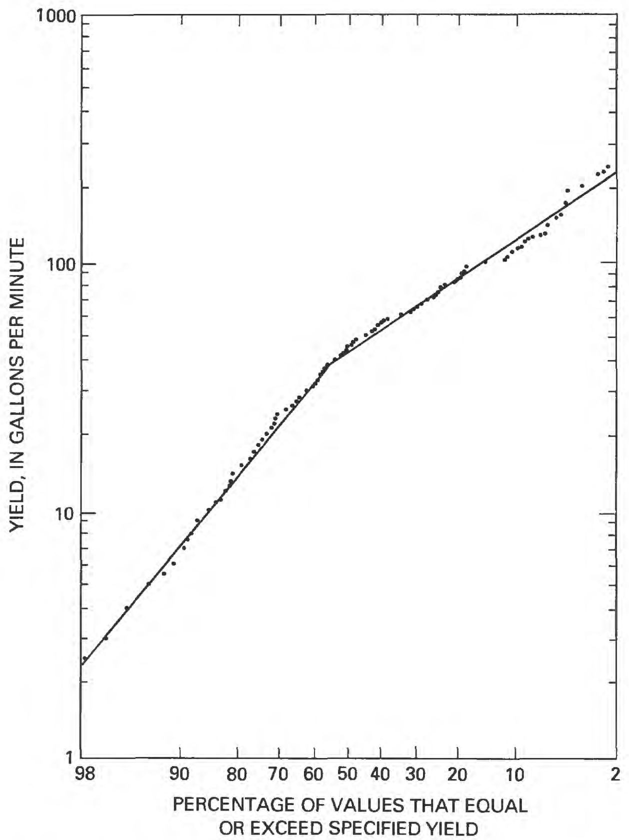


Figure 34. Cumulative-frequency distribution of well yields from the Wissahickon Formation.

The mean and median specific capacities of 103 wells in the Wissahickon Formation are 1.6 and 0.54 (gal/min)/ft, respectively. Wells in fractured or deeply weathered rock have specific capacities as high as 30 (gal/min)/ft, whereas wells in unfractured fresh rock have specific capacities of almost zero. The cumulative-frequency distribution (fig. 37) shows that 90 percent of the specific capacities exceed an estimated 0.07 (gal/min)/ft and that 10 percent exceed 3.2 (gal/min)/ft. The areal distribution of specific capacities corresponds generally to the distribution of well yields (fig. 35). Evaluation of data on specific capacity and yield of nearby wells may be used to guide selection of favorable drilling sites. Paulachok and others (1984, table 2) present additional data on specific capacities and yields of wells in Philadelphia.

Hydraulic Properties

Methods of aquifer-test analysis used in this study assume that the hydraulic properties of the aquifer are uniform (homogeneous) and independent of direction (isotropic). The properties of the unconsolidated sediments generally satisfy or at least approach these assumptions; the properties of the crystalline rocks commonly do not. Because the hydraulic properties of fractured crystalline rocks are highly variable, they usually cannot be estimated reliably by aquifer tests. When testing a well in crystalline rock, various combinations of fracture width, number, and location and degree of interconnection can produce almost any drawdown curve or graph of water-level decline with time. Close proximity to a source of recharge or leakage from overlying geohydrologic units also can influence the shape of the drawdown curve. For example, figure 38 shows the drawdown curve of well PH-783 resulting from pumping at 10 gal/min. This well probably is open to only a few producing fractures of limited areal extent. Consequently, the water level in the well declines rapidly when pumping begins and continues to decline as pumping continues. Thus, this well supplies only very small amounts of water. In contrast, the drawdown curve of well PH-567 (fig. 38) suggests that the well may derive water from nearby sources of recharge—possibly wastewater that has leaked from sewers or finished water that has leaked from the distribution system. The water level declines initially, but it stabilizes after about 20 min (minutes) of pumping. This well should provide a dependable water supply of considerably more than the test yield of 17 gal/min. Where possible, therefore, wells in fractured crystalline rocks should be constructed close enough to surface-water bodies or other sources of recharge to prevent depletion of water in the fractures, provided the quality of the recharge water is acceptable.

Summary of Well Yield and Specific Capacity

Reported yields and specific capacities of wells in the principal aquifers of Philadelphia are summarized in table 6. Figures in table 6 for the Trenton gravel combine all data for the upper sand unit of the Potomac-Raritan-Magothy aquifer system and the Trenton gravel. The greatest well yields are obtained from the Trenton gravel; however, wells in the lower sand unit have a much higher median yield. The largest specific capacities are for wells in the lower sand unit, and wells in the lower sand unit also have the highest median specific capacity.

Ground-Water Flow System

In general, the potentiometric surface of the confined aquifer system in Philadelphia is defined by the level to which water will rise in tightly cased wells open to either the lower or the middle sand unit of the Potomac-Raritan-Magothy aquifer system. The water table of the unconfined aquifer system is the upper surface of the ground-water reservoir in several aquifers, including the Wissahickon Formation in its outcrop area, the upper sand unit of the Potomac-Raritan-Magothy aquifer system where it is unconfined, and the Trenton gravel. The shape of these surfaces depends on aquifer hydraulic properties and on rates of recharge and discharge.

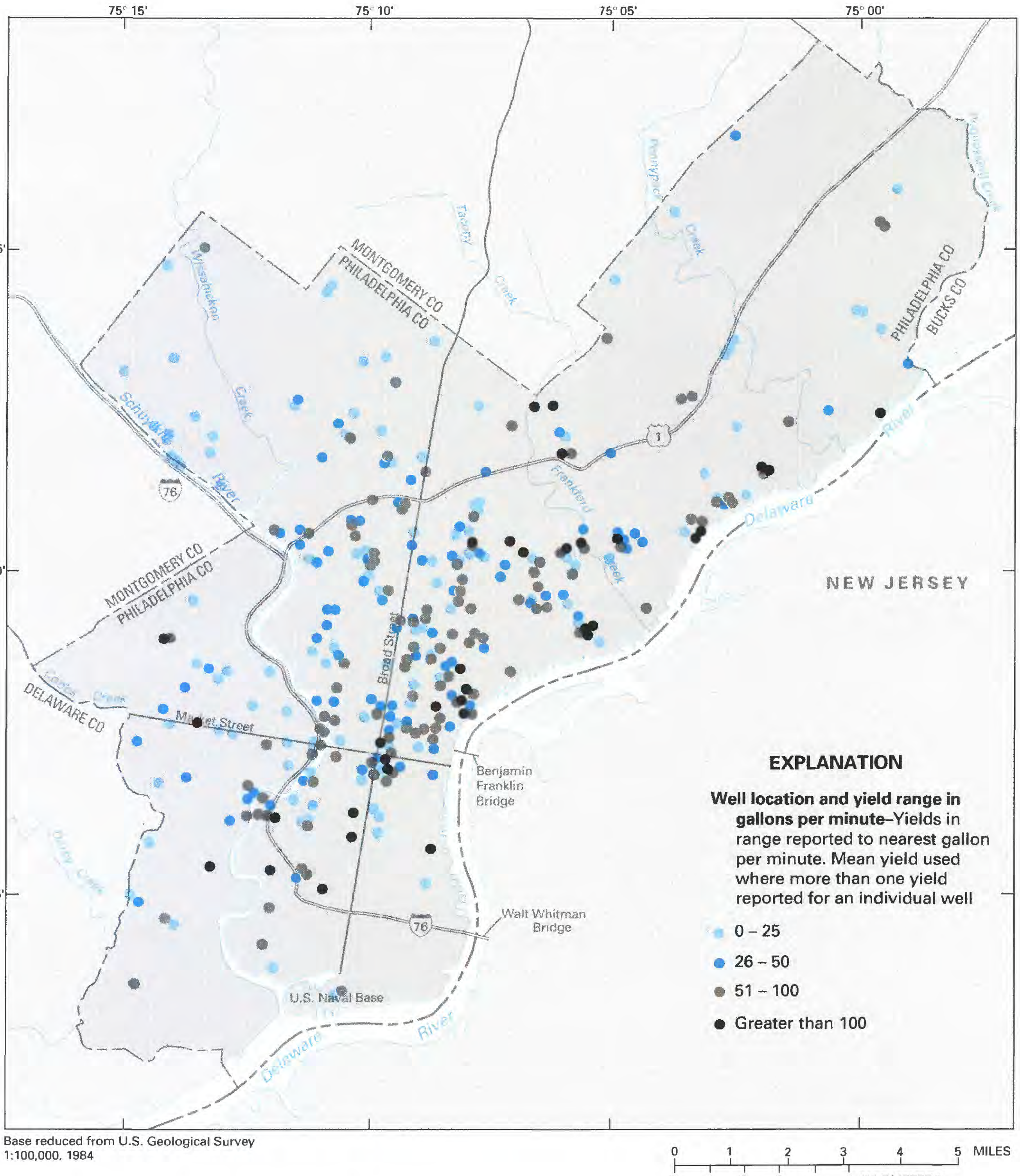


Figure 35. Yields of wells in the Wissahickon Formation.

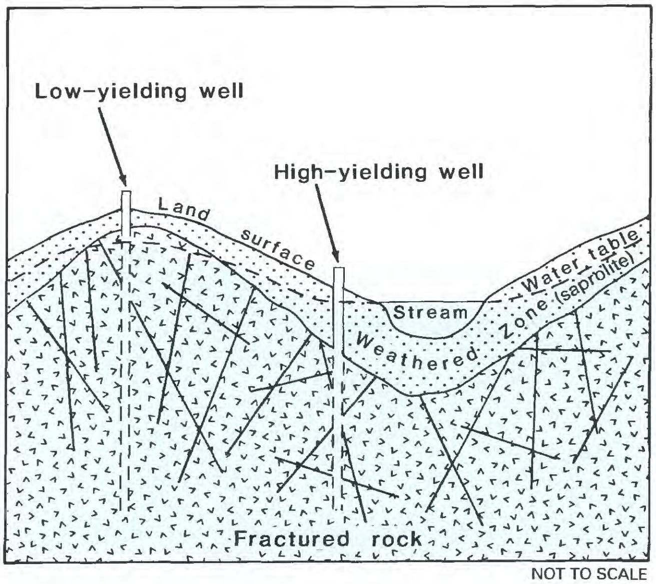


Figure 36. Idealized hydrologic section showing wells in fractured crystalline rock.

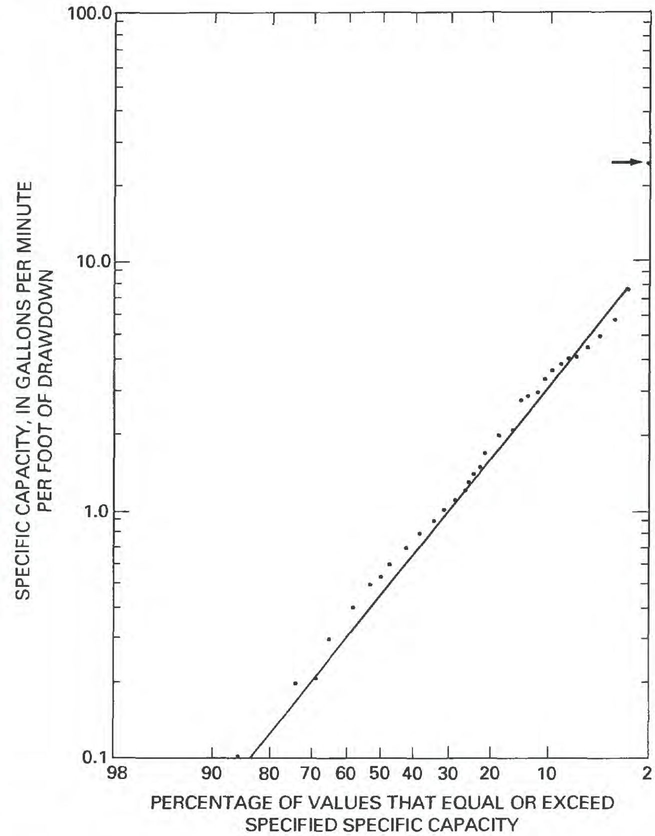


Figure 37. Cumulative-frequency distribution of specific capacities of wells in the Wissahickon Formation.

Confined Aquifer System

Figure 39 shows the configuration of the potentiometric surface of the lower sand unit of the Potomac-Raritan-Magothy aquifer system in 1900, prior to ground-water development. This map is based on the steady-state water-level distribution simulated by a computer model of ground-water flow in the lower sand unit (Sloto, 1988, p. 20). Greenman and others (1961, p. 54) estimated that

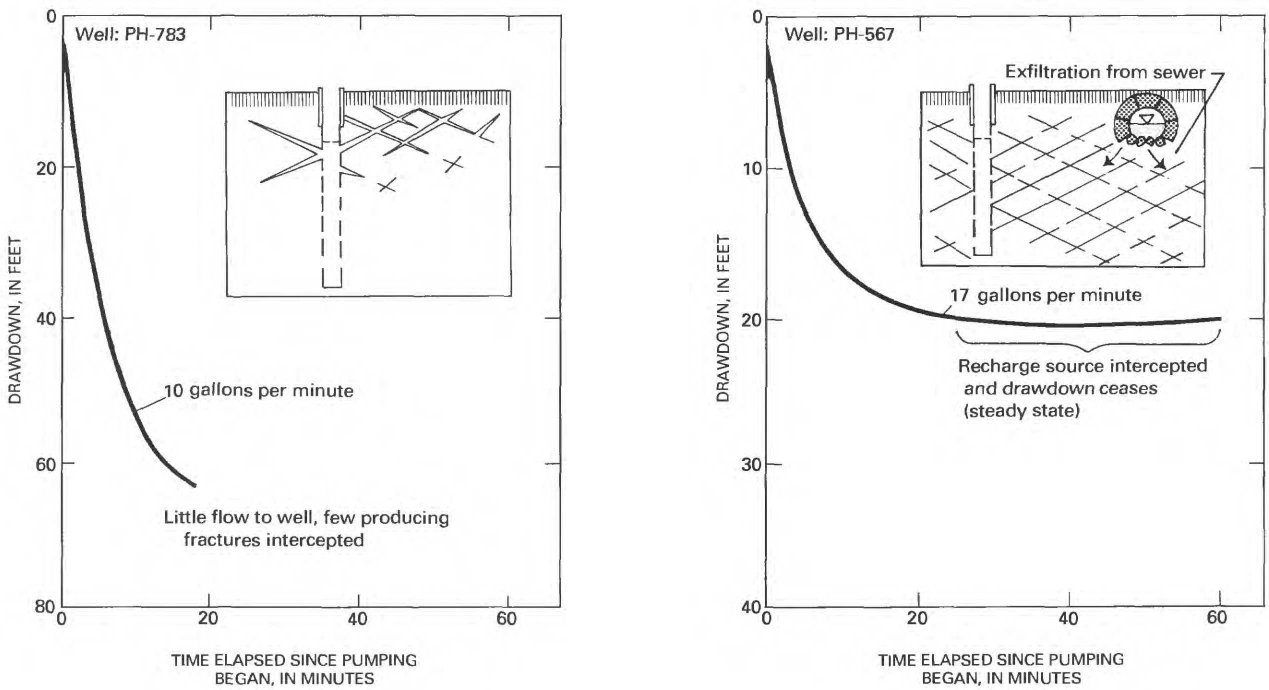


Figure 38. Drawdown curves for two wells in the Wissahickon Formation.

Table 6. Summary of reported yield and specific capacity of wells in principal aquifers

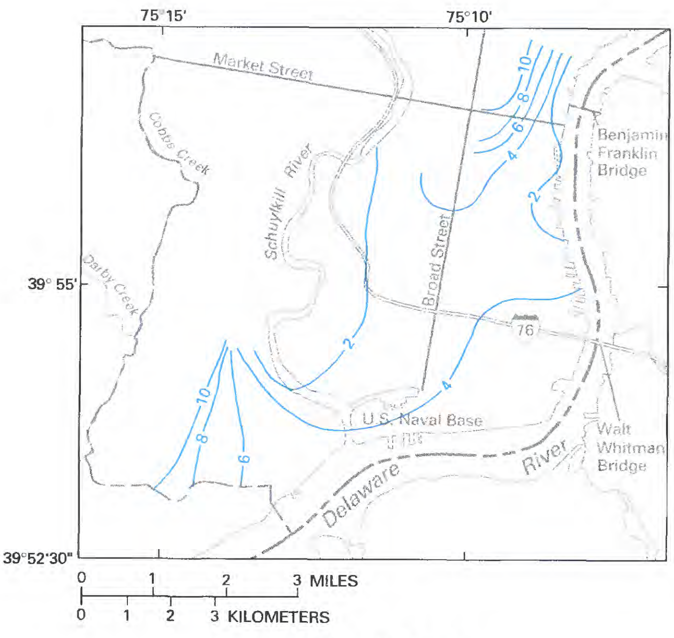
Geohydrologic Unit		Range	Mean	Well yield, in gallons per minute, exceeded by indicated percentage of values: 90 percent	(median) 50 percent	10 percent	Number of values included in frequency distribution	Range	Mean	Specific capacity, in gallons per minute per foot of drawdown[1], exceeded by indicated percentage of values: 90 percent	(median) 50 percent	10 percent	Number of values included in frequency distribution
Trenton gravel[2]		1.0-1,370	170	0.7	90	510	122	0.01-68	16	0.50	12	40	40
Potomac-Raritan-Magothy aquifer system	Middle sand unit	50-870	355	15	300	900	15	4.7-36	14	4.7	10	36	9
	Lower sand unit	3.3-1,350	360	53	275	830	155	.50-71	18	3.5	16	34	80
Wissahickon Formation		1.0-350	64	7.0	45	125	392	.01-30	1.6	.07	.54	3.2	103

1/ Specific capacity values not adjusted to a common duration of pumping.

2/ All values for Trenton gravel (informal usage) computed from data for the combined stratigraphic interval consisting of the upper sand unit of the Potomac-Raritan-Magothy aquifer system and the Trenton gravel.

the predevelopment hydraulic gradient in the lower sand unit in southern Philadelphia was about 2.5 ft/mi (feet per mile); consequently, the rate of water movement in the unit was low.

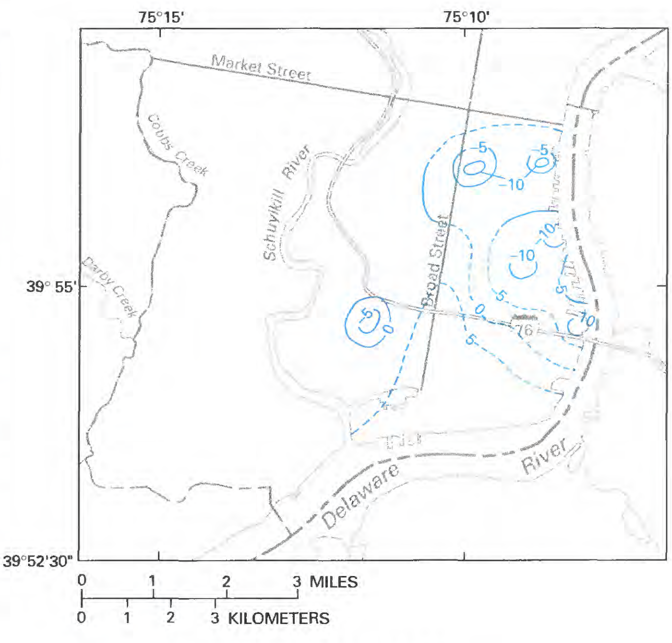
The initial effects of ground-water development on the potentiometric surface of the lower sand unit are shown by the map representing conditions during the early 1920's (fig. 40). The positions of the pumping centers are shown



EXPLANATION

—4— **Potentiometric contour**–Shows altitude at which water level would have stood in tightly cased wells. Contour interval 2 feet. Datum is sea level.

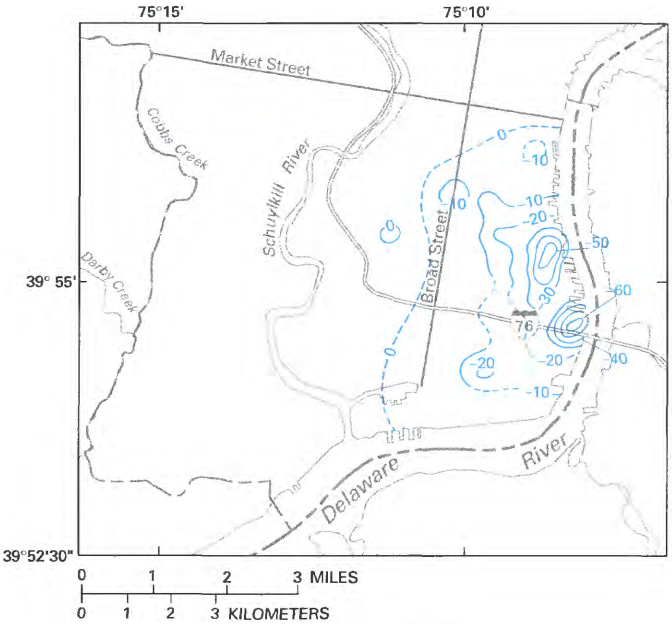
Figure 39. Simulated predevelopment potentiometric surface of the lower sand unit of the Potomac-Raritan-Magothy aquifer system. (Modified from Sloto, 1988.)



EXPLANATION

---—10— **Potentiometric contour**–Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximately located. Contour interval 5 feet. Datum is sea level

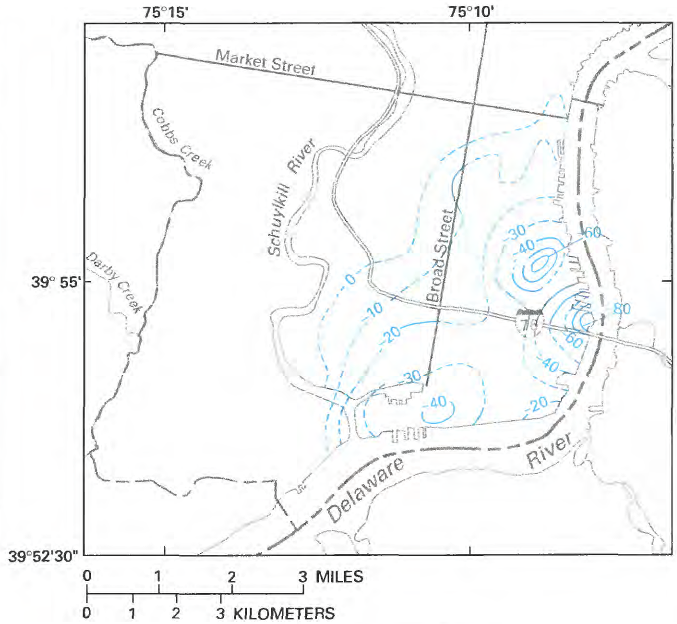
Figure 40. Potentiometric surface of the lower sand unit of the Potomac-Raritan-Magothy aquifer system, early 1920's. (Modified from Greenman and others, 1961.)



EXPLANATION

—10— **Potentiometric contour**–Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximately located. Contour interval 10 feet. Datum is sea level

Figure 41. Potentiometric surface of the lower sand unit of the Potomac-Raritan-Magothy aquifer system, 1940. (Modified from Greenman and others, 1961.)



EXPLANATION

—10— **Potentiometric contour**–Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximately located. Contour interval 10 feet. Datum is sea level

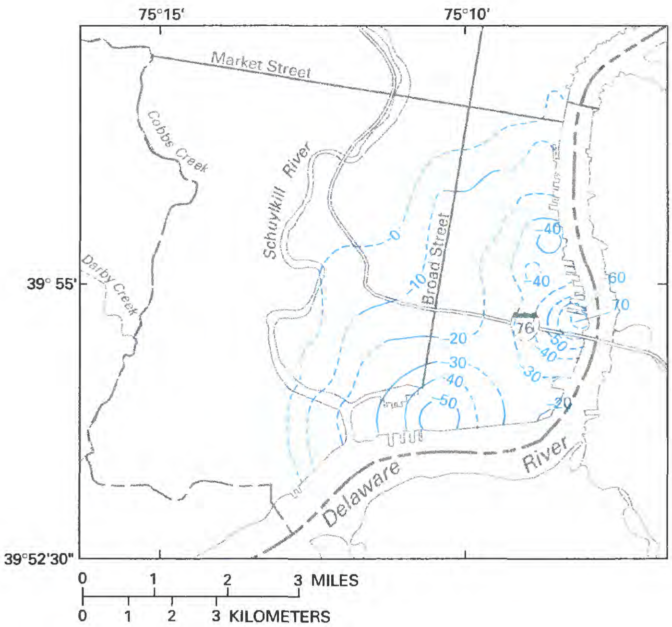
Figure 42. Potentiometric surface of the lower sand unit of the Potomac-Raritan-Magothy aquifer system, August 1945. (Modified from Greenman and others, 1961.)

by the circular contours that delineate cones of depression in the potentiometric surface. Comparison of figure 40 with the predevelopment potentiometric-surface map (fig. 39) shows that the principal change in the direction of ground-water flow was in the area near the Walt Whitman Bridge, where the greatest withdrawals were made.

The potentiometric surface of the lower sand unit in 1940 is shown in figure 41. The effect of the increase in ground-water withdrawals during 1920–40 on the potentiometric surface can be evaluated by comparing figures 40 and 41. Near the Walt Whitman Bridge, the additional water-level decline that accompanied the increased withdrawals caused a steepening of the local hydraulic gradient, resulting in a higher rate of ground-water movement toward the pumping centers. Also, differences in head between the lower sand unit and overlying geohydrologic units began to develop, causing water in the overlying units to flow downward to the lower sand unit.

Figure 42 shows the configuration of the potentiometric surface of the lower sand unit in August 1945, during the period of greatest withdrawals. Figure 43 shows the potentiometric surface on March 24, 1954, and is based on synoptic water-level measurements made in about 30 wells. Comparison of these two maps shows that the configuration of the potentiometric surface changed only slightly during that time. Both maps are dominated by three major cones of depression. The maps also show that the direction of ground-water movement near the U.S. Naval Base was influenced strongly by intensive pumping there that began in the early 1940's. Compared with that of earlier periods, the direction of ground-water movement near the Walt Whitman Bridge remained relatively unchanged, although the rate of movement was influenced by changes in the rates of pumping of nearby wells. Greenman and others (1961) present additional information on the altitude and configuration of the potentiometric surface of the lower sand unit during 1915–54.

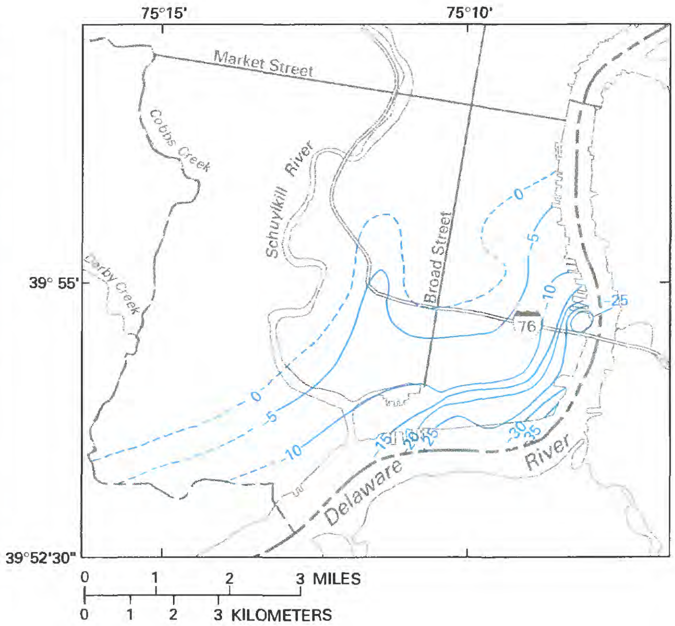
The effects of curtailment of pumping from the lower sand unit on water levels are illustrated by the map of the potentiometric surface during 1978–79 (fig. 44). Because of reductions in pumpage since the mid-1960's, ground-water levels at the U.S. Naval Base and in the area near the Walt Whitman Bridge recovered by about 25 and 45 ft, respectively. Since 1979, the configuration of the potentiometric



EXPLANATION

-10- **Potentiometric contour**–Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximately located. Contour interval 10 feet. Datum is sea level

Figure 43. Potentiometric surface of the lower sand unit of the Potomac-Raritan-Magothy aquifer system, March 24, 1954. (Modified from Greenman and others, 1961.)



EXPLANATION

-10- **Potentiometric contour**–Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximately located. Contour interval 5 feet. Datum is sea level

Figure 44. Potentiometric surface of the lower sand unit of the Potomac-Raritan-Magothy aquifer system, 1978–79.

surface of the lower sand unit in Philadelphia has been influenced more by withdrawals from the unit in nearby parts of New Jersey than by pumping in Philadelphia; consequently, water in the lower sand unit now flows chiefly toward pumping centers in New Jersey.

Unconfined Aquifer System

Prior to development by wells and drainage works, water in the unconfined aquifer system flowed from upland recharge areas toward lowland discharge areas, moving in the direction of decreasing head. In natural systems, the water-table profile generally resembles the land-surface profile. Hence, the altitude of the water table usually is highest under the highest areas of land surface, such as hilltops and ridges, and lowest in valleys, where it may intersect the land surface to form streams, ponds, and marshes. Available water-level data are inadequate to prepare a map representing the water table during the predevelopment period.

Human activities have greatly influenced the occurrence and movement of water in the unconfined aquifer system of Philadelphia. These activities include construction of large-scale water-distribution and sewer systems, pumping of wells, and use of dewatering systems. Other sections of this report describe the effects on ground-water levels of leakage from water pipes and seepage into and from sewers and present information on withdrawals by wells and dewatering systems.

The altitude and configuration of the water table in Philadelphia are influenced by human activities and by natural factors such as topography. Locally, the water table may be controlled chiefly by leakage, seepage, or ground-water pumping. Short-term, seasonal, and long-term water-table fluctuations may be dampened to a narrow range because of these processes and activities. Also, the water-table configuration may change when leaky brick sewers are replaced by relatively watertight sewers constructed of other materials or when the location or rate of ground-water pumping changes significantly.

The effects of human activities on the movement of water in the unconfined aquifer system are shown by the map of the water table in 1944–45 (fig. 45). The area along the Delaware and lower Schuylkill Rivers where the water table was below sea level is chiefly a result of pumping from the unconfined aquifers and from the lower sand unit of the Potomac-Raritan-Magothy aquifer system in Philadelphia and nearby parts of New Jersey. These withdrawals

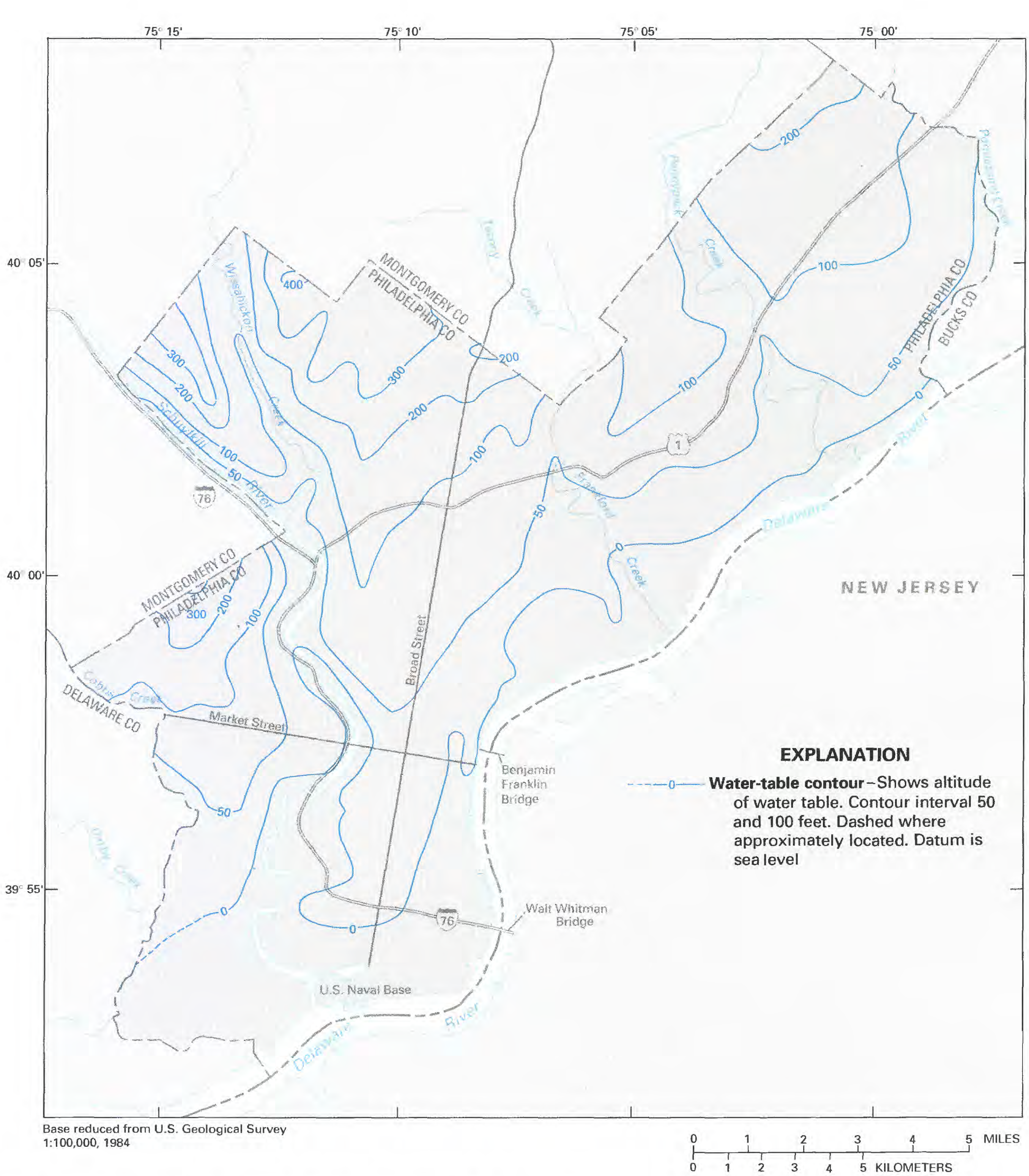


Figure 45. Water table, about 1944–45. (Modified from Graham, 1946.)

produced significant vertical differences in head between aquifers. Because of the head differences, water flowed downward from the unconfined aquifer system through the intervening confining units to the lower sand unit, causing head to decline locally below sea level in the unconfined aquifers. The effects on the water table of decreased pumpage from unconsolidated aquifers in Philadelphia are shown by the map of the water table from 1976 to 1980 (fig.

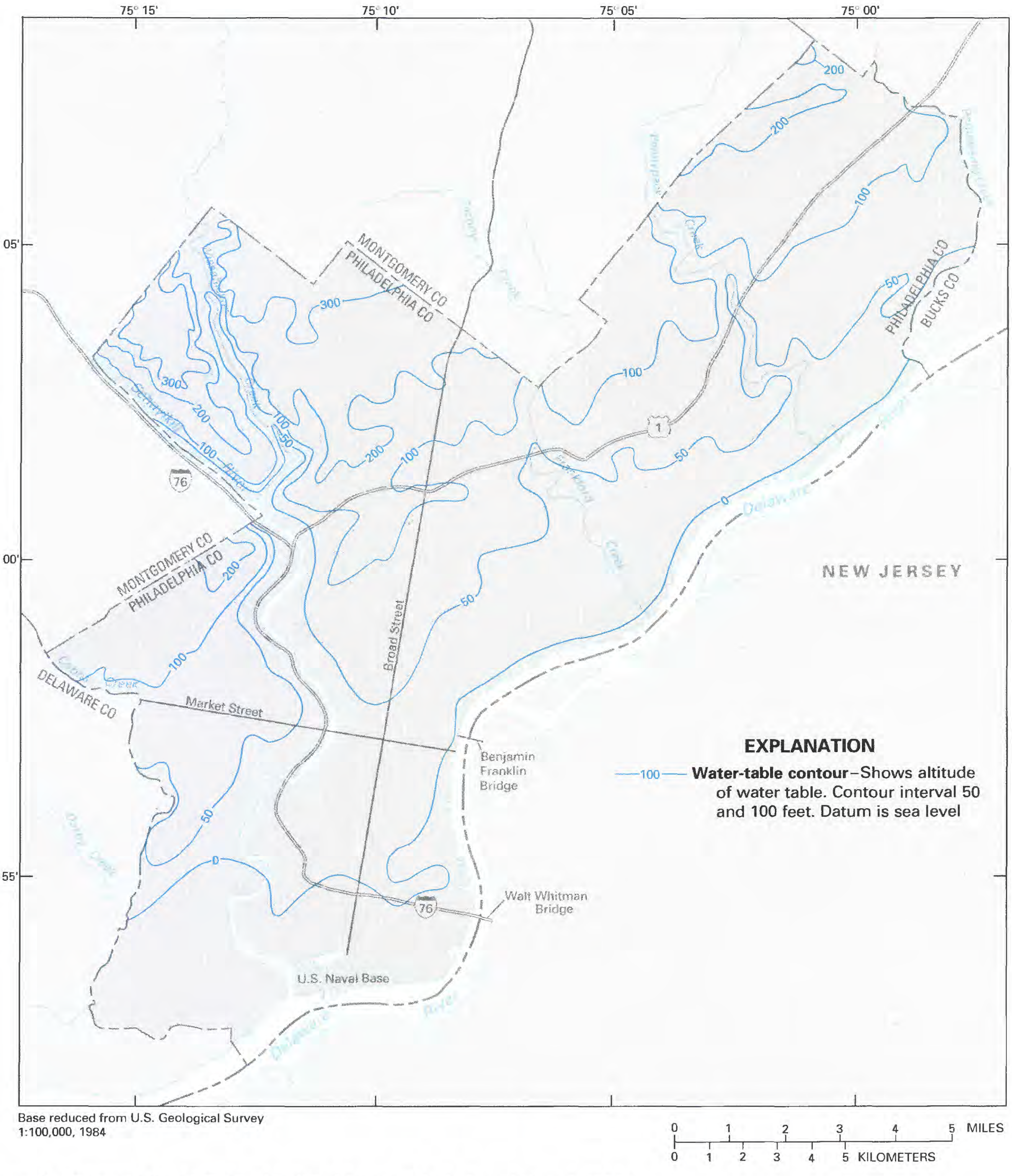


Figure 46. Water table, 1976–80. (Modified from Paulachok and Wood, 1984.)

46). Comparison of this map with that for the earlier period (fig. 45) shows that by 1980, the area where head was below sea level diminished because of the reduction in pumpage from the lower sand unit beginning in the mid-1960's. However, in areas where head was greater than 50 ft, differences in position of the water table were slight.

Because water moves in the direction of decreasing head, figures 45 and 46 can be used to determine the general direction of shallow ground-water flow. In areas where the water table is above sea level, water in the unconfined aquifer system generally moves laterally downgradient toward points of discharge; where the water table is below sea level, water moves laterally as well as vertically downward into deeper aquifers in which water has relatively lower head.

Where the water table is lower than adjacent surface-water levels, streams may furnish water to aquifers. Where the water table is at or above adjacent surface-water levels, streams receive ground-water discharge. Tidal streams receive ground-water discharge during low tide when the stream level is lower than ground-water levels; conversely, some surface water flows into the aquifers during high tide when the stream level is higher than ground-water levels.

Water-Level Fluctuations

The potentiometric surface fluctuates continuously as a result of natural variations in recharge and discharge, and because of external effects such as tidal loading. The most obvious pattern of natural water-level change is the seasonal cycle of fluctuation. The potentiometric surface is higher in winter and spring than in summer and autumn. The potentiometric surface also fluctuates through long-term cycles during which water levels show recovering or declining trends caused by climatic cycles of several years duration. Natural short-term and seasonal fluctuations were observed during the present study, but long-term changes could not be assessed.

Fluctuation of the potentiometric surface also can be caused by pumping of wells. Short-term, rapid fluctuations of ground-water levels are caused chiefly by pumping, and the amplitude of the fluctuations decreases with distance from the pumped wells. Such fluctuations usually have a duration of a few hours or days. Seasonal fluctuations are characterized by several months of rising ground-water levels followed by declining levels. In Philadelphia, seasonal fluctuations are caused mainly by the alternate use by industry of subsurface and surface sources of cooling water. Commonly, in summer, industry uses more ground water than the warmer surface water and, in winter, uses more surface water than the warmer ground water. Such short-term and seasonal fluctuations were observed during this study. Long-term fluctuations of ground-water levels are caused by the gradual depletion or accretion of water in an aquifer. For example, water levels in the Potomac-Raritan-Magothy aquifer system near the U.S. Naval Base rose steadily during the mid-1960's and the early 1970's in response to a major reduction in local pumping.

For this study, water-level measurements were made in 21 observation wells to determine the character and magnitude of fluctuations. Measurements at midmonth were made in 17 wells, and continuous measurements were made in 4 wells equipped with water-level recorders. Figure 47 shows the location of selected observation wells and the frequency of water-level measurements; figures 48 and 49 show water levels in those wells during 1979-81.

The hydrograph of observation well PH-409 (fig. 48) shows large water-level fluctuations caused by nearby ground-water pumping. The seasonal trend was caused chiefly by greater withdrawal of ground water during the warmer months. Superimposed on the seasonal cycle of fluctuation is a general rising trend, which resulted from a reduction of pumpage by industries near the Walt Whitman Bridge.

Hydrographs of observation wells PH-753, PH-242, and PH-754 (fig. 48) also show some fluctuations related to seasonal changes in pumpage. The fluctuation of water levels in well PH-753, which taps the upper sand unit of the Potomac-Raritan-Magothy aquifer system, is slightly greater than that in wells PH-242 and PH-754, which are screened in the lower sand unit; however, the water-level trend in the aquifers is similar.

Water-level fluctuations in well PH-397 (fig. 48), which taps the Trenton gravel, are typical of those in areas that are relatively unaffected by pumping, sewering, and leaking water mains. In Philadelphia, undisturbed areas such as these are relatively uncommon. The hydrograph shows a natural seasonal fluctuation, with higher water levels in winter and spring and generally lower levels in summer and autumn.

Water-level fluctuations in well PH-287 (figs. 48, 50), which taps the Trenton gravel, are typical of those in areas that are affected significantly by leakage from water pipes, ground-water flow into leaky sewers, and covering of the land surface by impervious surfaces. In Philadelphia, such areas are common. Near well PH-287, ground-water flow into sewers apparently prevents the water table from rising to levels much above that of the sewers; consequently, ground-water levels show little change (figs. 48, 50). Water levels in well PH-98 (fig. 48) exhibit a similar pattern of dampened fluctuations.

Figure 51 shows representative short-term water-level fluctuations in two observation wells near the Delaware and Schuylkill Rivers, and the corresponding fluctuation of the river stage measured at nearby tide-gaging stations. The amplitude of the fluctuations in well PH-400 is about 29 percent of that in the Delaware River at Palmyra, N.J.; the amplitude of the fluctuations in well PH-6 is about 14 percent of that in the Schuylkill River above Passyunk Avenue. Except for these differences and a slight time lag, the water levels in the wells mimic the tidal fluctuations. Table 7 summarizes the effects of river tides on water-level fluctuations in Philadelphia and Bucks Counties, Pa., and is based on data from Greenman and others (1961, p. 59), supplemented by data collected during this study. Greenman and others (1961, p. 55–59) present additional infor-

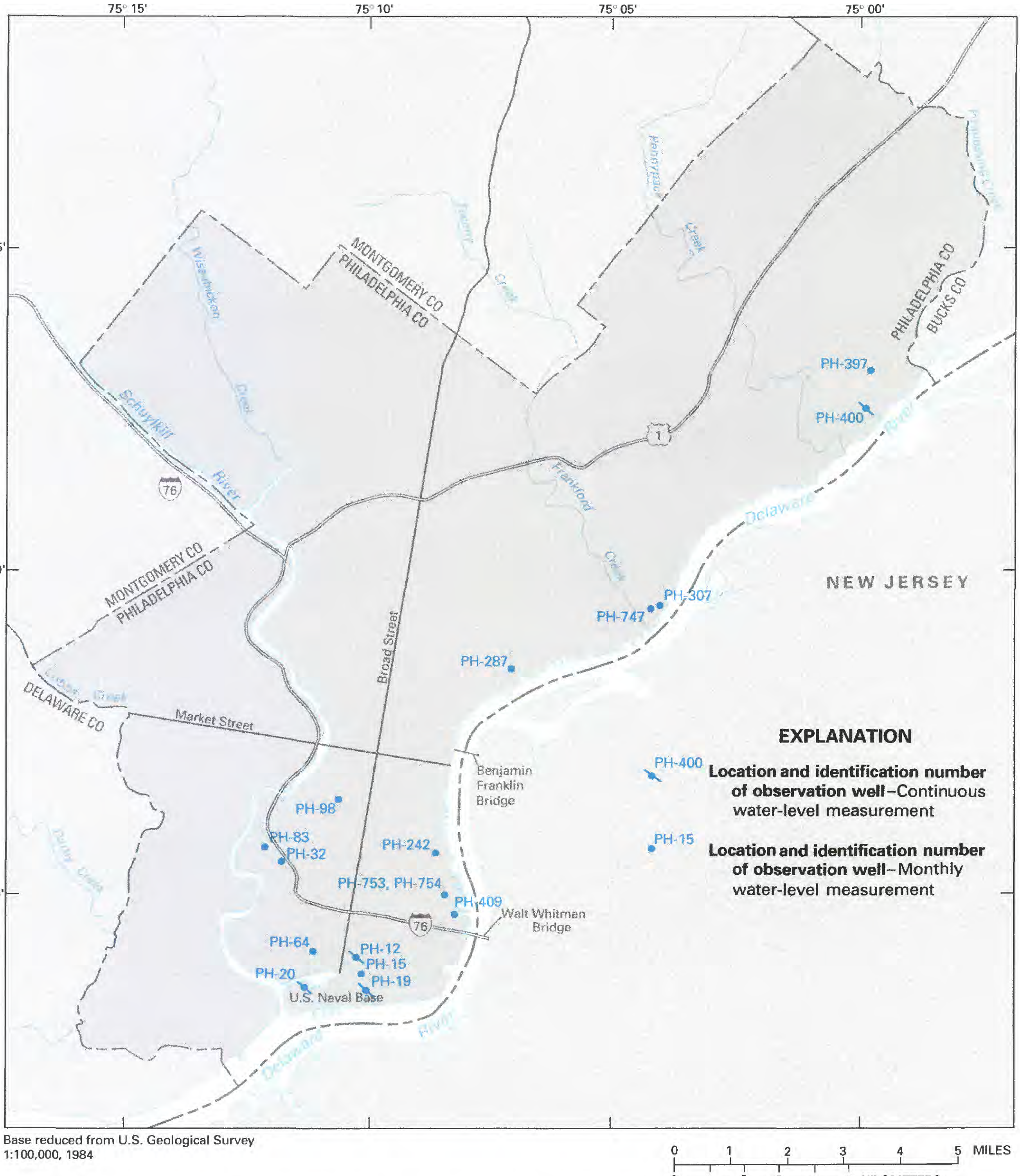


Figure 47. Location of selected observation wells and frequency of water-level measurements.

mation on the relation between ground-water levels and surface-water levels.

From the mid-1940's until the mid-1960's, the potentiometric surface of the confined aquifer system in southern Philadelphia was maintained at a relatively low level chiefly because of pumping from the lower sand unit at the U.S. Naval Base and at industrial sites near the Walt Whitman Bridge (figs. 42, 43). During that period, the water level in

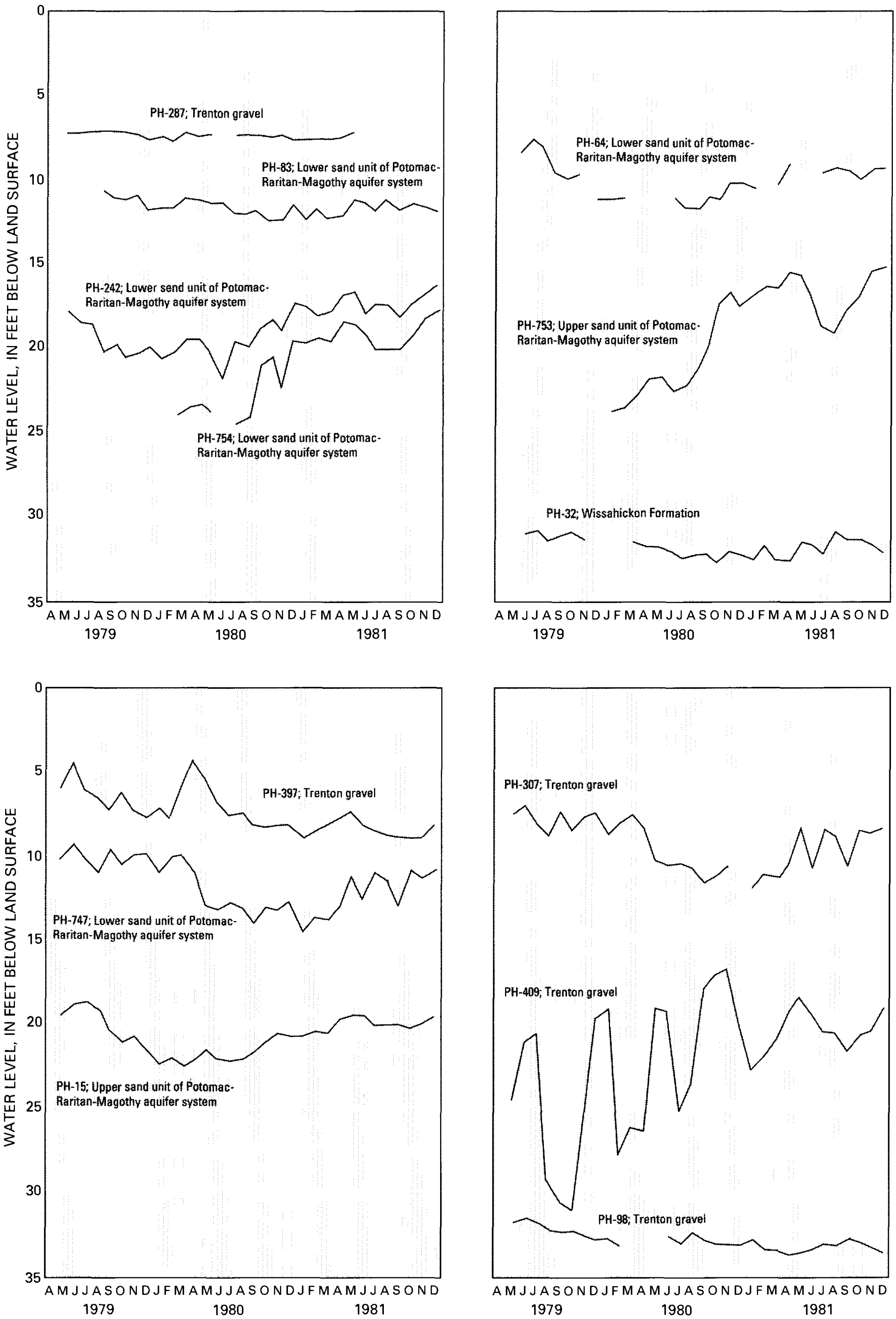


Figure 48. Midmonth water levels in selected wells.

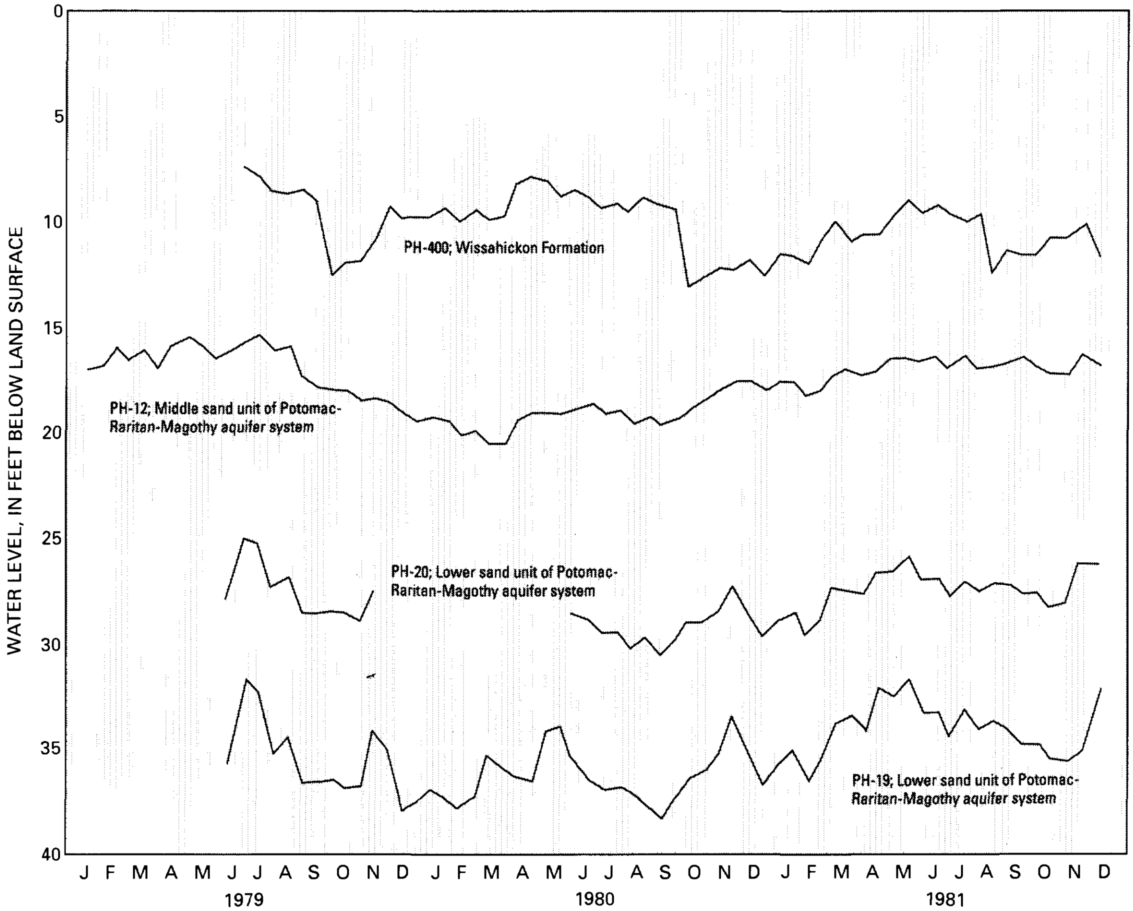


Figure 49. Water levels at midmonth and end of month in selected wells.

well PH-20, which is open to the lower sand unit, ranged from about 50 to 60 ft below land surface, whereas water levels in well PH-12, which is screened in the middle sand unit, were somewhat higher and ranged from 28 to 36 ft below land surface (fig. 52). Beginning around 1965, however, confined ground-water levels began to rise because of a reduction in pumpage. Water levels in well PH-20 recovered until they stabilized at 27 to 29 ft below land surface in 1972, and they have since remained at about that level (fig. 52). Similarly, water levels in well PH-12 recovered steadily to 16 to 19 ft below land surface in 1973. Since 1973, water levels in the confined aquifer system of southern Philadelphia have been controlled by pumping from the lower sand unit in nearby parts of New Jersey.

QUALITY OF GROUND WATER

Effects of Urbanization on Ground-Water Quality

The natural chemical quality of ground water is determined chiefly by the mineral composition of the soils and rocks the water comes in contact with and by the residence time of the water in those materials. Consequently, ground-water quality may differ greatly from place to place within a geohydrologic unit and between adjacent units. Superimposed on these natural determinants of ground-water quality are the effects of human activities.

Although chemical analyses of water from the unconfined aquifer system in Philadelphia before urbanization are not available, areal variations in natural water quality are thought to be minimal. The water probably was weakly acidic and slightly mineralized, with calcium, bicarbonate, and sulfate the principal ions (Greenman and others, 1961, p. 61). Analyses of natural water from the confined aquifers suggest a similar uniform composition. This water was chemically neutral, with sodium and bicarbonate the principal ions (Greenman and others, 1961, p. 64). Greenman and others (1961, p. 60–64) provide additional details on the presumed natural quality of ground water in Philadelphia.

The quality of ground water in Philadelphia has been degraded as a result of urbanization. Urbanization has resulted in chemical contamination and elevated ground-water temperatures, particularly in industrialized and

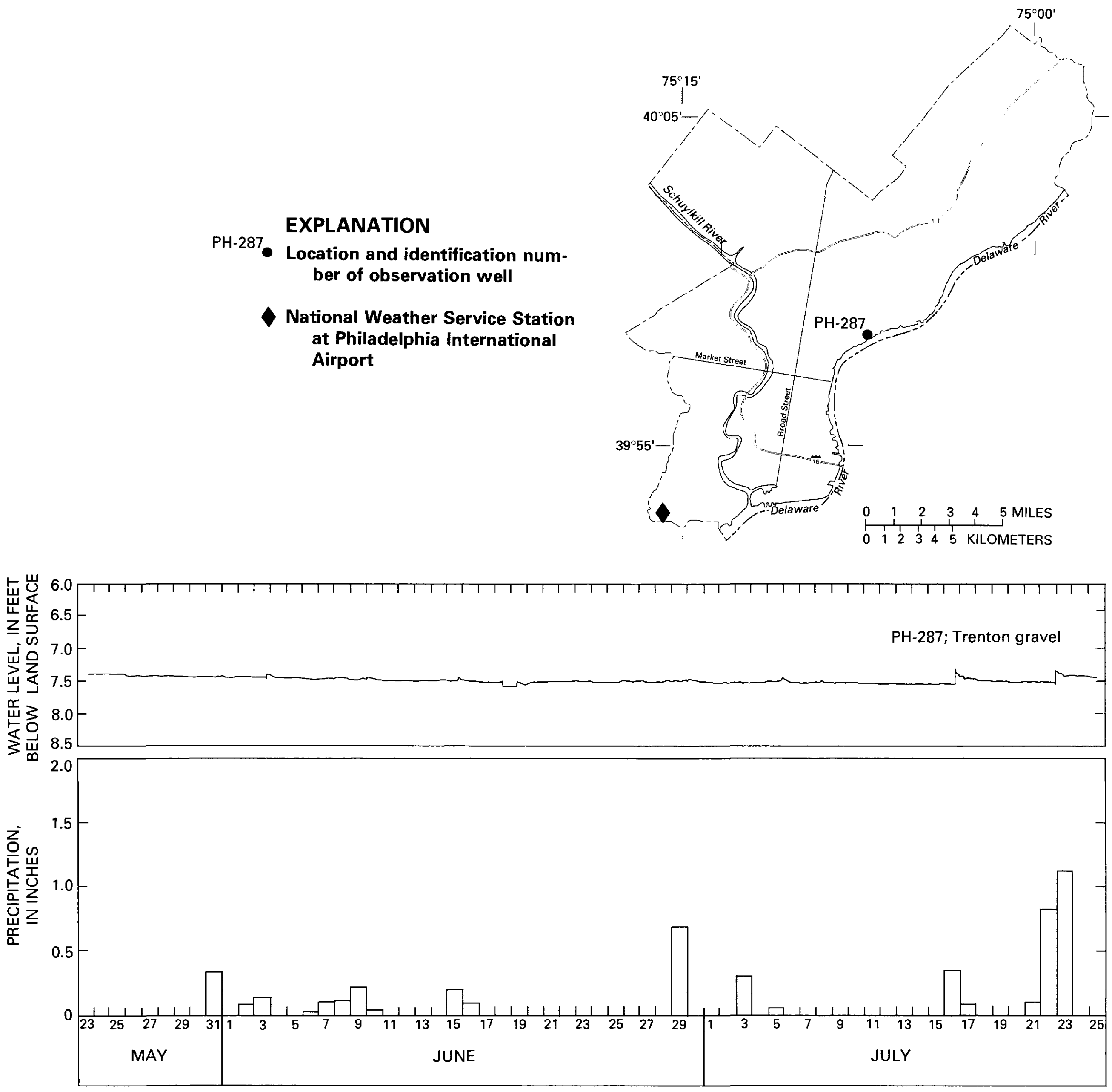


Figure 50. Short-term fluctuation of water levels in well PH-287.

densely populated areas. During the first of two phases of contamination, the quality of water in the unconfined aquifer system was severely degraded by contaminants originating at the land surface. As a result, water supplies from the deeper, uncontaminated confined aquifers were developed. During the second phase of contamination, withdrawal of water from the confined aquifers caused a decline of head sufficient to induce downward flow of contaminated water from the overlying unconfined aquifer system. Because of this influx of contaminated water, water in the confined aquifers has been altered progressively so that its chemical composition in 1982 resembled that of water in the unconfined aquifer system. Greenman and others (1961, p. 67–83) provide a detailed account of the progressive contamination of water in the unconfined aquifer system and point out that significant contamination by inorganic chemical species had occurred by 1945.

Water in the unconfined aquifer system is subject to direct contamination by inorganic and organic chemicals. Sources of contamination include sewage, chemical wastes, and leachate from reclaimed areas and disposal sites. Minerals, particularly iron and manganese, leached from the aquifer matrix also contribute to contamination. Because the nature of contamination may differ greatly with time and location, ground-water quality also may vary greatly. Early recognition of contamination by organic compounds in the unconfined aquifer system is evidenced in the following excerpt from the annual report of the New Jersey State Geologist (Woolman, 1900, p. 142). The contamination was observed by a well driller working at the U.S. Naval Base.

> Considerable water was found in the Pennsauken gravels, but tests showed much contamination thought to be derived from oils and other objectionable matter contributed to the Schuylkill River from oil refineries and other manufacturing establishments a few miles further up on the banks of the same.

Although the confined aquifers are not in direct contact with contaminant sources at the land surface, elevated concentrations of chemical constituents in water from the unconfined aquifer system have nonetheless degraded the quality of water in the confined aquifers. Greenman and others (1961, p. 93–105) document this degradation of water quality.

Contamination has rendered water in the unconfined and confined aquifers in parts of Philadelphia unsuitable for most uses. Many former ground-water users found it more economical to purchase municipal water or to withdraw water directly from surface sources when the cost of treating contaminated ground water became too high. At present, the most promising ground-water supply of acceptable quality is in unconfined aquifers that are recharged by surface water of acceptable quality. Pumping of water from such aquifers can mitigate the effects of ground-water contamination, as contaminants in the ground water are diluted by the better quality recharge water.

Water-quality standards differ according to intended water use; those cited in this report are the drinking water standards established by the U.S. Environmental Protection Agency (1977). Standards for other uses also have been established by the U.S. Environmental Protection Agency (1973).

The major inorganic and organic chemical constituents in ground water at Philadelphia that commonly are present in objectionable concentrations are discussed in the following sections. Inorganic constituents include dissolved solids, iron, manganese, sulfate, and trace elements. Organic constituents include selected volatile compounds.

The maps showing chemical quality of ground water were prepared from data given by Paulachok and others (1984, tables 3, 5, 6). These maps show only general conditions and should not be used to predict the precise quality of water at a particular location because the density of data points is not sufficient to show detailed areal variations, especially those caused by localized contamination.

Dissolved Solids

Dissolved-solids concentration is a general measure of the amount of soluble material in water. Although it does not necessarily represent the concentration of any specific chemical constituent, dissolved-solids concentration is useful for broadly evaluating and comparing water quality. Water containing an elevated dissolved-solids concentration is undesirable because of its possible adverse physiological effects, objectionable taste, or corrosive character. A limit of 500 mg/L (milligrams per liter) is recommended by the U.S. Environmental Protection Agency (1977). Water having dissolved-solids concentrations in excess of 500 mg/L can, in many cases, be consumed without obvious ill effects. However, water containing more than 1,000 mg/L of dissolved solids is unsuitable for domestic and many industrial uses.

Dissolved-solids concentrations in 83 water samples collected during 1945–58 ranged from 108 to 4,270 mg/L; the average concentration was 538 mg/L. Concentrations in 29 percent of the samples were greater than 500 mg/L, and concentrations in 10 percent of the samples were greater than 1,000 mg/L. In general, the highest concentrations were in water from the unconfined unconsolidated aquifer system, although one sample each from the crystalline rocks and the confined aquifers had dissolved-solids concentrations of 1,810 and 2,200 mg/L, respectively. Figure 53 shows the distribution of dissolved-solids concentrations during 1945–58. Although dissolved-solids concentrations generally were less than 500 mg/L, concentrations in two distinct areas exceeded 1,000 mg/L. According to Greenman and others (1961), ground water in those two areas was contaminated chiefly by inorganic chemical wastes from industrial sources. Information from other sources and data collected for this study suggest that considerable ground-water contamination in Philadelphia also was caused by organic materials. Water in the affected part of southern Philadelphia (fig. 53) was contaminated by chemical wastes disposed of through wells, drainfields, and cesspools (Greenman and others, 1961, p. 74). Contaminants also entered the ground-water reservoir as leachate from dump sites and where chemicals leaked or were spilled. Ground water in the affected part of east-central Philadelphia (fig. 53) was contaminated by industrial brine, chemical wastes, and sewage (Greenman and others, 1961, p. 76).

Dissolved-solids concentrations in 81 water samples collected during 1979–80 ranged from 90 to 4,480 mg/L. The average concentration was 778 mg/L—an increase of 45 percent over the average concentration during 1945–58. Dissolved-solids concentrations in 62 percent of the samples were greater than 500 mg/L, and concentrations in 14 percent of the samples were greater than 1,000 mg/L. Water from the crystalline rocks generally had the lowest dissolved-solids concentrations, and water from the uncon-

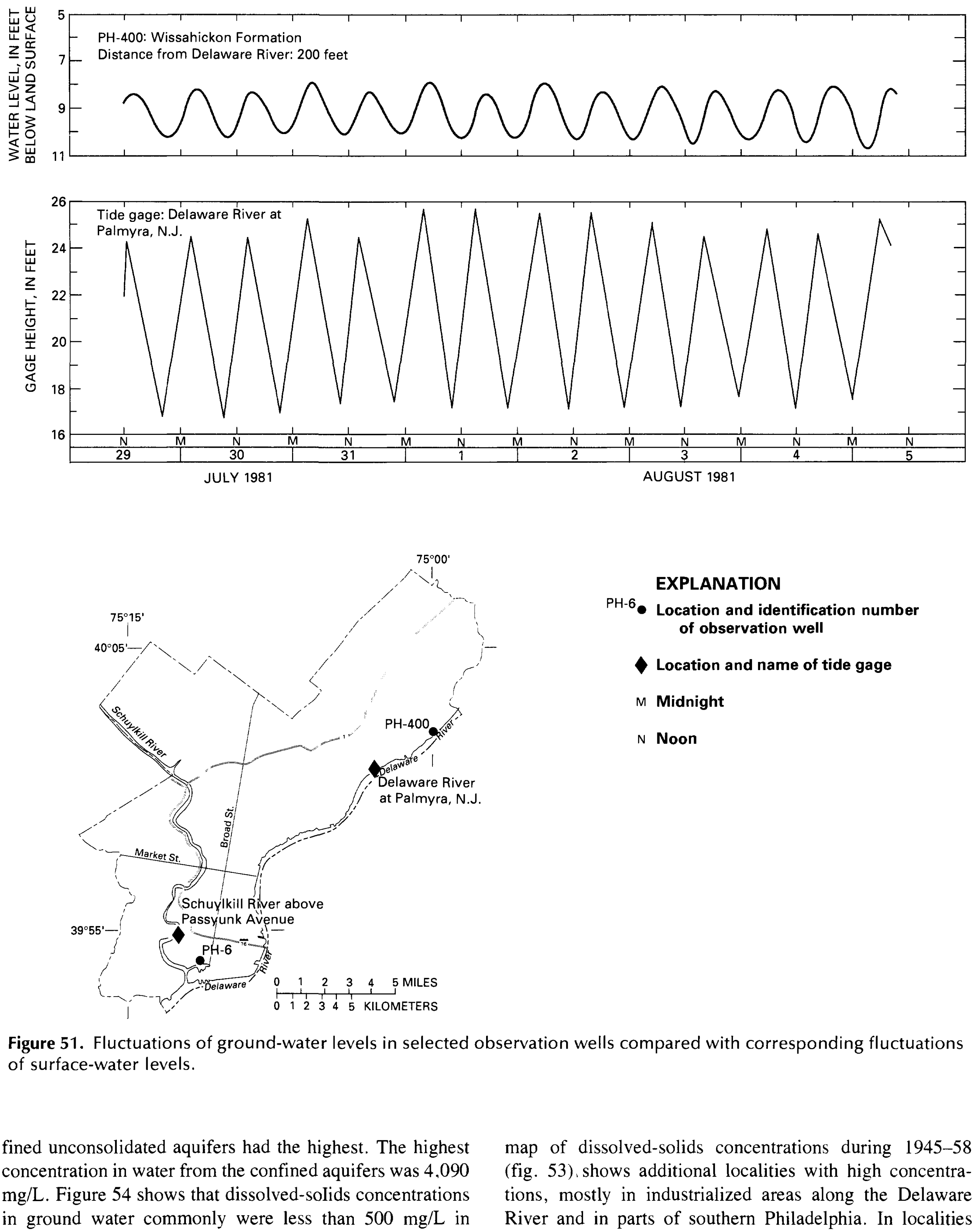


Figure 51. Fluctuations of ground-water levels in selected observation wells compared with corresponding fluctuations of surface-water levels.

fined unconsolidated aquifers had the highest. The highest concentration in water from the confined aquifers was 4,090 mg/L. Figure 54 shows that dissolved-solids concentrations in ground water commonly were less than 500 mg/L in western and northeastern Philadelphia but were greater than 500 mg/L in central Philadelphia and in several areas along the Delaware River. Comparison of this map with the map of dissolved-solids concentrations during 1945–58 (fig. 53), shows additional localities with high concentrations, mostly in industrialized areas along the Delaware River and in parts of southern Philadelphia. In localities where dissolved-solids concentrations have not changed significantly over time, future changes probably will be slight unless affected by new sources of contamination.

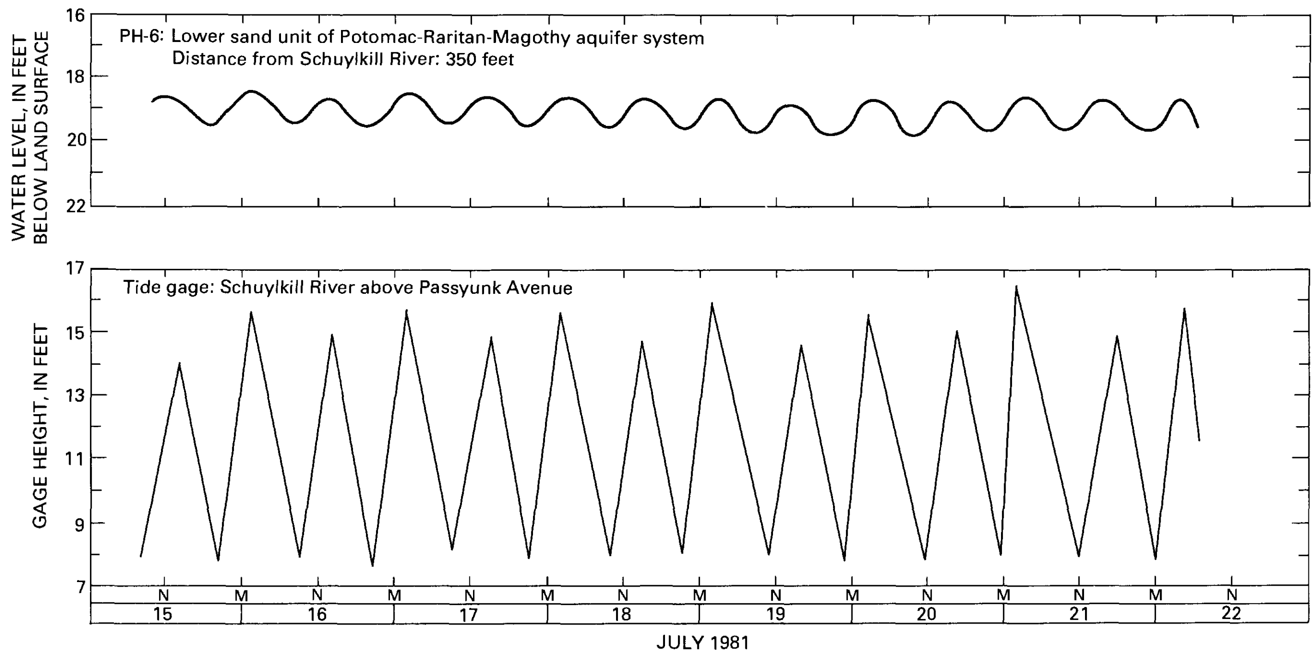


Figure 51. Continued.

Table 7. Summary of effect of river tides on water-level fluctuations in wells

[BK means well located in Bucks County; PH means well located in Philadelphia. A dash indicates lag time not determined]

Local well number[1]	Distance from shoreline (feet)	Average ground-water level fluctuation divided by average tidal fluctuation	Lag time (hours)
		Confined Aquifers	
BK-548	120	0.77	0.65
BK-628	1,700	.02	-
PH-6	350	.14	-
PH-13	1,200	.04	-
PH-19	150	.31	-
PH-20	400	.32	-
PH-30	4,400	.00	-
PH-32	1,000	.05	2.74
PH-77	1,100	.03	-
PH-83	1,500	.13	3.04
PH-143	1,700	.13	-
PH-190	3,000	.01	2.35
PH-242	1,400	.22	-
PH-249	1,500	.20	-
PH-374	350	.38	.47
PH-400	200	.29	1.90
PH-747	400	.26	1.30
		Unconfined Aquifers	
BK-500	30	0.09	0.62
BK-647	120	.03	-
BK-671	300	.03	-
BK-672	200	.04	2.79

[1] Locations of selected wells in Philadelphia are shown in figure 47. For locations of remaining wells, see Greenman and others (1961).

Iron and Manganese

Iron and manganese, which chemically are similar elements, are abundant constituents of the unconsolidated sediments and crystalline rocks of the Philadelphia area. Most of the iron and manganese in ground water is derived from the solution of minerals in the aquifer matrix. Lesser amounts may come from industrial chemical wastes or other manmade sources. Elevated concentration of iron and manganese is a major ground-water-quality problem in Philadelphia, and many wells have been abandoned because of excessive concentrations of these elements.

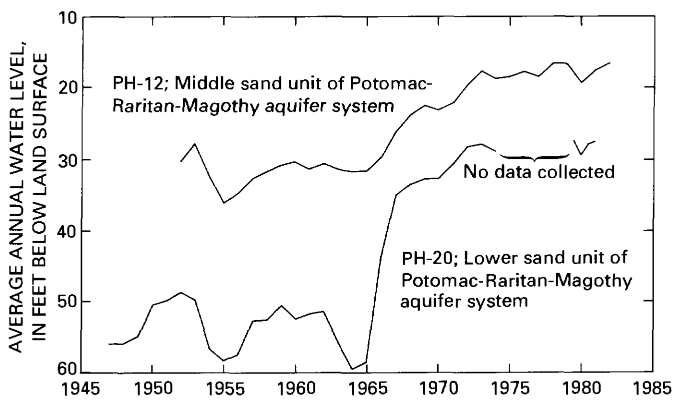


Figure 52. Long-term fluctuations of water levels in observation wells PH-12 and PH-20.

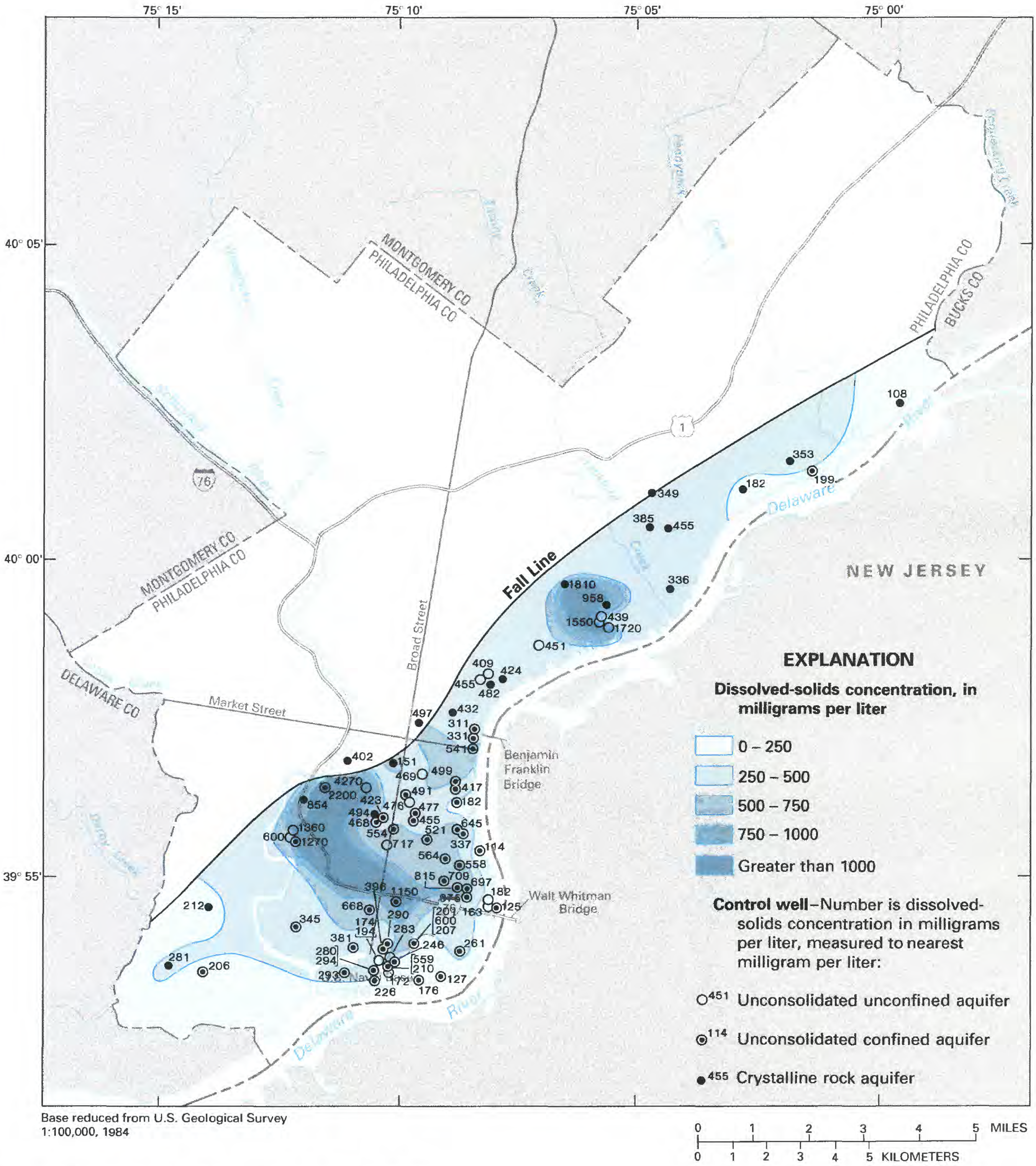


Figure 53. Dissolved-solids concentration, 1945–58.

Even small concentrations of iron and manganese in domestic water supplies are undesirable because they may cause turbidity, stains on plumbing fixtures and laundry, and objectionable taste and color. For these reasons, the U.S. Environmental Protection Agency (1977) recommends maximum drinking water concentrations of 300 μg/L (micrograms per liter) for iron and 50 μg/L for manganese. In industrial water supplies, high concentrations can result

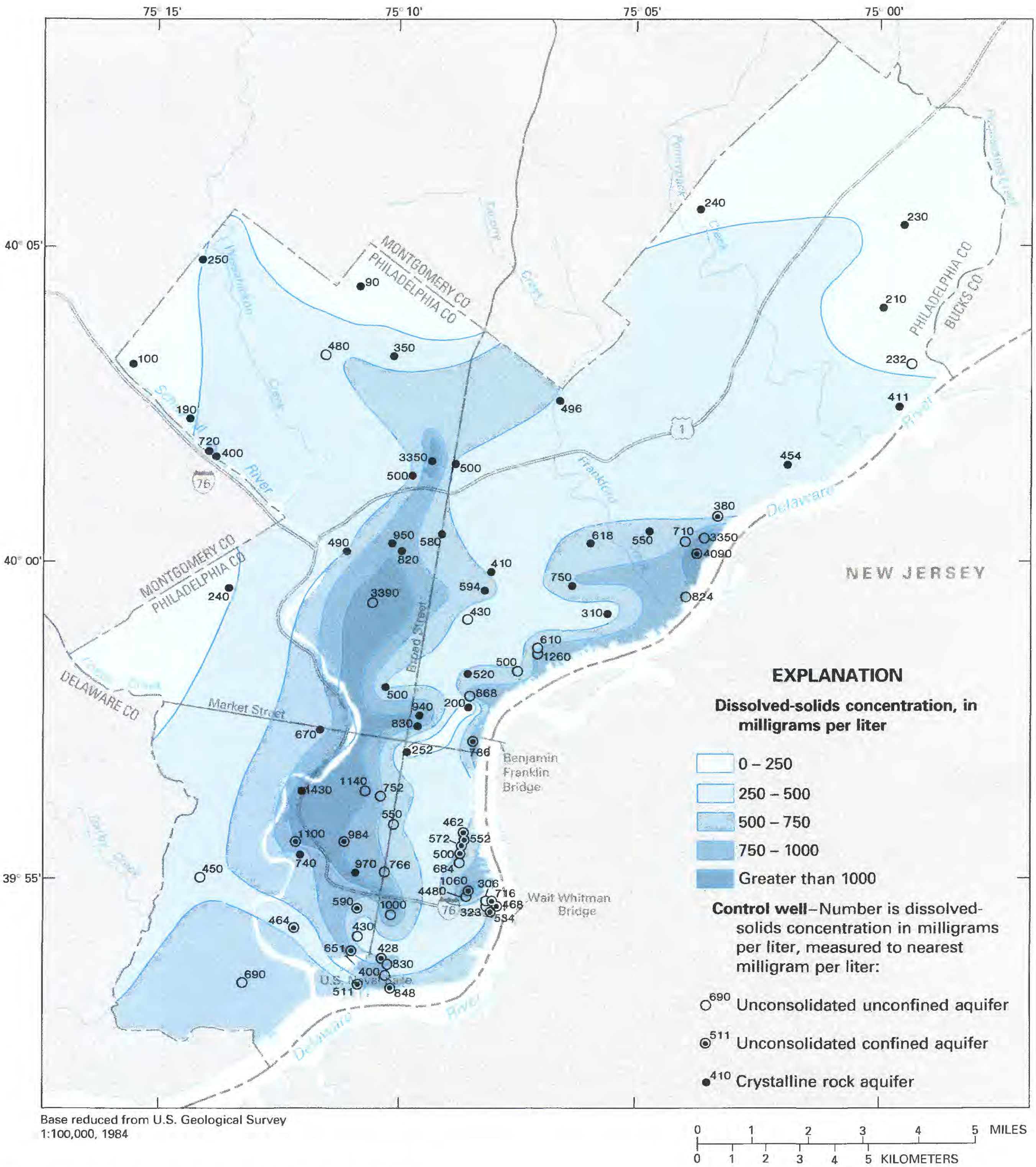


Figure 54. Dissolved-solids concentration, 1979–80.

in insoluble deposits accumulating in pipes and boiler tubes, which restrict flow and decrease the efficiency of heat exchange.

In Philadelphia, ground water commonly contains moderate to high concentrations of iron and manganese; in most places, iron is present in greater amounts than manganese. Typically, the water is clear when first discharged from a well, but soon it becomes cloudy when exposed to the atmosphere. This turbidity is caused by chemical precipitation of iron-bearing compounds. Excessive concentrations of iron and manganese in water can be reduced by oxidation and filtration and ion exchange. These methods are described in table 8. Such treatment generally is expensive and often is incomplete.

Iron

Figure 55 shows the increase in dissolved-iron concentration from 1943 through 1982 in representative water samples from the lower sand unit of the Potomac-Raritan-Magothy aquifer system at the U.S. Naval Base. Although values are not available for several intervening years, figure 55 shows a progressive increase in iron concentration from 0.20 mg/L in 1943 to 30 mg/L in 1979. Chemical reactions involving oxygen and organic substances may have contributed to the significant increase. According to Langmuir (1969a, p. 21), these high concentrations of iron probably result under reducing conditions from leaching of iron-bearing minerals from the aquifer matrix. Microbiological decomposition of organic substances in ground water promotes these reactions by consuming oxygen and lowering the pH of the water. The median concentration of iron in 29 samples of ground water containing no detectable dissolved oxygen was 22 mg/L. The median concentration of iron in 55 samples of ground water containing at least 0.3 mg/L of oxygen was 0.68 mg/L.

In parts of Philadelphia, ground water is isolated from oxygen-enriched recharge water by impervious surfaces and low-permeability clay layers. This situation promotes the development of reducing conditions and the presence of ferrous iron in ground water. Where oxygenated recharge reaches the ground-water reservoir, it reacts with aqueous ferrous iron to produce insoluble ferric hydroxide; however, microbiological activity may deplete the oxygen before it reaches that reservoir. Similarly, when ground water containing ferrous iron is exposed directly to the atmosphere, ferric hydroxide precipitates from solution. Many wells in Philadelphia, including those at the U.S. Naval Base, were abandoned primarily because of problems associated with ferric hydroxide precipitation. Common problems include clogging of well screens, accumulation of deposits in water-distribution systems, and objectionable taste and color of water.

Dissolved-iron concentrations in 127 water samples collected during 1945–58 ranged from 0.02 to 429 mg/L; the average concentration was 13 mg/L. Iron concentrations in 75 percent of the samples exceeded the 0.30-mg/L drinking water standard recommended by the U.S. Environmental Protection Agency (1977). Figure 56 shows that the iron concentration in ground water was 5 mg/L or less, except in a few areas, particularly along the Delaware and lower Schuylkill Rivers. Water in the unconfined aquifers of southern Philadelphia had the highest concentrations; these concentrations are shown separately on the inset map of figure 56. Elsewhere, concentrations did not vary appreciably from aquifer to aquifer. By 1958, many wells were abandoned because of problems caused by excessive concentrations of iron.

Dissolved-iron concentrations in 79 water samples collected during 1979–80 ranged from 0 to 220 mg/L. The average concentration was 17 mg/L, an increase of nearly 30 percent over the average concentration during 1945–58. Iron concentrations in 71 percent of the samples exceeded 0.30 mg/L. Figure 57 shows that except for higher concentrations in areas along the Delaware and lower Schuylkill Rivers, iron concentrations in ground water generally were less than 5 mg/L. Comparison of this map with the map of dissolved-iron concentrations during 1945–58 (fig. 56) shows the expansion over time of areas affected by high concentrations. Differences in head caused by withdrawals from the confined aquifers in Philadelphia and nearby parts of New Jersey caused water containing high concentrations of iron to flow downward from the unconfined aquifer system into the confined aquifers. Consequently, iron concentrations in ground water in Philadelphia, particularly in the unconsolidated sediments, now differ little with depth.

Concentrations of iron are elevated in water from wells in parts of New Jersey adjacent to southern Philadelphia. This suggests that water from the lower sand unit in the vicinity of the U.S. Naval Base is migrating beneath the Delaware River into New Jersey.

Manganese

Figure 58 shows the change in dissolved-manganese concentration from 1945 through 1982 in representative water samples from the lower sand unit of the Potomac-Raritan-Magothy aquifer system at the U.S. Naval Base. The graph shows relatively stable concentrations of about 500 μg/L from 1945 through 1973, followed by an increase to a maximum concentration of greater than 4,000 μg/L in 1980. Manganese concentrations increased over time much the same as iron concentrations (fig. 55), although somewhat more slowly.

Dissolved-manganese concentrations in 58 water samples collected during 1945–58 ranged from 0 to 2,900 μg/L; the average concentration was 190 μg/L. Of these samples, 21 percent had manganese concentrations exceeding the 50-μg/L drinking water standard recommended by the U.S. Environmental Protection Agency (1977). Concentrations did not differ significantly from aquifer to aquifer. Figure 59 shows that, except for higher concentrations in a few parts of southern Philadelphia, manganese concentrations in ground water generally were less than 50 μg/L.

Table 8. Selected methods of removing and reducing concentrations of chemical constituents in water

[Modified from Hobba, 1976]

Constituent	Symptoms	Treatment processes
Iron (Fe)	Forms reddish-brown stains on plumbing fixtures and laundry. May impart objectionable taste to food and beverages. A slimy deposit indicates the presence of iron bacteria.	1. Oxidation and filtration--aeration of water or treatment with chloride or potassium permanganate converts most Fe and Mn to insoluble precipitates which can then be removed by sedimentation and filtration. Aeration commonly is used when the water contains little organic matter; chemical agents are utilized when large amounts of organic material are present, as in ground water containing iron bacteria. The water to be treated should be made alkaline before Fe or Mn removal is attempted.
Manganese (Mn)	Same objectionable symptoms as iron, but generally forms brown or black stains. Removal is more difficult and commonly is less complete than for iron.	2. Oxidation and filtration through manganese greensand--the greensand liberates oxygen which in contact with the water produces insoluble iron hydroxide and manganese oxide. When the available oxygen supply has been exhausted, the greensand is regenerated by backflushing a potassium permanganate solution through it.
		3. Ion exchange--zeolite minerals or synthetic resin beads exchange sodium (Na) ions in their structure for Ca, Mg, Fe, and Mn ions in the water. When their exchange capacity has been exhausted, they are regenerated by backflushing with a strong sodium chloride solution. The resin beads have a greater exchange capacity than the zeolite minerals.
Hardness, Calcium (Ca), and Magnesium (Mg)	Forms scale in cooking utensils, pipes, and plumbing fixtures; consumes soap.	1. Lime-soda treatment--chemical reactions convert most Ca and Mg to insoluble calcium carbonate and magnesium hydroxide. The resulting precipitate can then be removed by sedimentation and filtration.
		2. Ion exchange - see above.
Sulfate (SO_4)	Has bitter taste, may have laxative effect, and usually is corrosive.	Demineralization by ion exchange--resin beads remove nearly all dissolved chemical species by ion exchange. Treatment cost is relatively high for water containing more than 2,500 mg/L dissolved solids.
Chloride (Cl)	Has salty taste and usually is corrosive.	
Volatile Organic Compounds (VOCs)	At low concentrations in water, the chlorinated aliphatic compounds essentially are odorless whereas the aromatic compounds may have a detectable odor. At very high concentrations, the VOCs may form a phase visibly distinguishable from the water.	1. Aeration--water and air are brought into contact with each other to transfer volatile substances from the water. The rate at which a volatile organic compound is removed from water by aeration depends on the air/water ratio, contact time, air and water temperature, contact area, and the chemical properties of the compound.
		2. Adsorption by granular activated carbon (GAC)--water and GAC are brought into contact with each other to transfer VOCs to the GAC. However, the effectiveness of GAC for removing the volatiles depends on the types of organic compounds in the water. For example, unsaturated organic compounds such as ethylenes may be adsorbed on GAC more readily than saturated compounds such as ethanes.

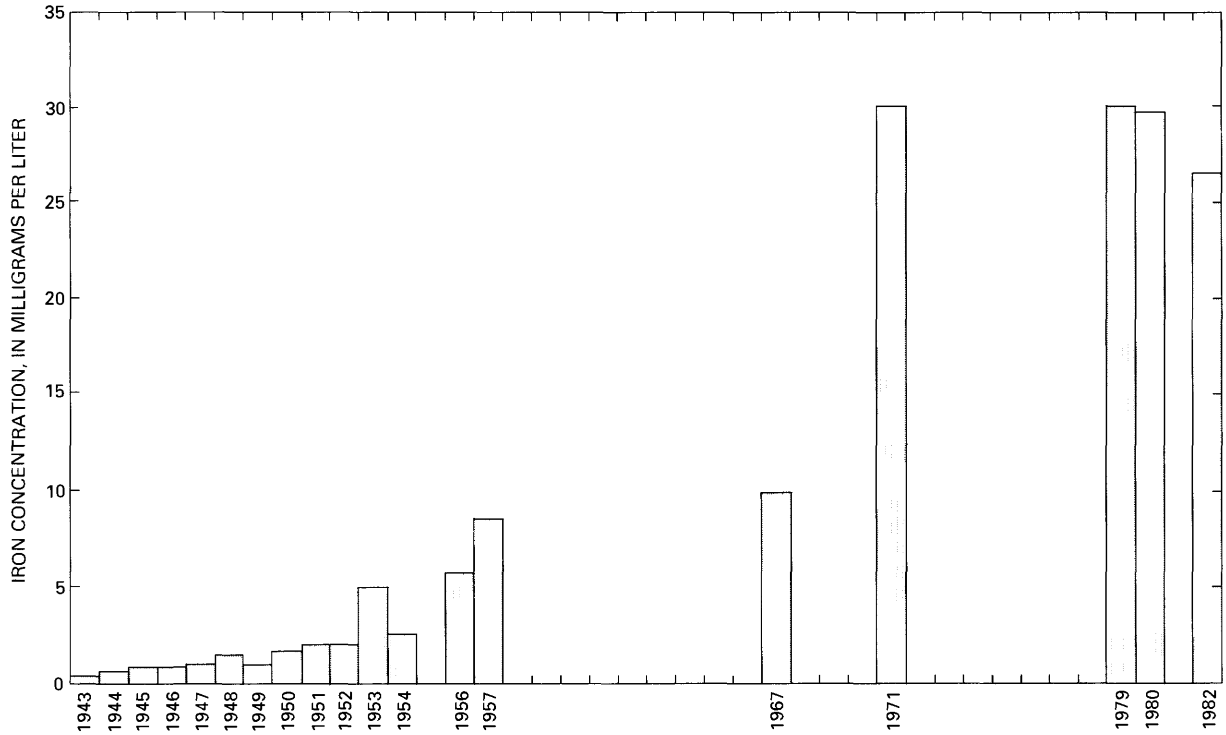


Figure 55. Concentration of dissolved iron in water from the lower sand unit of the Potomac-Raritan-Magothy aquifer system at the U.S. Naval Base, 1943–82.

Dissolved-manganese concentrations in 79 water samples collected during 1979–80 ranged from 0 to 31,000 μg/L. The average concentration was 1,700 μg/L, which is about nine times greater than the average for 1945–58. Of these samples, 78 percent had manganese concentrations greater than 50 μg/L. Figure 60 shows the prevalence of ground water having manganese concentrations in excess of 50 μg/L, particularly in eastern, central, and southern Philadelphia. Comparison of this map with the map of dissolved-manganese concentrations during 1945–58 (fig. 59) shows the expansion of the area affected by elevated concentrations of manganese. Chemical reactions involving oxygen and organic substances in ground water may leach manganese from the aquifer matrix, thereby increasing its concentration. In the Coastal Plain, hydraulic gradients between the unconfined and confined aquifers resulted in the downward flow of water containing elevated concentrations of manganese. Consequently, manganese concentrations in ground water in that part of Philadelphia vary little with depth.

Sulfate

Sulfide minerals, chiefly pyrite and marcasite, are relatively common in the unconsolidated sediments of the Philadelphia area (Langmuir, 1969b, p. 225). Where oxygenated recharge water comes in contact with these minerals, sulfide ions are oxidized to sulfate ions that can dissolve in ground water. Smaller amounts of sulfate in ground water may be products of weathering of crystalline rocks. In addition, some of the sulfate probably originates from sewage and industrial chemical wastes.

Elevated sulfate concentrations in drinking water are undesirable because they cause a bitter taste and may have a laxative effect. For these reasons, the U.S. Environmental Protection Agency (1977) recommends a maximum concentration in drinking water of 250 mg/L. Elevated concentrations in industrial water supplies are undesirable because the sulfate may cause corrosion or may react with calcium to form insoluble scale in boilers. Ground water in Philadelphia commonly contains moderate concentrations of sulfate; however, concentrations may be elevated locally. Excessive concentrations of sulfate can be reduced by ion exchange (table 8).

Figure 61 shows the change in dissolved-sulfate concentration from 1942 through 1982 in representative water samples from the lower sand unit of the Potomac-Raritan-Magothy aquifer system at the U.S. Naval Base. Although data on sulfate concentrations are not available for several intervening years, figure 61 shows a progressive increase in sulfate concentration from 2.8 mg/L in 1942 to 82 mg/L in 1956, fairly stable concentrations of about 100 mg/L during 1967–73, and a peak concentration of 185 mg/L in 1979.

Dissolved-sulfate concentrations in 138 water samples collected during 1945–58 ranged from 2 to 1,340

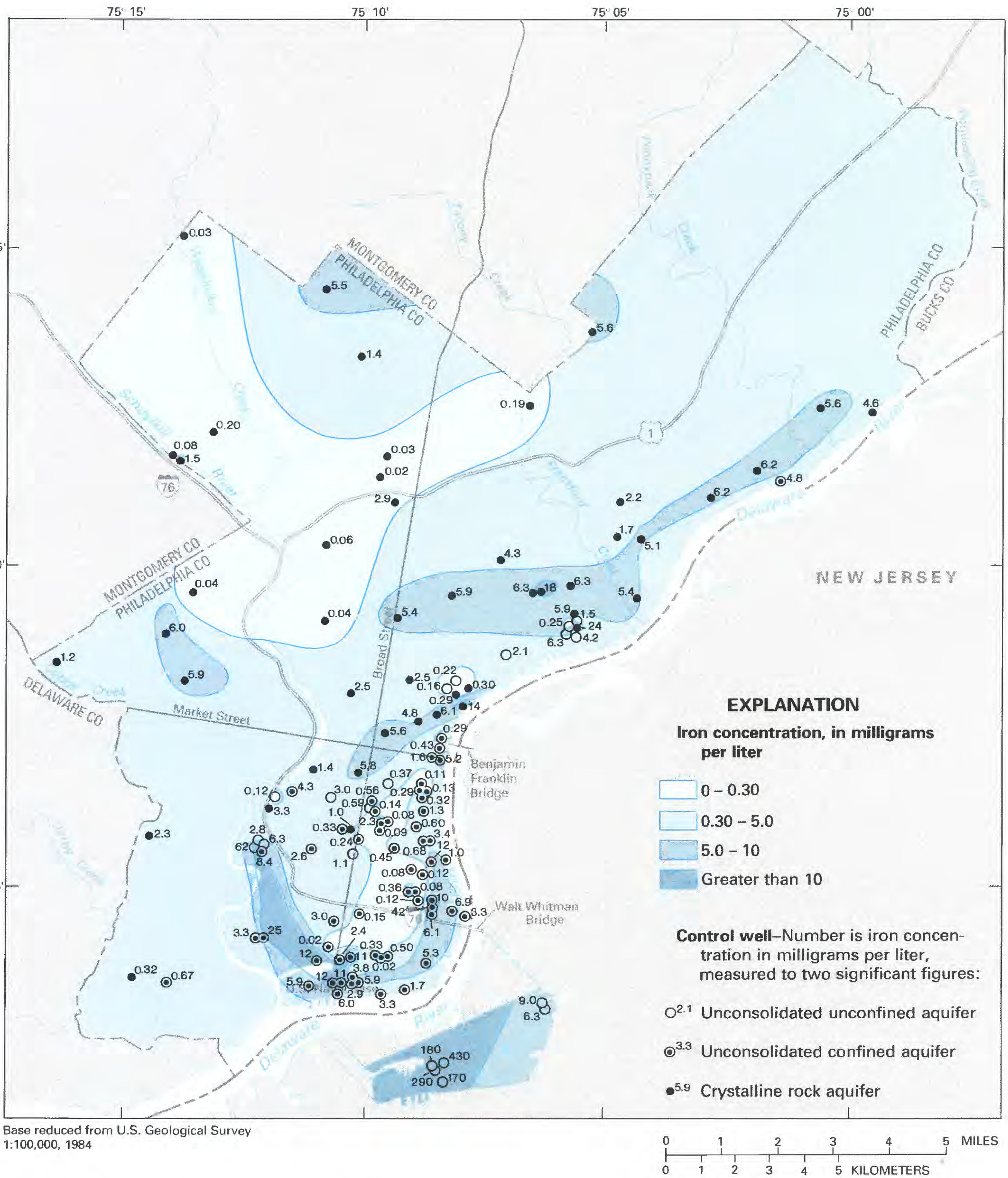


Figure 56. Dissolved-iron concentration, 1945–58.

mg/L; the average concentration was 148 mg/L. More than 12 percent of these samples had sulfate concentrations exceeding 250 mg/L. Average concentrations in all the aquifers were similar. Figure 62 shows that most ground water had a sulfate concentration of less than 250 mg/L except in relatively small parts of southern and north-central Philadelphia. Water in the affected part of southern Philadelphia (fig. 62) was contaminated by chemical wastes

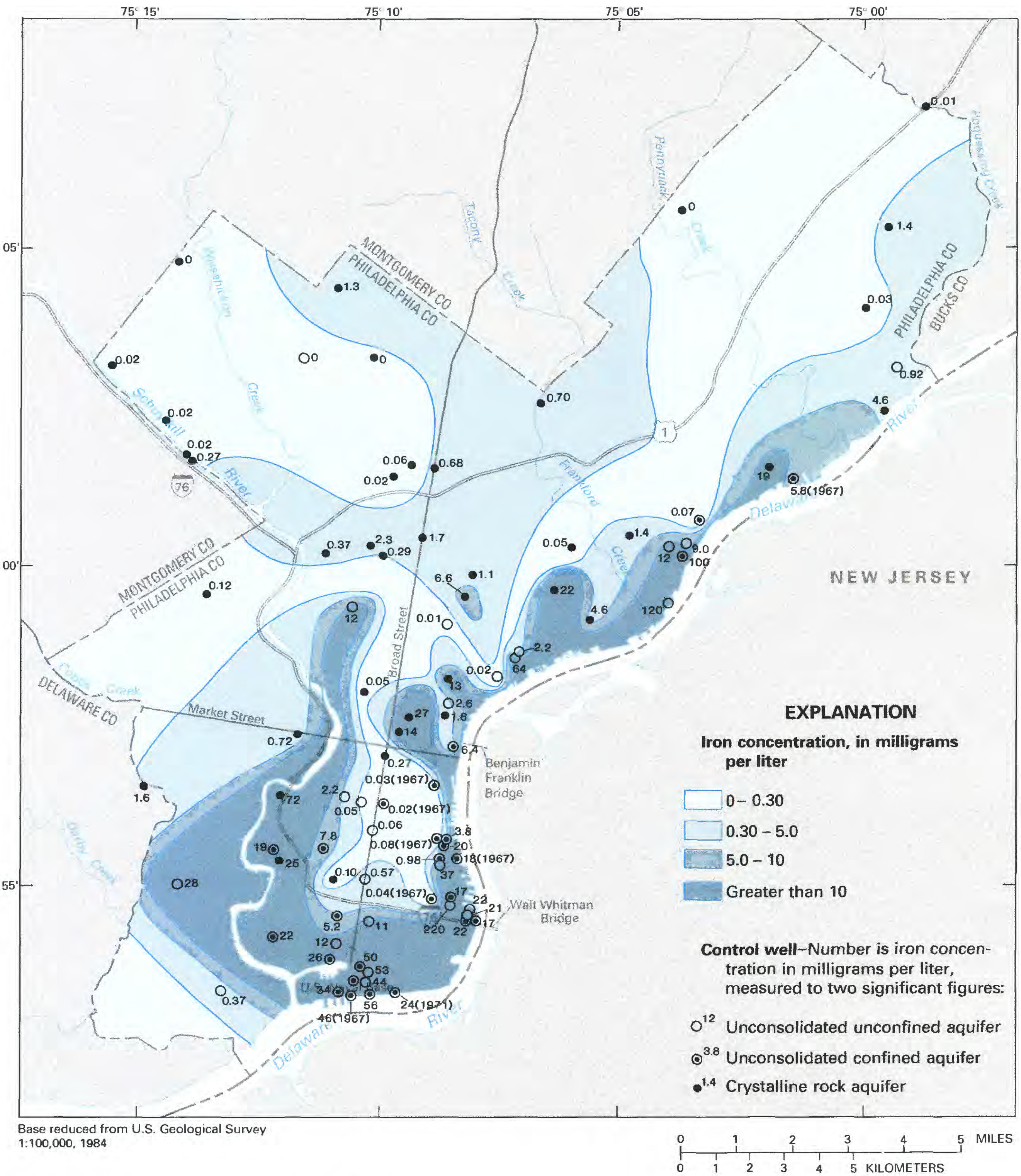


Figure 57. Dissolved-iron concentration, 1979–80.

originating from industrial sources near the Schuylkill River (Greenman and others, 1961, p. 70–74). After the wastes reached the ground-water system, they migrated toward the southeast, resulting in an elongated plume of contaminated water. This migration can explain the increase in sulfate concentration over time at the U.S. Naval Base (fig. 61), which is downgradient from these sources. Elevated concentrations in the affected part of north-central Philadelphia

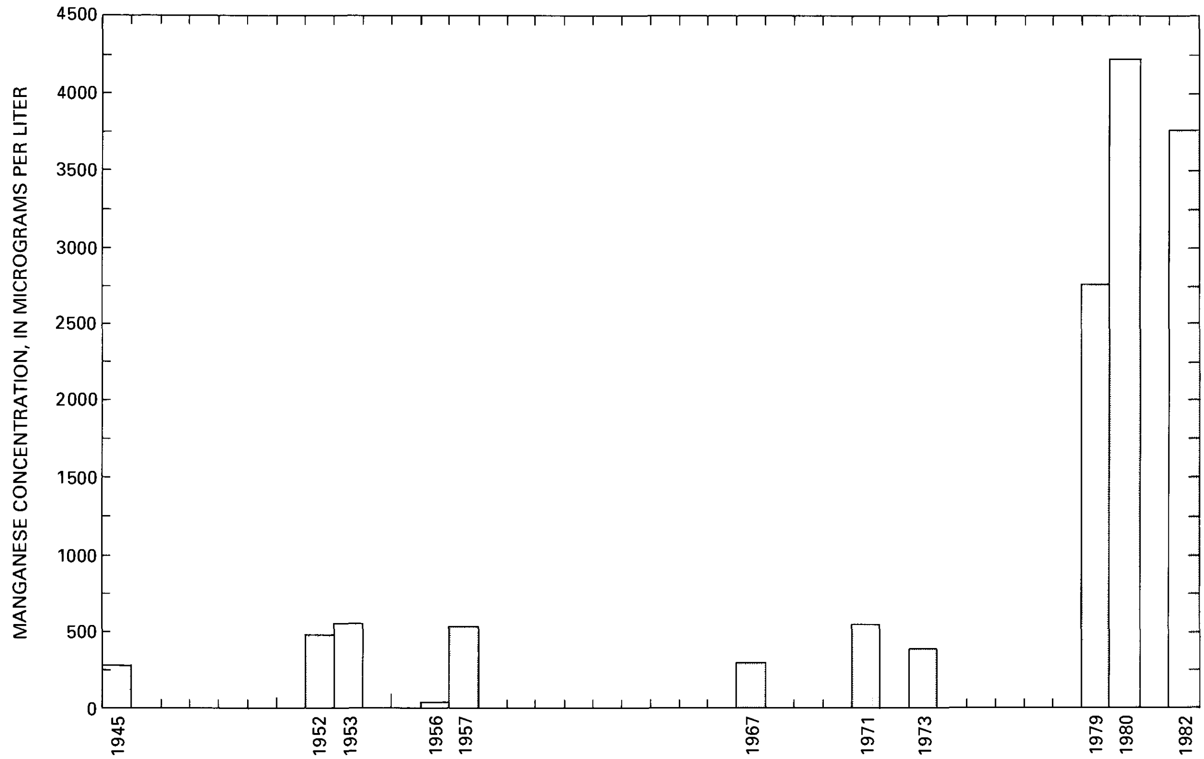


Figure 58. Concentration of dissolved manganese in water from the lower sand unit of the Potomac-Raritan-Magothy aquifer system at the U.S. Naval Base, 1945–82.

(fig. 62) probably were caused by industrial chemical wastes and sewage.

Dissolved-sulfate concentrations in 79 water samples collected during 1979–80 ranged from 0.9 to 2,200 mg/L. The average concentration was 161 mg/L, an increase of about 9 percent over the average for 1945–58. Figure 63 shows that during the later period, sulfate concentrations commonly were less than 250 mg/L. About 11 percent of these samples had sulfate concentrations greater than 250 mg/L. Comparison of this map with the map of dissolved-sulfate concentrations during 1945–58 (fig. 62) shows a significant reduction in the size of the contaminated area in southern Philadelphia. Flushing of sulfate-contaminated water from the aquifers, dilution, and decrease of source concentration likely have contributed to the reduction.

Nutrients

Phosphorus and nitrogen are elements necessary for plant growth. Phosphorus is not prevalent in most ground water. Water from only 4 of 91 wells had more than 1 mg/L of either total phosphorus or dissolved orthophosphorus. The median concentration of total phosphorus was 0.032 mg/L.

The principal nitrogen species present in ground water are nitrite, organic nitrogen, ammonium, and nitrate. Nitrite is present in very low concentrations—the median concentration in water from 81 wells and drainage sumps was 0.01 mg/L, and only one sample had a concentration greater than 0.12 mg/L. Organic nitrogen also is present in relatively small amounts; the median concentration in water from 78 wells and sumps was 0.91 mg/L, and water from only 10 percent of the sites contained more than 3 mg/L.

Ammonium and nitrate have similar median concentrations. Ammonium (as nitrogen) concentrations exceeded 10 mg/L in water from 5 of 80 wells and sumps. These five sites are in the upper and lower sand units of the Potomac-Raritan-Magothy aquifer system and the Trenton gravel. The median concentration of ammonium was 0.35 mg/L for 39 sites in the Wissahickon Formation, 2.1 mg/L for 18 sites in the lower sand unit, and 1.6 mg/L for 19 sites in the Trenton gravel.

Nitrate (as nitrogen) concentrations exceeded 10 mg/L in water from 17 of 195 wells and sumps. One of these sites was in hornblende gneiss, 12 were in the lower sand unit, and 4 were in the Trenton gravel. The median concentration of nitrate was 0.37 mg/L for water from 78 sites in the Wissahickon Formation, 3.2 mg/L for 71 sites in the lower sand unit, and 1.1 mg/L for 36 sites in the Trenton gravel.

Generally, ground water containing no detectable dissolved oxygen has very high ratios of ammonium to

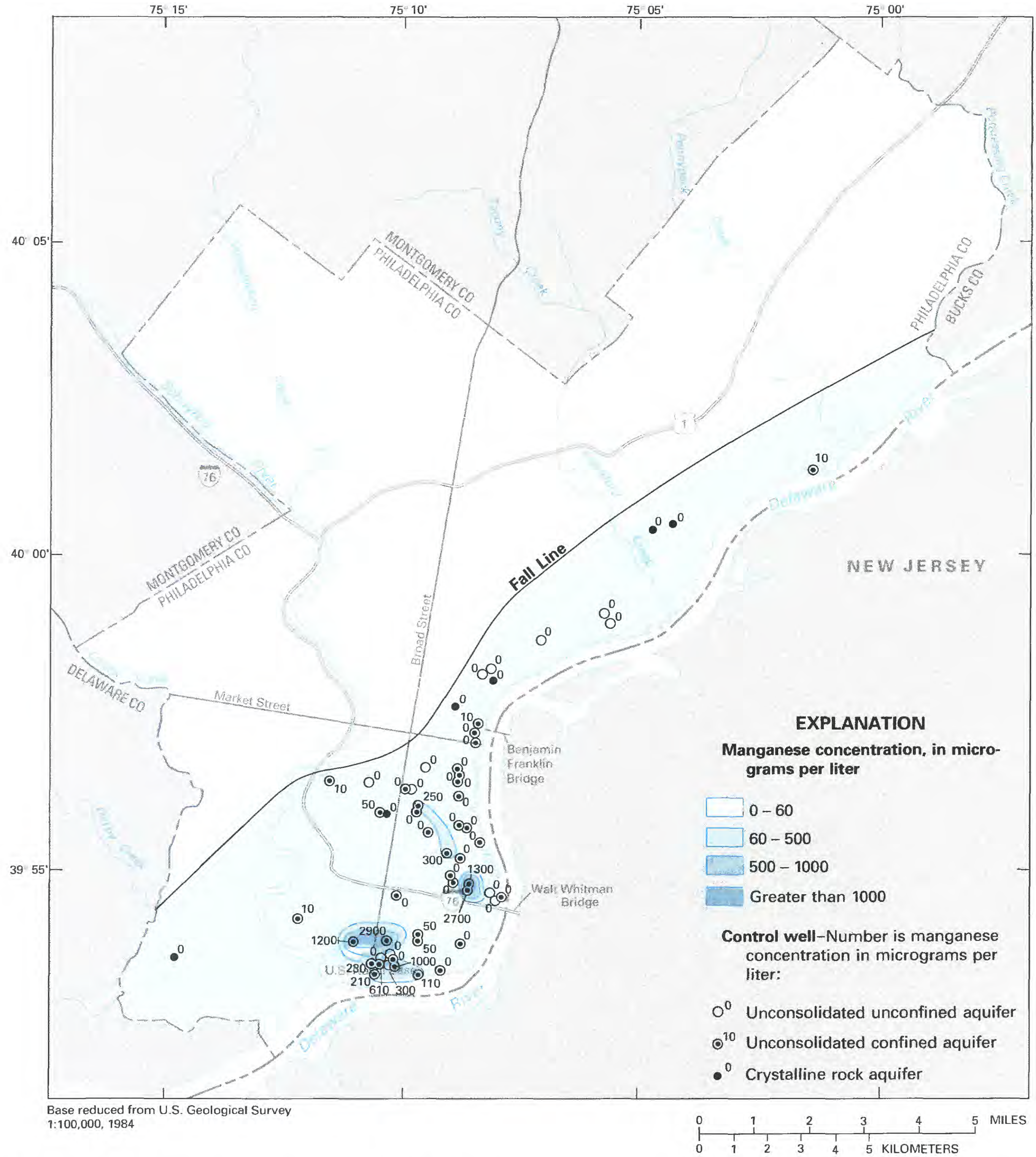
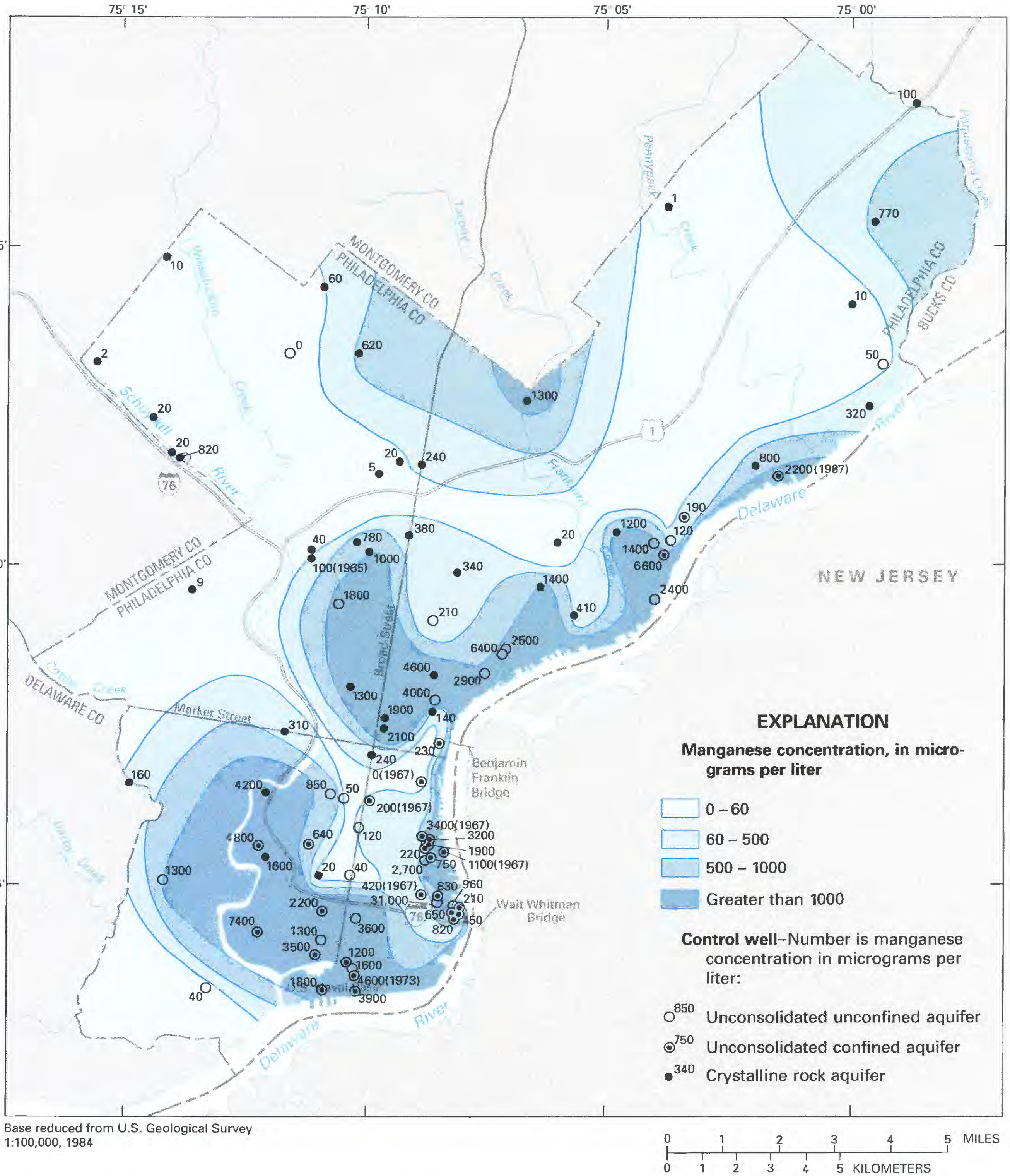


Figure 59. Dissolved-manganese concentration, 1945-58.

nitrate—the median ratio for 19 samples containing more than 1 mg/L of ammonium plus nitrate was 165 parts of ammonium (as nitrogen) to 1 part of nitrate (as nitrogen). A strong reducing environment in the aquifer is indicated where most of the nitrogen is present as ammonium. Conversely, ground water containing any measurable amount of oxygen (more than about 0.3 mg/L) has low ratios of ammonium to nitrate—the median ratio for 40



Base reduced from U.S. Geological Survey 1:100,000, 1984

Figure 60. Dissolved-manganese concentration, 1979-80.

samples containing more than 1 mg/L of ammonium plus nitrate was 0.28 part of ammonium to 1 part of nitrate. Because some types of water treatment can convert ammonium to nitrate, concentrations of nitrate in treated water may be much higher than in raw water in which ammonium is the dominant nitrogen species.

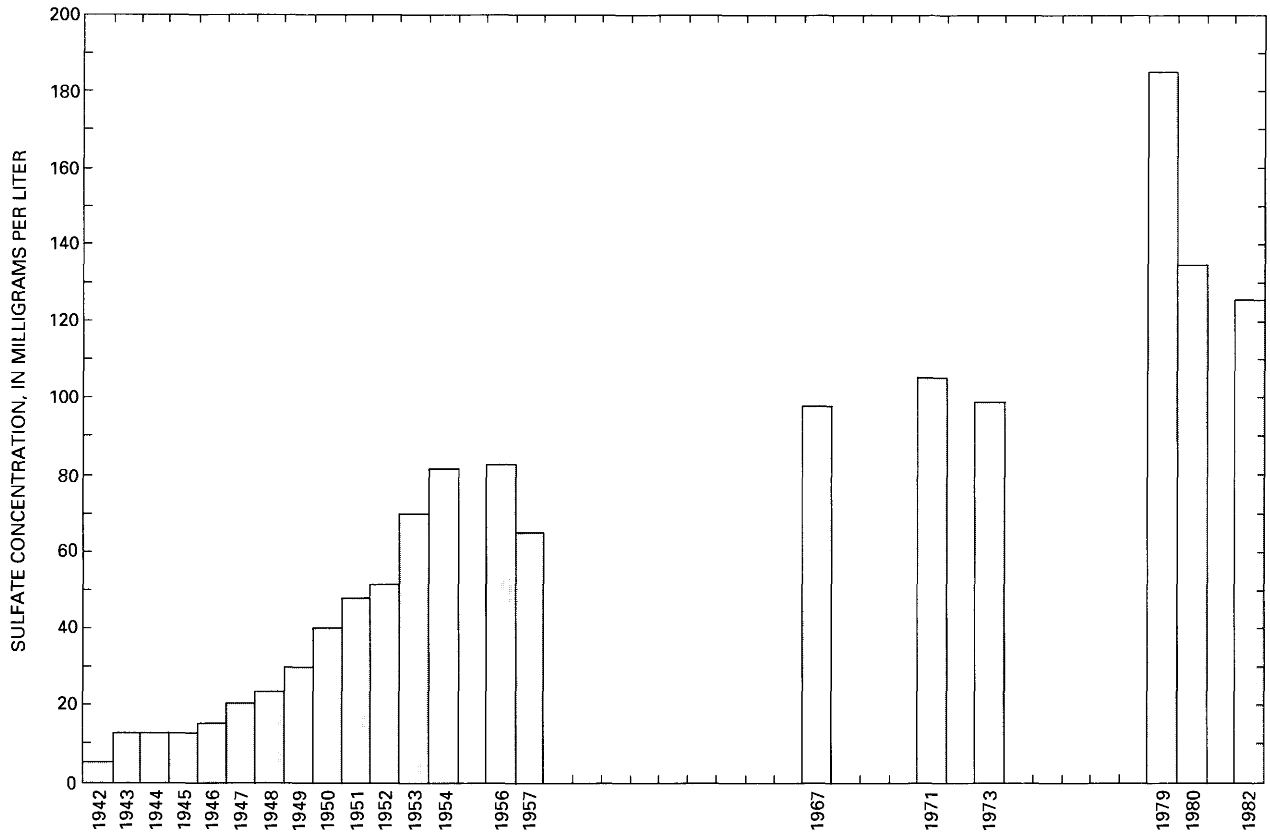


Figure 61. Concentration of dissolved sulfate in water from the lower sand unit of the Potomac-Raritan-Magothy aquifer system at the U.S. Naval Base, 1942–82.

Trace Elements

Trace elements are those chemical species that commonly are present at low concentrations in natural environments. Usually, concentrations in ground water are low because of adsorption of trace elements, particularly by clay minerals and organic matter in the aquifer matrix. Because some trace elements are known to be detrimental to human health, even at low concentrations, limits on concentration have been established by various public health agencies.

Except in localized areas, ground water in Philadelphia contains undetectable or low concentrations of trace elements. During 1979–80, 103 water samples were analyzed for one or more of the following dissolved trace elements: arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, lead, lithium, mercury, nickel, selenium, strontium, and zinc (Paulachok and others, 1984, table 5). Except for those shown in table 9, trace-element concentrations did not exceed the water-quality criteria established by the U.S. Environmental Protection Agency (1977).

Table 9. Summary of trace-element concentrations that exceeded U.S. Environmental Protection Agency drinking water standards

[µg/L, micrograms per liter]

Trace element	Drinking water standard, in µg/L	Number of analyses	Number that exceeded standard	Percentage that exceeded standard
Cadmium	10	103	1	0.97
Chromium	50	91	2	2.2
Mercury	2	76	13	17

Figure 64 shows concentrations of cadmium, chromium, and mercury in ground water at sites where the concentrations exceeded drinking water standards. In general, these sites are in industrialized areas. The relatively high concentrations of trace elements probably have been caused by leaks or spills of industrial chemicals and waste products.

Volatile Organic Compounds

Volatile organic compounds are a group of manmade chemical substances used extensively for synthesizing other chemicals and as industrial solvents. Examples of such compounds are benzene, carbon tetrachloride, chloroform, and trichloroethylene. These substances do not occur naturally in ground water; rather, they enter the ground-water system as a result of disposal practices, leaks, and spills. At the land surface, many of these compounds volatilize (vaporize) and diffuse into the atmosphere. If volatile

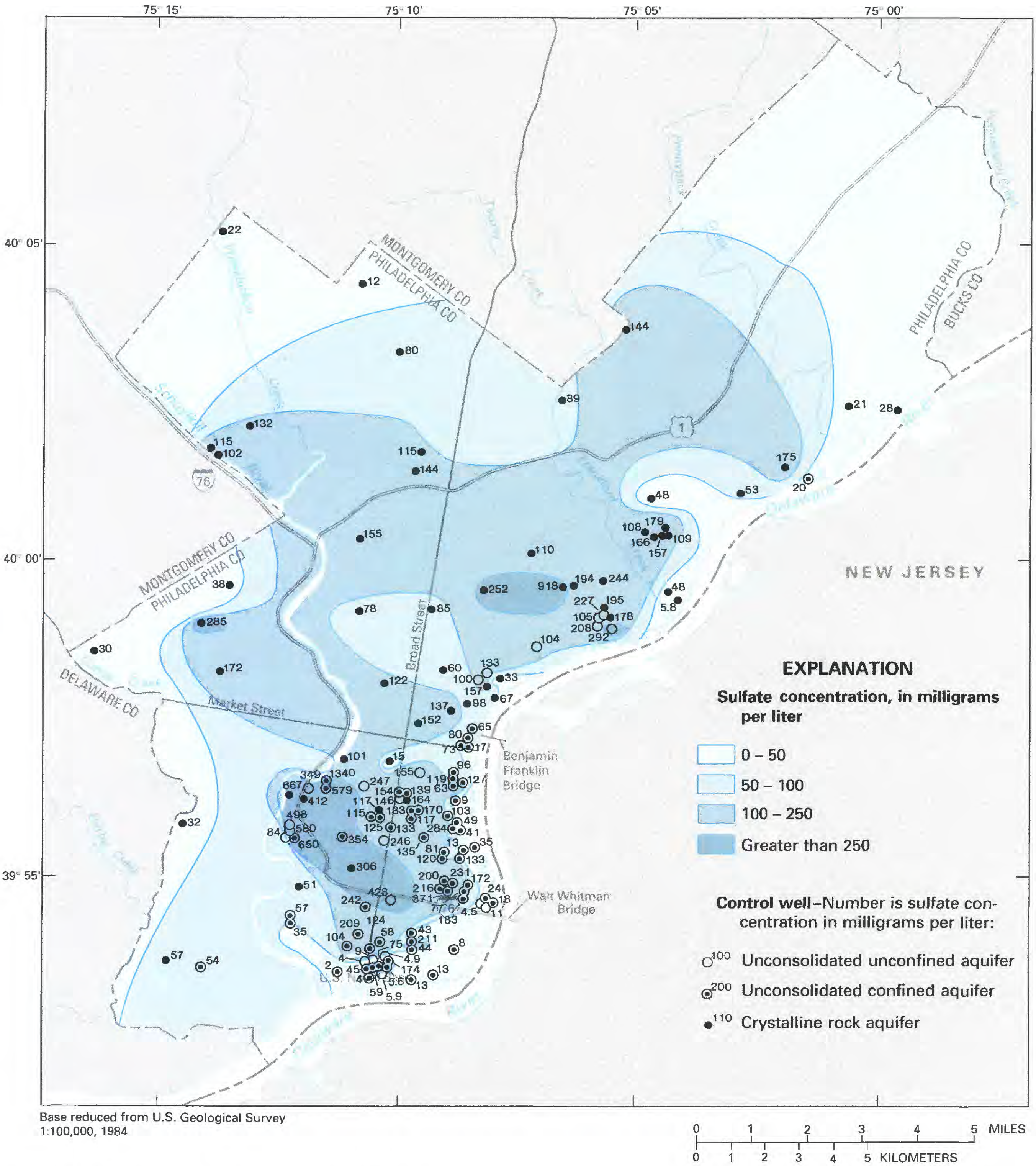


Figure 62. Dissolved-sulfate concentration, 1945–58.

organic compounds make their way into the unsaturated zone, the processes of adsorption, biological and chemical degradation, and biological uptake may inhibit their downward migration. The most effective of these attenuation processes is adsorption of compounds on the mineral surfaces of the sediment or rock matrix. However, none of these processes reduces concentrations rapidly in the saturated zone.

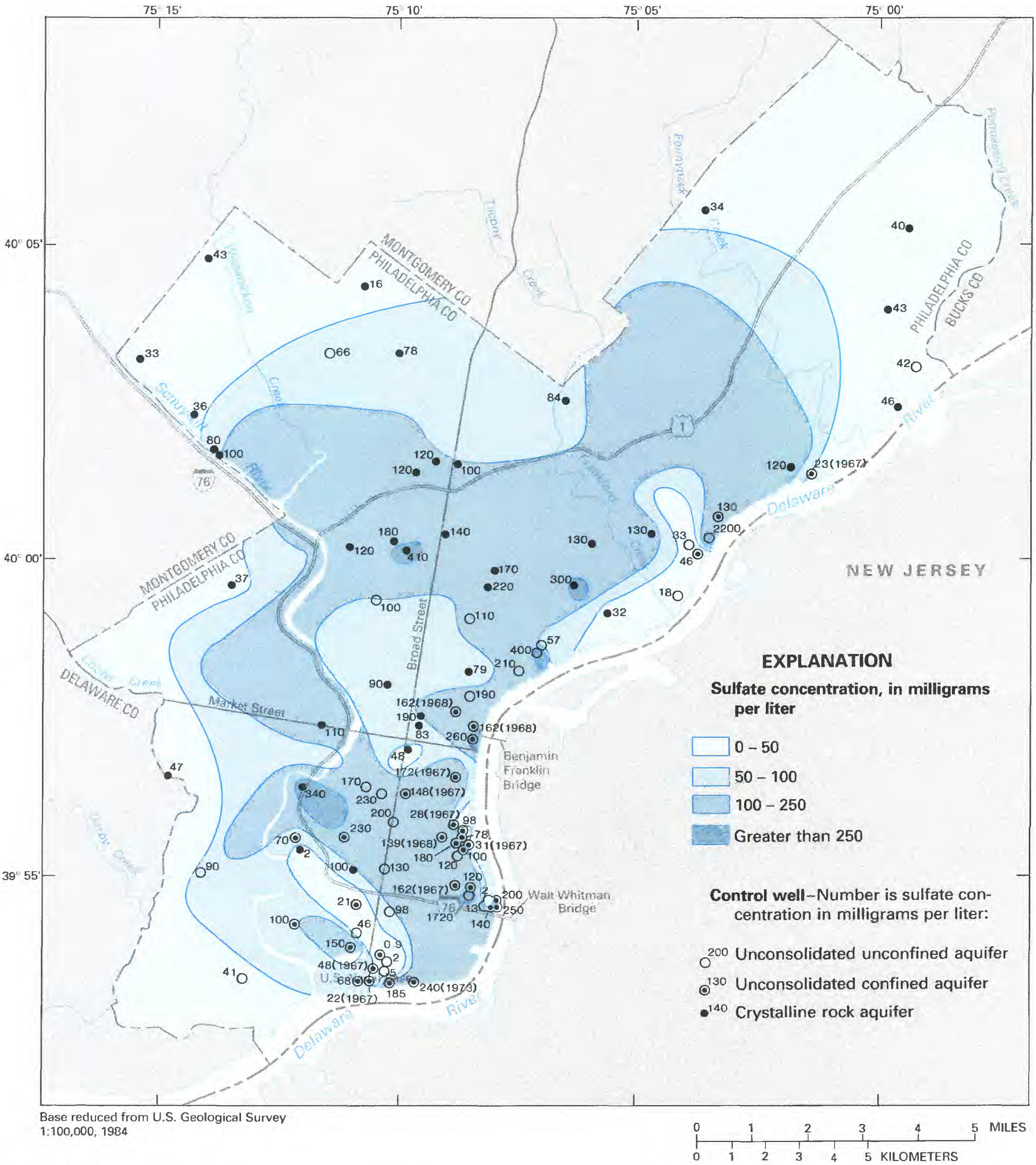


Figure 63. Dissolved-sulfate concentration, 1979-80.

During 1979–80, 68 water samples were analyzed for several or all of 14 selected volatile organic compounds noted in a companion report (Paulachok and others, 1984, table 6). The analytical data are summarized in table 10. The analyses show that ground water in Philadelphia commonly contains low concentrations of these substances except in localized areas of contamination. Chloroform, 1,2-dichloroethane, 1,1,2-tetrachloroethylene, 1,1,1-tri-

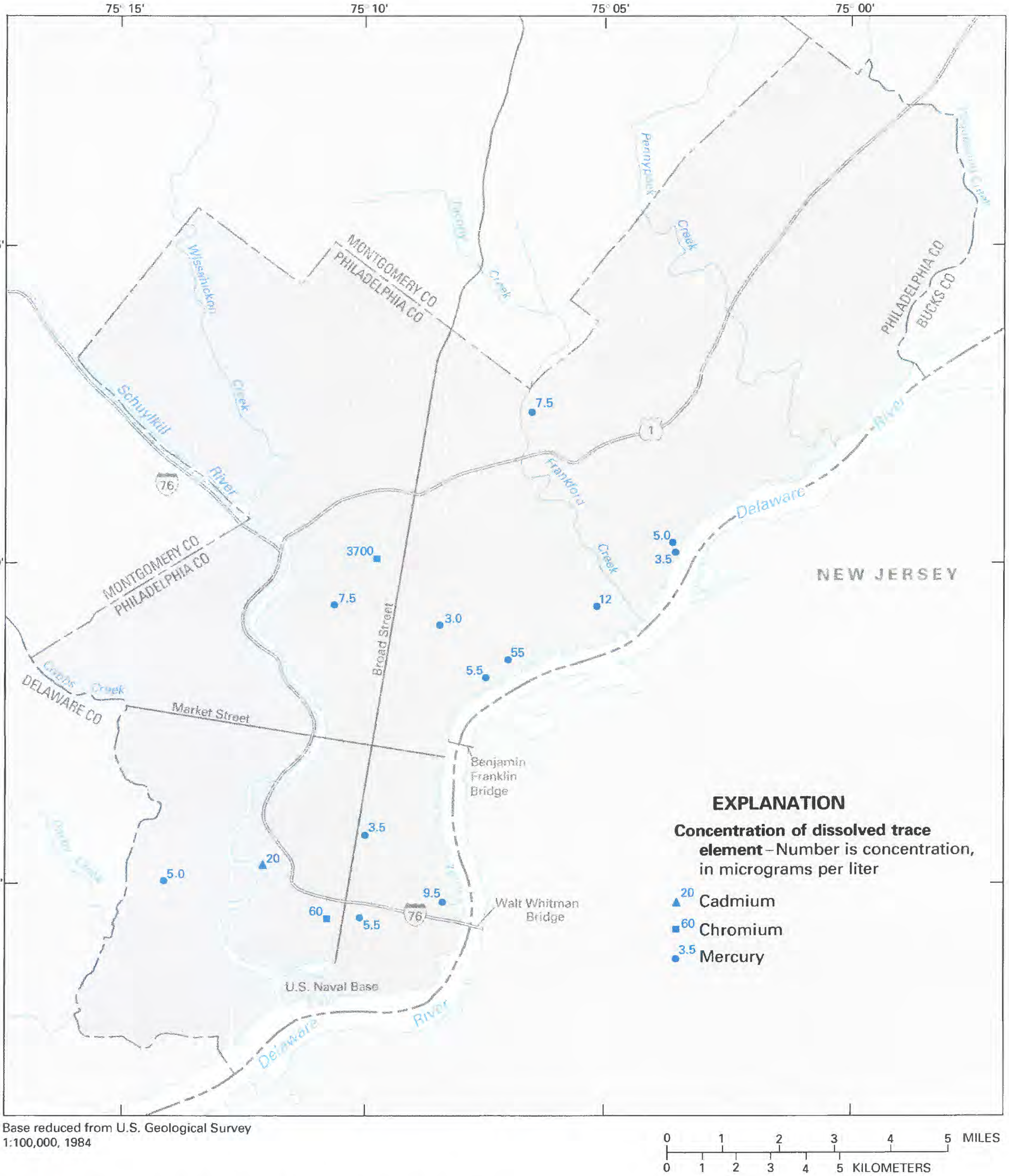


Figure 64. Concentration of selected trace elements, 1979–80.

chloroethane, and trichloroethylene were the most commonly detected volatile organic compounds.

Because many volatile organic compounds are toxic at low concentrations and are known or suspected carcinogens, their complete absence in drinking water is desirable. A limit of 0.10 mg/L has been established for total trihalomethanes (the sum of concentrations of the volatile organic compounds bromoform, chlorodibromomethane, chloroform, and dichlorobromomethane) in a drinking water supply (U.S. Environmental Protection Agency, 1986). Total trihalomethanes did not exceed this limit in any of the water samples analyzed for this study.

Excessive concentrations of volatile organic compounds in water can be reduced by aeration and adsorption on granular activated carbon (table 8). The effectiveness of the latter method depends on the types of organic compounds present, however. Conventional water-treatment processes such as flocculation, clarification, and filtration do not remove volatile organic compounds to any appreciable degree (Dyksen, 1982).

Figure 65 shows the concentration of phenols and selected volatile organic compounds in ground water during 1979–80. Affected sites are citywide, with highest concentrations in industrialized parts of north-central Philadelphia. The elevated concentrations probably result from leaks or spills of chemical products; however, the extent of the areas affected is not known.

Temperature

Table 11 summarizes statistical data on ground-water temperatures. Water temperatures in the shallow aquifers vary more than those in the deep aquifers. Temperatures in the shallow aquifers are less uniform because the shallow ground water is affected more by seasonal climatic variations and local heat production than is water in the deep aquifers.

Heat production by human activities has raised ground-water temperatures in many parts of Philadelphia, as shown by temperatures of 98 water samples and logs of 40 wells measured during 1979–80. Most sample temperatures were higher than the local mean annual air temperature of 12.6 °C, and many logs show cooling trends with depth, or anomalous gradients. Heating of surface and shallow subsurface materials likely has caused the elevated temperatures and anomalous gradients. Solar radiation on concrete and asphalt surfaces, fossil-fuel combustion, and thermal losses from buried pipelines containing steam and process chemicals are the chief sources of heat.

The contours in figure 66 are based on 81 temperature measurements, 2 of which were made in adjoining parts of Bucks and Delaware Counties. Mean temperature is shown if more than one measurement was made at a particular site. The map shows that the lowest temperatures are in the wooded and less urbanized northern and western localities, whereas the highest are in the densely urbanized north-central and south-central areas. Cells of anomalously warm water (20 to 25 °C) are present in several industrialized areas. Although the median depth of wells in the crystalline rocks is considerably greater than that in the unconsolidated

Table 10. Summary of data on concentration of volatile organic compounds
[μg/L, microgram per liter; <, less than]

Volatile organic compound	Range of concentration, in μg/L. Smaller value is detection limit	Number of analyses	Number that exceeded detection limit	Percentage that exceeded detection limit
Benzene	<1.0-18	12	2	17
Bis 2-chloroethylether	<.10-2.1	48	1	2
Bromoform	<.10-.30	57	4	7
Carbon tetrachloride	<.10-35	67	7	10
Chlorobenzene	<.10-320	57	17	30
Chlorodibromomethane	<.10-2.1	67	6	9
Chloroform	<.10-36	68	49	72
Dichlorobromomethane	<.10-2.7	67	26	39
1,2-dichloroethane	<.10-50	67	40	60
1,2-dichloropropane	<.10-30	57	29	51
Methylene chloride	<.10-2.7	59	24	41
1,1,2-tetrachloroethylene	<.10-650	68	46	68
1,1,1-trichloroethane	<.10-570	57	42	74
Trichloroethylene	<.10-3,700	68	43	63

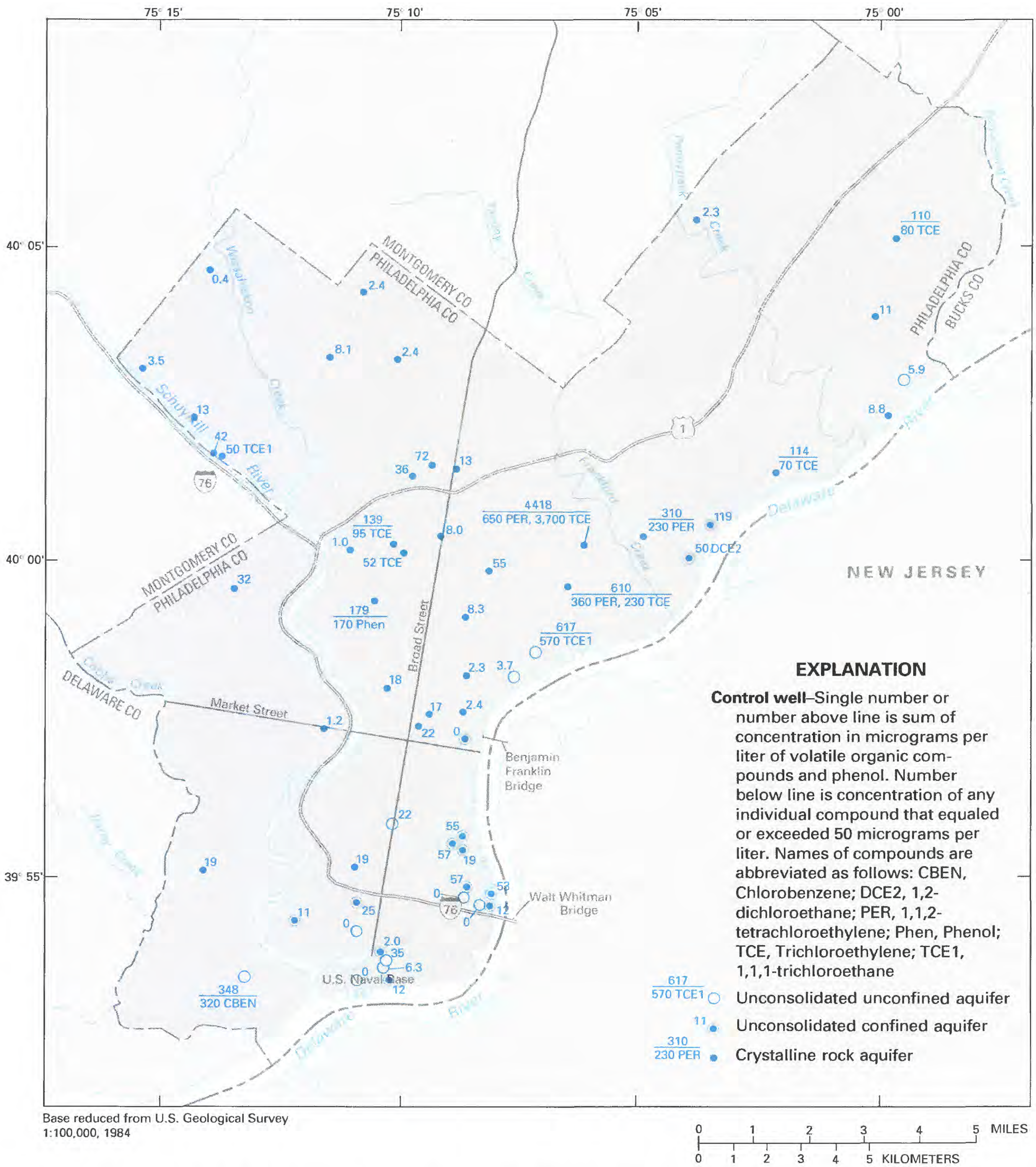


Figure 65. Concentration of phenols and selected volatile organic compounds, 1979–80.

rocks, most of the water enters crystalline-rock wells in the upper part of the well. Thus, most of the temperature data are for water present within about 200 ft of the land surface. Accordingly, differences in well depth should have only a minor influence on the water-sample temperatures shown in the figure.

Temperature logs of 40 water wells in Philadelphia indicate that human activities greatly influence the distribu-

Table 11. Summary of ground-water temperature data
[°C, degrees Celsius]

Aquifer	Temperature				Number of measurements	Median depth of wells (feet)
	Range, in °C	Median, in °C	Standard deviation, in °C	Coefficient of variation		
Unconsolidated, unconfined	13.5-25.0	17.0	2.9	0.17	30	50
Unconsolidated, confined	14.0-26.0	16.0	2.7	.16	27	142
Crystalline rocks	11.0-20.5	16.0	2.2	.14	41	278

tion of ground-water temperatures with depth. As shown by the logs of wells PH-135, PH-706, and PH-83 (fig. 67), temperatures in densely urbanized and industrialized areas commonly are highest near the water table and decrease with depth. Logs for depths of 20 to 580 ft show temperatures at the water table as high as 32 °C, or approximately 19 °C higher than the local mean annual air temperature. These anomalous temperature gradients prevailed to depths of 60 to 480 ft. Temperatures in less developed areas, as shown by the log of well PH-538 (fig. 67), increase downward at about 1 °C per 100 ft, which is the rate of natural temperature change with depth. Additional information on ground-water temperatures in Philadelphia is given by Paulachok (1984).

GROUND-WATER WITHDRAWALS

The city of Philadelphia and a few adjoining suburban areas are served by a municipal water supply obtained exclusively from surface sources. On the average, approximately 356 Mgal/d are withdrawn, about half from the Delaware River and half from the Schuylkill River, mainly for domestic and industrial uses. However, some industrial water supplies are obtained from privately owned wells, especially in the Coastal Plain, where geohydrologic conditions in most places favor on-site development of moderate to large supplies. Generally, only small ground-water supplies are available from the crystalline rocks of the Piedmont; however, they are important to several local industries.

Withdrawals from Wells

In Philadelphia, significant withdrawal of water from wells began in the early 1900's, increased steadily to a maximum in the decade of the 1940's, then declined continually through 1979 (fig. 68). Because well owners rarely kept records, the pumpage data shown in figure 68 were estimated by multiplying known or estimated pumping rates by the length of time the wells were known to be operated. Because the computations do not account for seasonal variations and economic or other factors that affect pumpage, they may overestimate ground-water withdrawals. However, unreported withdrawals by small users probably compensate for any overestimation.

For practical reasons, early settlements in Philadelphia were clustered mainly in the Coastal Plain. Hence, sediments of the unconfined aquifer system, particularly the Trenton gravel, probably were the first to be developed for water supply because of their shallow depth to the water table and ease of excavation. During early development of water supply from the Trenton gravel, many wells were constructed in industrialized districts of central and northeastern Philadelphia. From 1900 through 1909, the volume of water pumped from shallow wells averaged about 0.74 Mgal/d (fig. 68). During later development, many more shallow wells were constructed, especially along the eastern bank of the Schuylkill River and along the Delaware River upstream from the Benjamin Franklin Bridge, so that by 1930–39, withdrawals averaged about 1.6 Mgal/d. Because of increased industrial production, pumpage reached a maximum of nearly 2.3 Mgal/d during 1940–49; it then decreased steadily to about 1.1 Mgal/d during 1970–79. The decline in pumpage from the Trenton gravel can be attributed chiefly to the severely degraded water quality, which rendered much of the shallow ground water unsuitable for most uses. During 1900–79, nearly 44 billion gallons of water were pumped from wells in the Trenton gravel.

The development of water supplies from the confined aquifers, particularly the lower sand unit of the Potomac-Raritan-Magothy aquifer system, did not begin until the early 1900's. During the initial stage of development, most wells in the unconsolidated sediments were not equipped with screens but were cased their entire length; consequently, their yields were limited by the small area of the aquifer exposed to the open bottom of the well. Neverthe-

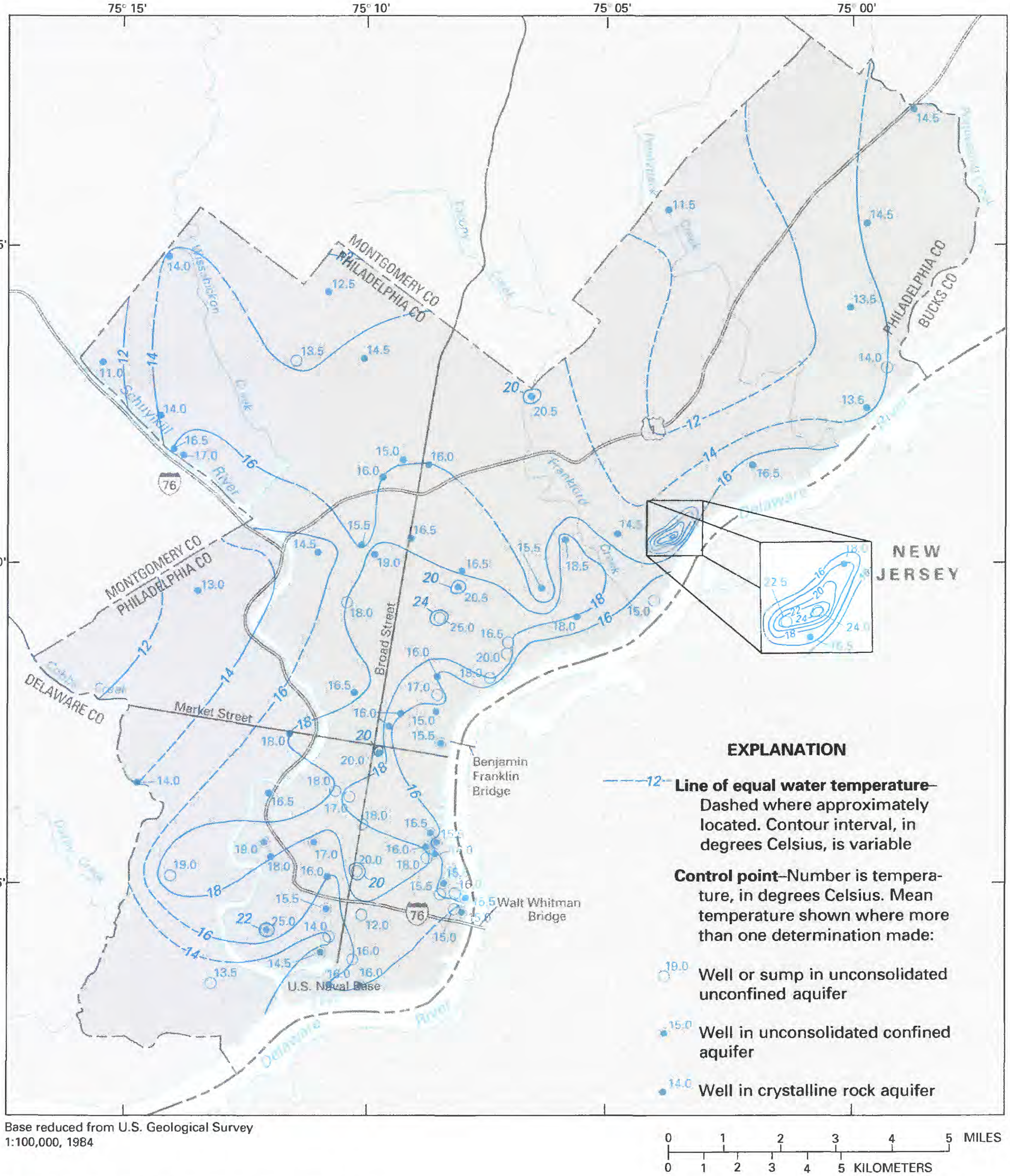


Figure 66. Ground-water temperatures, 1979–80.

less, the average pumpage from the lower sand unit increased from about 0.19 Mgal/d during 1900–09 to 1.8 Mgal/d during 1910–19 (fig. 68). During this early period, most of the water was withdrawn from wells along the Delaware River between the present-day locations of the Benjamin Franklin and Walt Whitman Bridges. Subsequent development of water-intensive industries and improvements in well design contributed to a steady increase in

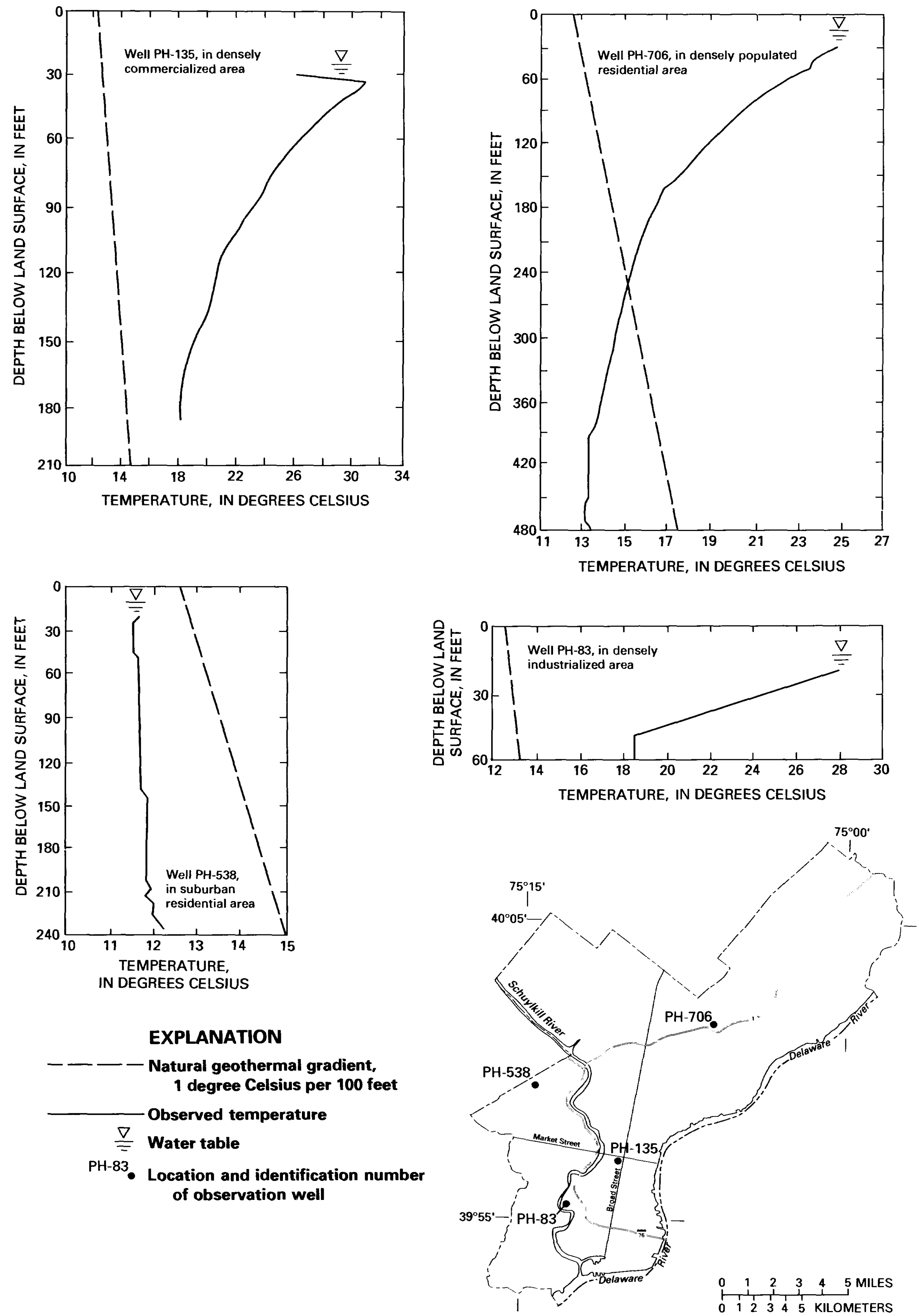


Figure 67. Temperature logs of wells PH-135, PH-538, PH-706, and PH-83.

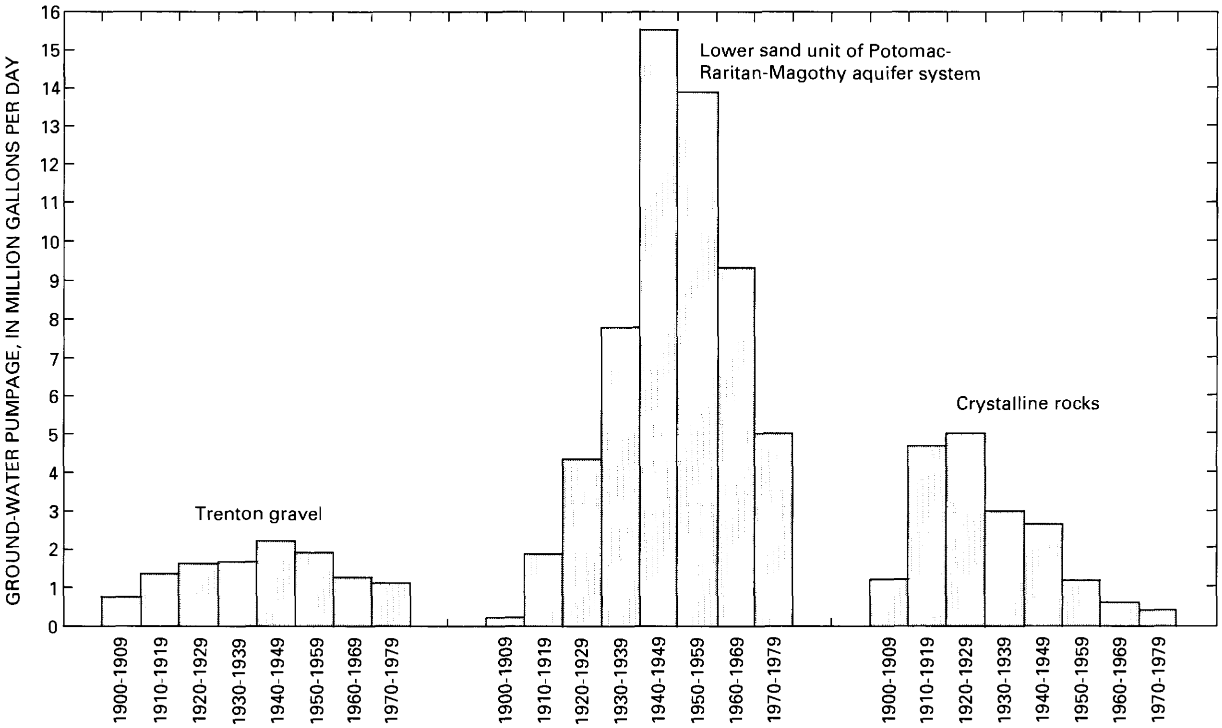


Figure 68. Pumpage from wells in Philadelphia, 1900-79.

ground-water use, so that by 1930–39, the average pumpage from the lower sand unit increased to 7.7 Mgal/d. From 1940 through 1945, the average rate of withdrawal increased to about 23 Mgal/d because of the expansion of local industries and other facilities involved in wartime production. Most of this increase resulted from the installation of six additional supply wells at an industrial site near the Walt Whitman Bridge and from the construction of eight production wells at the U.S. Naval Base. Pumpage from the lower sand unit declined during 1946–47 following a reduction in industrial activity immediately after World War II. Over the next few years, however, demand for ground water was renewed, so that by 1951 the rate of withdrawal again averaged about 23 Mgal/d. From 1951 through 1953, pumpage changed very little. Since 1954, withdrawals from the lower sand unit have decreased considerably, averaging about 5.0 Mgal/d during 1970–79. Pumpage declined when the U.S. Naval Base started using municipal water and because the cost of treating highly mineralized ground water was prohibitive. From 1900 through 1979, pumpage from wells in the lower sand unit totaled about 210 billion gallons.

The earliest intensive development for water supply was in the crystalline rocks (fig. 68). Withdrawals of water from the crystalline rocks increased significantly, from an average of 1.2 Mgal/d during 1900–09 to 4.7 Mgal/d during 1910–19, mainly because of increased urbanization and industrial development of the Piedmont area. Average pumpage reached a maximum of about 5.1 Mgal/d during 1920–29, then decreased steadily to slightly more than 0.4 Mgal/d during 1970–79. This decline in pumpage is attributed chiefly to increased availability of municipal water supply in outlying areas and to a general degradation of ground-water quality caused by urbanization. During 1900–79, about 69 billion gallons of water were pumped from wells in the crystalline rocks.

Of the 244 wells known to exist in Philadelphia during this study (1978–82), most (78 percent) were unused because of the availability of the municipal water supply and because of unsuitable ground-water quality. Water from the remaining 22 percent of wells was used for the following purposes: industrial (mostly for cooling), 11.2 percent; dewatering, 2.9 percent; domestic, 2.9 percent; and miscellaneous, including fire protection, irrigation, aquaculture, institutional and recreational, and small-scale heating using ground-water heat pumps, 5.0 percent.

Withdrawals from Drainage Sumps

In addition to withdrawals from wells, large quantities of ground water are pumped from sumps that collect seepage into tunnels of Philadelphia's subway systems and drain the subsurface at Veterans Stadium. The locations of the principal drainage sumps and average annual pumpage are shown in figure 69.

Three subway systems serve Philadelphia: the Broad Street Subway, the Market Street Subway, and the PATCO

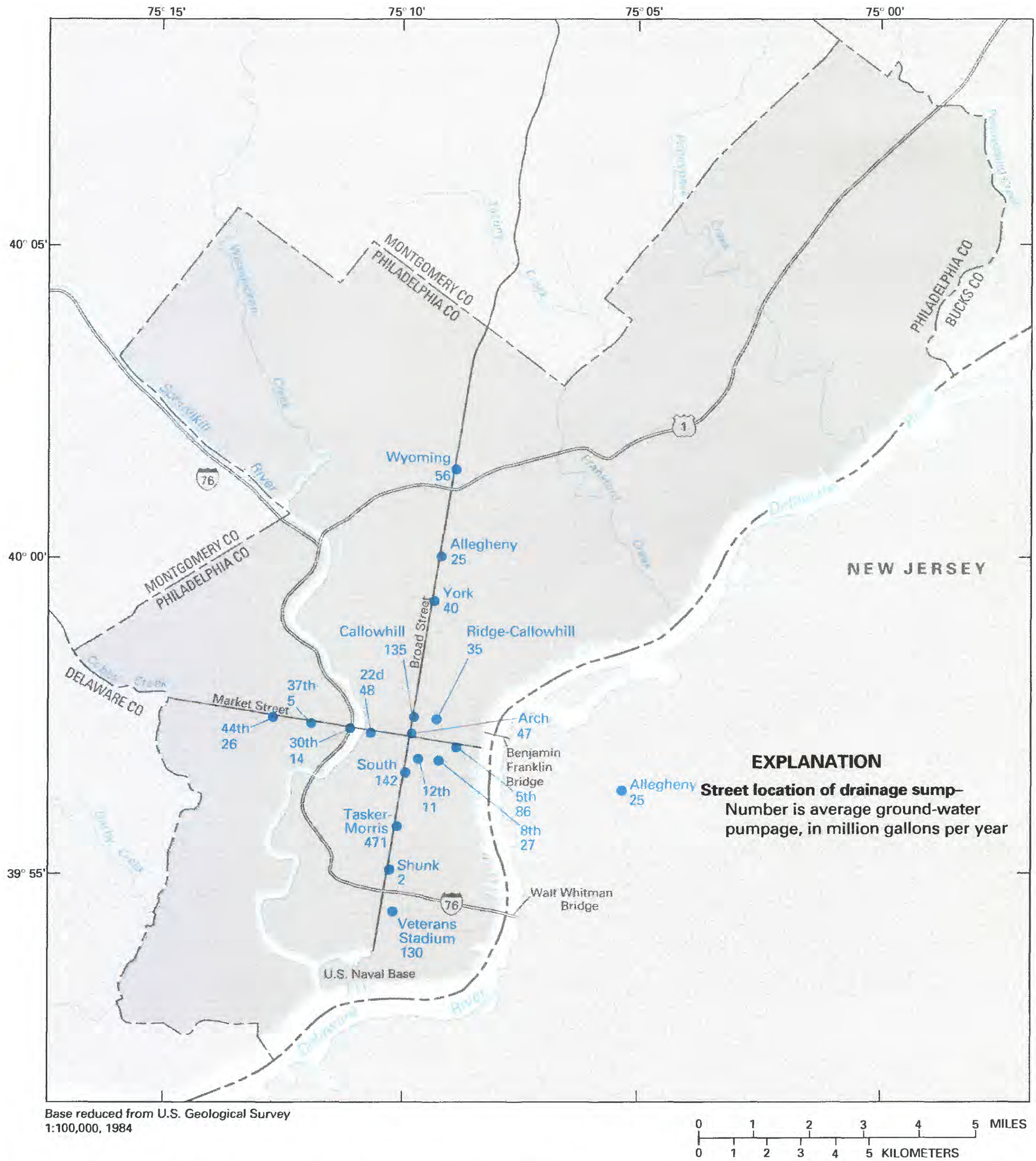


Figure 69. Locations of and pumpage from principal drainage sumps.

(Port Authority Transit Corporation) system along Locust Street. Because the subway tunnels generally are within the zone of water-table fluctuations, pumping of influent ground water is necessary to keep them dry. Ground-water seepage into the tunnels drains to sumps and subsequently is pumped to sewers. During rainless periods, pumpage from the 16 sumps that drain the three subway systems totals about 3.2 Mgal/d (City of Philadelphia Water Department, Water Pollution Control Division, 1975). Sumps for the Broad Street Subway at the Wyoming, Allegheny, York, and Ridge-Callowhill stations, as well as sumps for the Market Street Subway at the 30th, 37th, and 44th Street stations, collect about 0.55 Mgal/d of drainage from crystalline rocks. Broad Street Subway sumps at the Arch, South, Callowhill, Tasker-Morris, and Shunk stations, Market Street Subway sumps at the 5th and 22d Street stations, and PATCO system sumps at the 8th and 12th Street stations, collect about 2.65 Mgal/d of drainage from unconsolidated sediments.

Construction of Veterans Stadium was completed in 1971. Because the elevation of its playing field is below the water table, ground water seeps into the field and substructure and is removed by a drainfield that discharges to a sump. During rainless periods, about 0.36 Mgal/d of influent ground water is pumped from the Veterans Stadium sump (City of Philadelphia Water Department, Water Pollution Control Division, 1975).

Development of an Emergency Ground-Water Supply

Philadelphia's drinking-water supply is obtained entirely from the Delaware and Schuylkill Rivers. On the average, about 356 Mgal/d are withdrawn from these sources. About 743 million gallons of treated water can be stored in the distribution system. If water from both rivers simultaneously was rendered unfit for consumption even after treatment, the supply in storage would last only a few days. During emergency conditions, water supplies from the unconsolidated sediments and the crystalline rocks could be developed on a limited basis through the use of properly located wells. Development of a supply-well system could include use of high-capacity wells in the unconsolidated sediments or use of wells in various aquifers at strategic locations throughout Philadelphia. To obtain maximum yield of water of acceptable quality, wells open to unconsolidated sediments could be constructed in areas where deposits are thick and are not affected by surface and subsurface contamination. Wells in crystalline rocks could be drilled near surface-water sources of acceptable quality and in lowlands and valleys, where the weathered zone generally is thickest. Information on aquifer thickness, well yield, and specific capacity included in this and related reports may be useful in choosing suitable locations for emergency water-supply wells. Spacing wells as far apart as possible would minimize water-level declines caused by interference. However, practical considerations such as the availability of suitable drilling sites may necessitate well spacing that results in greater declines.

Sloto (1988) used a computer model to simulate the effects of pumping 60 Mgal/d from the lower sand unit. This withdrawal was simulated as pumpage from 48 wells at rates that ranged from 0.5 to 1.9 Mgal/d, depending on aquifer thickness. The simulations showed that pumping of 60 Mgal/d continuously for 30 days would lower head in the lower sand unit by as much as 121 ft.

Water from emergency supply wells could be made suitable for drinking with appropriate treatment. Water from high-capacity wells open to unconsolidated sediments could be conveyed to existing treatment plants for finishing. However, this option would require the use of pumping stations and transmission mains because the sediments are in low-lying areas. Treated water from centralized plants could be distributed through the existing transmission network. Alternatively, the quality of water from lower capacity wells could be improved through the use of on-site treatment facilities. Water upgraded in this manner could be distributed locally. Although ground-water supplies for uses other than emergency potable supply also could be developed, the cost of treating the highly mineralized water that underlies substantial parts of Philadelphia may be prohibitive.

SUMMARY

This report assesses the occurrence, availability, and quality of ground water in the 134.6-mi^2 city of Philadelphia. Philadelphia lies in two physiographic provinces. The Fall Line divides the consolidated-rock aquifers, chiefly the Wissahickon Formation, of the Piedmont from the unconsolidated aquifers of the Coastal Plain. Ground water is present under confined and unconfined conditions. The confined aquifer system consists mainly of the lower and middle sand units of the Potomac-Raritan-Magothy aquifer system and the crystalline rocks of the Wissahickon Formation where they are overlain by confining beds. The unconfined, or water-table, aquifer system consists chiefly of the upper sand unit of the Potomac-Raritan-Magothy aquifer system, the Bridgeton Formation, the Trenton gravel (informal usage), the alluvium, and the crystalline rocks where they crop out or are connected directly to overlying, unconfined unconsolidated sediments.

The principal aquifers of the confined ground-water system are the lower and middle sand units of the Potomac-Raritan-Magothy aquifer system. The lower sand unit is the most productive aquifer in Philadelphia. It consists of gravel and sand deposits up to 90 ft thick. The median yield of wells tapping the lower sand unit is 275 gal/min, and yields of some wells are as great as 1,350 gal/min. The median specific capacity of wells that tap the lower sand unit is 16 (gal/min)/ft. The average hydraulic conductivity is 135 ft/d; the average storage coefficient is 3.0×10^{-4}. The middle sand unit consists of coarse to fine sand. It is small in areal extent and commonly is less than 20 ft thick. The median yield of wells tapping the middle sand unit is 300 gal/min, and yields of some wells are as high as 870 gal/min. The median specific capacity of wells that tap the middle sand unit is 10 (gal/min)/ft.

The principal unconsolidated unconfined aquifers are the upper sand unit of the Potomac-Raritan-Magothy aquifer system and the Trenton gravel. The upper sand unit consists of coarse to medium sand and is about 35 ft thick. The Trenton gravel consists of gravel and sand and has an average thickness of about 40 ft. The median yield of wells tapping these two undifferentiated units is 90 gal/min, and yields of some wells are as great as 1,370 gal/min. The median specific capacity of wells in these units is 12 (gal/min)/ft. The principal consolidated unconfined aquifer is the Wissahickon Formation in its outcrop area. Water generally is present in fractures within 300 ft of the land surface. The median yield of wells in the Wissahickon Formation is 45 gal/min, and yields may be as high as 350 gal/min. The median specific capacity of wells in the Wissahickon Formation is 0.5 (gal/min)/ft.

Urbanization has considerably modified the hydrologic cycle in Philadelphia. Impervious surfaces have reduced recharge areas and evapotranspiration and have increased direct runoff. Withdrawal of water from wells and sumps has significantly altered the ground-water flow system. Leakage from the water-distribution system was estimated to range from 60 to 72 Mgal/d in 1980. Ground-water infiltration to sewers was estimated to be as great as 135 Mgal/d when the water table is high.

The predevelopment potentiometric surface in the lower sand unit was above sea level but has since been lowered substantially by pumping. By the early 1920's, several cones of depression with water levels greater than 10 ft below sea level formed along the Delaware River because of ground-water withdrawals. By 1940, because of increased withdrawals, two major cones of depression with water levels greater than 50 ft below sea level at their centers developed along the Delaware River. This caused the downward flow of water from overlying aquifers to the lower sand unit. Ground-water withdrawals at the U.S. Naval Base began in 1940. By 1954, water levels in the cone of depression at the U.S. Naval Base were greater than 50 ft below sea level, and levels in the cone centered farther north along the Delaware River were greater than 70 ft below sea level.

Beginning in the mid-1960's, ground-water withdrawals from the lower sand unit decreased. By 1979, water levels had risen about 25 ft at the U.S. Naval Base and about 45 ft farther north along the Delaware River. Water levels recovered at the U.S. Naval Base, and levels in the cone of depression along the Delaware River were less than 30 ft below sea level. Water levels in the lower sand unit at Philadelphia now are controlled largely by pumping in nearby parts of New Jersey.

Prior to development, the water-table configuration was a subdued replica of topography. The altitude and configuration of the water table now are controlled primarily by human activities, particularly leakage to and from sewers, leakage from the water-distribution system, and ground-water withdrawals. Differences between the water table and head in the deeper confined aquifers have caused the water table to decline below sea level along the Delaware River. The reduction of pumpage from the lower sand unit beginning in the mid-1960's caused a reduction in the size of this area of lowered water table. The water table has remained relatively stable in areas where its altitude is 50 ft or more above sea level.

Water-level fluctuations are caused by variations in recharge, water use, and evapotranspiration. Water levels also are affected by sewers and by tidal fluctuations in the Delaware and Schuylkill Rivers.

Urbanization also has caused substantial degradation of the quality of ground water in Philadelphia. During the first phase of contamination, the quality of water in the unconfined aquifers was degraded severely because of contaminants originating at the land surface. As a result, water supplies from the deeper, uncontaminated aquifers were developed. During the second phase of contamination, withdrawal of water from the confined aquifers caused a decline in head sufficient to induce downward flow of contaminated water from the overlying unconfined aquifers. Because of this influx of poor-quality water, water in the confined aquifers has been degraded so that its chemical quality now resembles that of water in the unconfined aquifers.

The concentration of dissolved solids in 83 ground-water samples collected from all of the aquifers during 1945–58 ranged from 108 to 4,270 mg/L, and the average concentration was 538 mg/L. The concentration of dissolved solids in 81 samples collected during 1979–80 ranged from 90 to 4,480 mg/L. The average concentration of 778 mg/L was 45 percent higher than that of samples collected during 1945–58. In general, water from the unconfined unconsolidated aquifers had the highest dissolved-solids concentration of any aquifer sampled.

The concentration of dissolved iron in 127 ground-water samples collected from all the aquifers during 1945–58 ranged from 0.02 to 429 mg/L, and the average concentration was 13 mg/L. The concentration of iron in 79 samples collected during 1979–80 ranged from 0 to 220 mg/L. The average concentration of 17 mg/L was nearly 30 percent higher than that of samples collected during 1945–58. Iron concentrations in water from wells in the lower sand unit at the U.S. Naval Base increased progressively from 0.20 mg/L in 1943 to 30 mg/L in 1979. Seventy-one percent of water samples collected during 1979–80 exceeded the U.S. Environmental Protection Agency's 0.30-mg/L standard for iron in drinking water. Many wells have been abandoned because of elevated iron concentrations.

The concentration of dissolved manganese in 58 ground-water samples collected from all the aquifers during 1945–58 ranged from 0 to 2,900 μg/L, and the average concentration was 190 μg/L. The concentration of manganese in 79 samples collected during 1979–80 ranged from 0 to 31,000 μg/L. The average concentration of 1,700 μg/L was about nine times greater than the average during 1945–58. Manganese concentrations in water from wells in the lower sand unit at the U.S. Naval Base remained stable at 500 μg/L from 1945 to 1973 and then increased to greater than 4,000 μg/L by 1980. Seventy-eight percent of water samples collected during 1979–80 exceeded the U.S. Environmental Protection Agency's 50-μg/L standard for manganese in drinking water.

The concentration of dissolved sulfate in 138 ground-water samples collected from all the aquifers during 1945–58 ranged from 2 to 1,340 mg/L, and the average concentration was 148 mg/L. The concentration of sulfate in 79 samples collected during 1979–80 ranged from 0.9 to 2,200 mg/L. The average concentration of 161 mg/L was 9 percent higher than that of samples collected during 1945–58. Sulfate concentrations in water from wells in the lower sand unit at the U.S. Naval Base increased progressively from 2.8 mg/L in 1942 to 185 mg/L in 1979. Eleven percent of water samples collected during 1979–80 exceeded the U.S. Environmental Protection Agency's 250-mg/L standard for sulfate in drinking water. Between 1945–58 and 1979–80, the extent of ground water containing sulfate concentrations greater than 250 mg/L was reduced significantly because of flushing of contaminated water from the aquifers, dilution, and decrease of source concentration.

Except in localized areas, ground water in Philadelphia contains undetectable or low concentrations of trace elements. During 1979–80, 103 water samples were analyzed for one or more of the following dissolved trace elements: arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, lead, lithium, mercury, nickel, selenium, strontium, and zinc. Concentrations in 1 percent of the water samples exceeded the U.S. Environmental Protection Agency's standard for cadmium in drinking water, in 2 percent exceeded the standard for chromium, and in 17 percent exceeded the standard for mercury.

During 1979–80, 68 ground-water samples collected from all the aquifers were analyzed for several or all of 14 selected volatile organic compounds. The most commonly detected compounds were 1,1,1-trichloroethane (74 percent of samples), chloroform (72 percent), 1,1,2-tetrachloroethylene (68 percent), trichloroethylene (63 percent), 1,2-dichloroethane (60 percent), and 1,2-dichloropropane (51 percent).

Heat production from human activities has caused elevated ground-water temperatures in many parts of Philadelphia. Most ground-water-sample temperatures were higher than the local mean annual air temperature of 12.6 °C, and many logs show anomalous cooling trends with depth. Heating of surface and shallow subsurface materials likely has caused the elevated temperatures and anomalous vertical gradients. Temperatures in densely urbanized areas commonly are highest near the water table and decrease with depth. Ground-water temperatures in less developed areas generally increase downward at about 1 °C per 100 ft, which is the rate of natural change of temperature with depth.

The earliest source of ground water to be developed was the Trenton gravel. From 1900 through 1979, an average of 1.5 Mgal/d was withdrawn. Peak withdrawals, which averaged 2.3 Mgal/d, occurred during 1940–49. Withdrawals during 1970–79 averaged 1.1 Mgal/d. The major source of ground water is the lower sand unit of the Potomac-Raritan-Magothy aquifer system. From 1900 through 1979, an average of 7.6 Mgal/d was withdrawn from the lower sand unit. Peak withdrawals, which averaged 23 Mgal/d, occurred during 1940–45 and 1951–53. Withdrawals during 1970–79 averaged 5.0 Mgal/d. From 1900 through 1979, an average of 2.4 Mgal/d was withdrawn from the crystalline rocks. The period of peak withdrawal occurred earlier for the crystalline rocks than for the unconsolidated aquifers. Peak withdrawals, which averaged 5.1 Mgal/d, occurred during 1920–29. Withdrawals during 1970–79 averaged 0.4 Mgal/d. By 1982, 78 percent of the 244 wells known to exist in Philadelphia were unused. The chief use of ground water from the remaining wells was for industrial cooling. Pumpage of ground water from 16 sumps draining the three subway systems is about 3.2 Mgal/d during rainless periods. Pumpage from the sump at Veterans Stadium is about 0.36 Mgal/d during rainless periods.

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1935	777	1944	1016	1953	1265
1936	817	1945	1023	1954	1321
1937	840	1946	1071	1955	1404
1938	845	1947	1096	1956–57	1537
1939	886	1948	1126	1958–62	1782
1940	906	1949	1156	1963–67	1977
1941	936	1950	1165	1968–72	2140
1942	944	1951	1191	1973–74	2164
1943	986	1952	1221		

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METRIC CONVERSION FACTORS

For readers who wish to convert measurements from the inch-pound system of units to the metric system of units, the conversion factors are listed below:

Multiply inch-pound unit	By	To obtain metric unit
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon (gal)	3.785	liter (L)
	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic mile (mi^3)	4.166	cubic kilometer (km^3)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
	0.00006308	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter [(L/s)/m]
square foot per day (ft^2/d)	0.09290	square meter per day (m^2d)

To convert to degrees Fahrenheit (°F) from degrees Celsius (°C), use the following equation:

$$°F=1.8\times°C+32$$

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