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

HISTORICAL GROUND-WATER-FLOW PATTERNS AND TRENDS IN IRON CONCENTRATIONS IN THE POTOMAC-RARITAN-MAGOTHY AQUIFER SYSTEM IN PARTS OF PHILADELPHIA, PENNSYLVANIA, AND CAMDEN AND GLOUCESTER COUNTIES, NEW JERSEY

by Ronald A. Sloto

Water-Resources Investigations Report 03-4255

In cooperation with the

U.S. ENVIRONMENTAL PROTECTION AGENCY

New Cumberland, Pennsylvania
2003

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Volume	
gallon (gal)	3.785	liter
million gallons (Mgal)	3,785	cubic meter
billion gallons (Bgal)	3,785,000	cubic meter
	Flow rate	
million gallons per day (Mgal/d)	3,785	cubic meter per day
billion gallons per year (Bgal/yr)	3,785,000	cubic meter per year
	Gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29) and the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27) and the North American Datum of 1983 (NAD 83).

Abbreviated water-quality units used in report:

mg/L, milligrams per liter

HISTORICAL GROUND-WATER-FLOW PATTERNS AND TRENDS IN IRON CONCENTRATIONS IN THE POTOMAC-RARITAN-MAGOTHY AQUIFER SYSTEM IN PARTS OF PHILADELPHIA, PENNSYLVANIA, AND CAMDEN AND GLOUCESTER COUNTIES, NEW JERSEY

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ABSTRACT

The Potomac-Raritan-Magothy (PRM) aquifer system is an important sole-source ground-water supply in Camden and Gloucester Counties, N.J. Elevated iron concentrations are a persistent water-quality problem associated with ground water from the PRM. In Philadelphia, the PRM no longer is usable as a water supply because of highly elevated concentrations of iron (as high as 429 mg/L [milligrams per liter]), manganese (as high as 4 mg/L), and sulfate (as high as 1,720 mg/L). A strongly reducing environment in the PRM in south Philadelphia causes these constituents to be remobilized by reductive dissolution of the aquifer matrix.

By the 1920s, ground-water pumping changed the natural ground-water-flow patterns, and ground water flowed toward pumping centers in Philadelphia. By 1940, recharge areas changed from the topographically high areas east of Trenton, N.J., to the outcrop area of the PRM in Philadelphia, and the Delaware River became a source of recharge instead of a point of ground-water discharge. By 1954, the cone of depression caused by pumping at the former Philadelphia Naval Ship Yard (PNSY) exceeded 50 feet below NGVD 29, and the direction of ground-water flow was from New Jersey toward Philadelphia. Because of highly elevated concentrations of iron and manganese, pumping at the former PNSY ceased in the mid-1960s. Beginning about 1951, increased ground-water withdrawals from the PRM in New Jersey reversed the hydraulic gradient so that ground-water flow was from Philadelphia toward New Jersey under the Delaware River, making Philadelphia a recharge area for the PRM aquifer system in parts of Camden and Gloucester Counties. By 1988, water levels in the lower aquifer of the PRM in New Jersey had declined to 103 feet below NAVD 88.

In 1943, dissolved iron concentrations ranged from 0.07 to 0.6 mg/L at the former PNSY. By 1967 when the wells at the PNSY were abandoned, dissolved iron concentrations had reached 46 mg/L. Dissolved iron concentrations in water from industrial wells in Philadelphia increased from 0.17 mg/L in 1949 to 19 mg/L in 1979. The concentration of dissolved iron in water from wells screened in the lower aquifer in New Jersey also increased with time. By 1985, dissolved iron concentrations were as high as 16 mg/L for Eagle Point refinery wells.

INTRODUCTION

The Potomac-Raritan-Magothy (PRM) aquifer system has been designated a sole-source aquifer by the U.S. Environmental Protection Agency (USEPA). A sole-source aquifer designation is intended to protect ground-water supplies in areas with few or no alternative drinking-water sources, and where, if contamination occurred, using an alternative source would be extremely expensive. This unconsolidated aquifer system is an important water-supply source in New Jersey. In 1998, about 167 Mgal/d were withdrawn from the PRM aquifer system in New Jersey for a variety of uses including public supply (Lacombe and Rosman, 2001). Most withdrawals from the lower aquifer of the PRM are in Camden and Gloucester Counties, N.J.

The PRM aquifer system no longer is used as a source of water supply in Philadelphia because of highly elevated concentrations of iron (as high as 429 mg/L), manganese (as high as 4 mg/L), and sulfate (as high as 1,720 mg/L) that have contaminated the aquifer in south Philadelphia and have made the ground water unusable for most purposes (Paulachok, 1991). A strongly reducing environment in the PRM in south Philadelphia causes these constituents to be remobilized by reductive dissolution of the aquifer matrix. The reducing environment results from oxygen depletion by organic wastes, such as sewage, leachate from landfills, dumped or spilled hydrocarbons, and other chemicals decomposed within the aquifer (Langmuir, 1969, p. 21). The microbiological decomposition of organic substances in ground water consumes oxygen. In low dissolved oxygen waters, naturally occurring iron, manganese, and sulfate leach from the aquifer matrix. Subsequently, when ground water containing these reduced constituents is exposed to oxygen, the metals reoxidize and hydroxides precipitate from the water. The precipitates can clog well screens, accumulate in treatment and distribution systems, stain fixtures, and impart an objectionable taste and color to the water. Many wells in Philadelphia, including those at the former Philadelphia Naval Ship Yard (PNSY), were abandoned primarily because of problems associated with the precipitation of iron hydroxides.

Organic compounds from industrial waste sources in south Philadelphia have the potential to effect the quality of ground water withdrawn from the lower aquifer of the PRM in adjacent areas of New Jersey where the lower aquifer is not in direct hydraulic connection with the Delaware River. During most of the 1940s and 1950s, ground water flowed under the Delaware River from New Jersey to Pennsylvania in response to heavy pumping in Philadelphia. However, with the cessation of ground-water pumping in Philadelphia in the mid-1960s and in response to heavy pumping in Camden and Gloucester Counties, hydraulic gradients reversed, and ground water began to flow beneath the Delaware River from Pennsylvania toward New Jersey (Navoy and Carleton, 1995, p. 33). The outcrop area of the PRM in Philadelphia became a recharge area for the lower aquifer of the PRM in parts of New Jersey.

Although ground-water withdrawals in New Jersey have declined since the 1980s, ground water of poor quality may still be flowing under the Delaware River from Pennsylvania toward pumping centers in parts of New Jersey. Potentiometric-surface maps show that the cones of depression caused by pumping of wells in the lower aquifer of the PRM in New Jersey extend under the Delaware River into Pennsylvania. Under the present pumping conditions, the quality of water in the PRM aquifer system in New Jersey is likely to degrade with time. Although direct withdrawal of the organic contaminants themselves is always a concern, the primary threat to supply wells is elevated concentrations of iron and manganese remobilized by degradation of organic contaminants.

Purpose and Scope

This report, which was prepared in cooperation with the USEPA, documents ground-water-flow patterns and water-quality trends in the lower aquifer of the PRM aquifer system. This report provides an overview of the geology of the PRM underlying south Philadelphia and adjacent parts of Camden and Gloucester Counties, N.J. (fig. 1). It presents a summary of historical and current ground-water withdrawals and flow in the lower aquifer of the PRM and a summary of historical iron concentration data, which shows a substantial increase with time. The report presents suggestions for further study of the effects of ground-water withdrawals on iron concentrations in the PRM aquifer system in south Philadelphia and adjacent areas in New Jersey.

Previous Investigations

The hydrogeology of Philadelphia County was described by Greenman and others (1961) and Paulachok (1991). Data for wells in Philadelphia County are given by Paulachok and others (1984). The hydrology of Camden County was described by Farlekas and others (1976). The hydrology of Gloucester County was described by Hardt and Hilton (1969). The hydrogeology of Gloucester and Salem Counties was described by Cauller and others (1999). Zapecza (1989) provided maps of structure contours and thickness for the principal aquifers and confining units of the New Jersey Coastal Plain.

Potentiometric-surface maps of the PRM aquifer system in Philadelphia in the 1920s, 1945, and 1954 were presented in Greenman and others (1961). Generalized potentiometric-surface maps of the PRM aquifer system in New Jersey were presented by Gill and Farlekas (1976) for 1956 and 1968, and by Luzier (1980) for 1973. Detailed potentiometric-surface maps of the PRM aquifer system in New Jersey were constructed for 1978 by Walker (1983), for 1983 by Eckel and Walker (1986), for 1988 by Rosman and others (1995), for 1993 by Lacombe and Rosman (1997), and for 1998 by Lacombe and Rosman (2001). Potentiometric-surface maps for the PRM near National Park, N.J., for 1996 were presented by Rosman (1997).

Ground-water-flow models were constructed by Sloto (1988) for the lower sand unit of the PRM aquifer system in Philadelphia and adjacent New Jersey and by Schreffler (2001) for the PRM aqui-

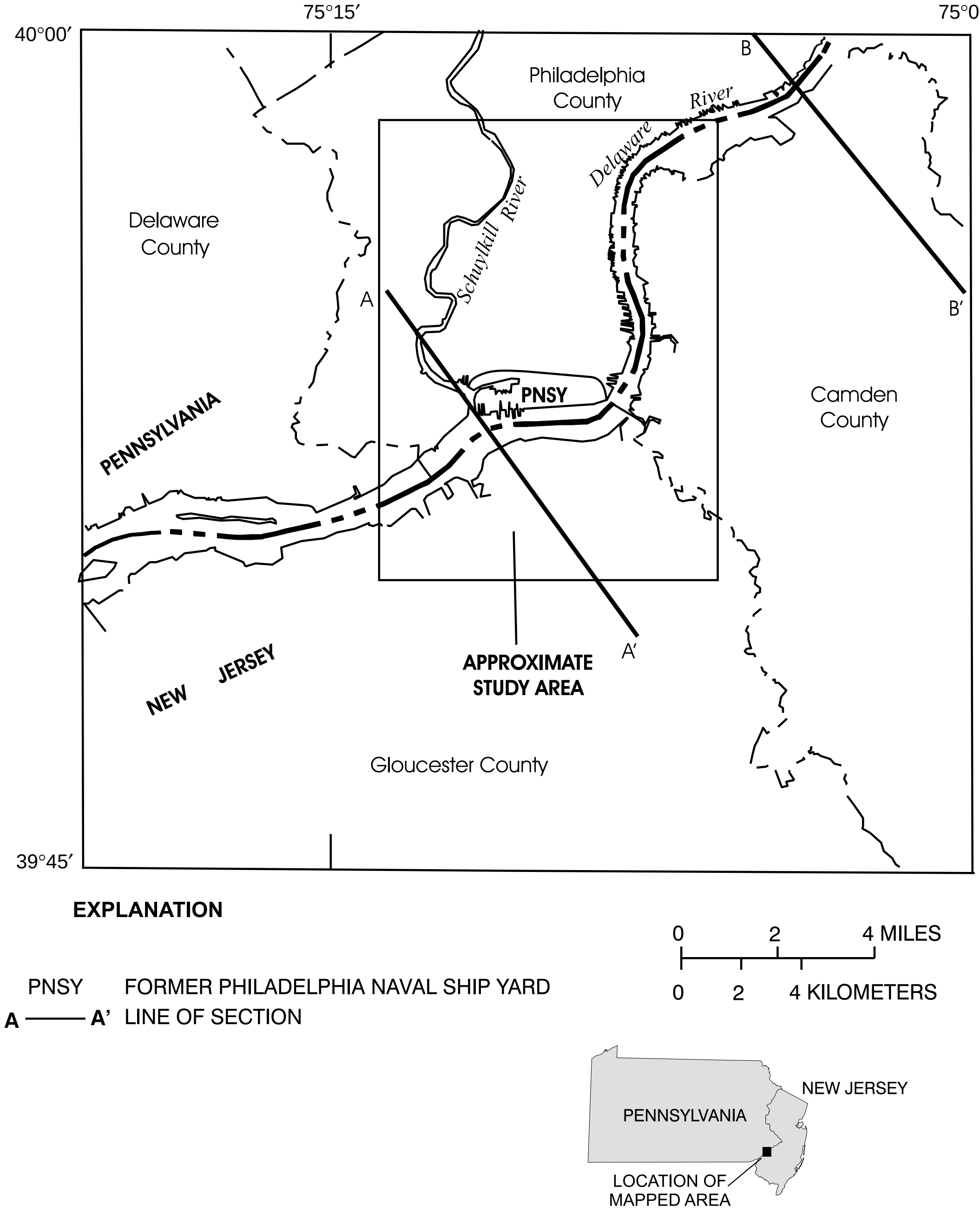


Figure 1. Location of the study area and hydrogeologic sections A-A′ (shown in fig. 3) and B-B′ (shown in fig. 4).

fer system in Philadelphia and adjacent New Jersey. Luzier (1980) used a single-layer model of the New Jersey Coastal Plain to determine ground-water-flow paths. Martin (1998) developed an 11-layer model of the New Jersey Coastal Plain. Navoy and Carleton (1995) used a flow model to evaluate induced flow from the Delaware River into the PRM in the Camden area.

Water-quality data for wells in Philadelphia County are given by Paulachok and others (1984). Studies of ground-water quality in the Camden area were conducted by Rush (1962), Donsky (1963), Langmuir (1969), Fusillo and Voronin (1981), and Fusillo and others (1984). Water-quality data for wells in the PRM aquifer system in Camden County are given by Fusillo and others (1984).

Acknowledgments

A technical advisory committee was formed to discuss issues related to ground-water contamination and to guide development of the *Suggestions for Further Study* section in this report. The members of the committee were Hon Lee and Dale Long, USEPA, Region III; Ruth Izraeli, USEPA, Region II; Patrick Anderson, David Burke, and Michelle Geissler, Pennsylvania Department of Environmental Protection; Karl Muessig, New Jersey Geological Survey; Greg Cavallo, Delaware River Basin Commission; and Daryll Pope, USGS.

The assistance of water purveyors in providing data and discussing ground-water issues is greatly appreciated, especially Mark Huff, Bellmawr Water Department; Donna Demico, Brooklawn and Westville Borough Water Departments; John Meier, Collingswood Borough Water Department; Ed Deak, Deptford Township Municipal Authority; Tom Souch, National Park Borough Water Department; Ken Christy and Kevin Dixon, New Jersey American Water Company; Michael Stevens, U.S. Water, Camden Water Division; Ed Phelps, West Deptford Township Water Department; and Richard Midland and Richard Leidy, Woodbury City Water Department.

The author thanks Charles A. Cravotta, III of the USGS Pennsylvania District for his critical review of the report and his assistance with the geochemistry. Daryll Pope of the USGS New Jersey District also provided a critical review of this report.

GROUND-WATER-FLOW PATTERNS

The PRM aquifer system is the largest and most productive of the Coastal Plain aquifers in New Jersey. The aquifers of the PRM generally are confined; however, they can be unconfined at their outcrop areas. Development of the Coastal Plain aquifers for water supply has greatly altered the natural ground-water-flow system. The high rate of water withdrawal has created large, regional cones of depression in the potentiometric surface of all three PRM aquifers in New Jersey. The cones of depression extend to more than 80 ft below NAVD 88. Large withdrawals of ground water have caused hydraulic gradients and ground-water-flow directions to reverse.

Regional Hydrogeologic Framework

The Cretaceous-age PRM aquifer system underlies the southeastern part of Philadelphia and southern New Jersey. These sediments unconformably overlie pre-Cretaceous basement crystalline rocks southeast of the Fall Line, which is the demarcation between consolidated rocks and unconsolidated sediments. Beginning at the Fall Line, the sediments of the PRM form an eastward-thickening wedge that dips gently to the southeast from 40 to 60 ft/mi (Zapecza, 1989, p. 5). The sediments were deposited in a complex fluvial-deltaic environment (Owens and others, 1968) and are considered to be nonmarine in the Delaware Valley.

Regionally, the PRM is divided into three aquifers and two confining units in Pennsylvania and New Jersey (fig. 2). Beneath and near the Delaware River, however, differentiation of the units of the PRM is particularly difficult. In this area, the units commonly do not seem to fit the “layer-cake” model of the coastal plain (figs. 3 and 4). The following description of the PRM was compiled from Greenman and others (1961) and Zapecza (1989).

In Pennsylvania, the upper sand unit unconformably overlies the middle clay unit and consists mainly of fairly well-sorted medium to coarse sand that contains minor amounts of fine to very fine sand. Gravel beds are common, especially at the base. The upper sand unit occupies erosional depressions or scour channels in the underlying middle clay unit. The upper sand unit apparently was deposited by the same streams that scoured channels in the middle clay unit. Therefore, it is assumed that erosion of the middle clay unit took place contemporaneously with deposition of the upper sand unit. In a few places, the middle clay unit was completely removed, and the upper sand was deposited directly on the middle sand unit. In south Philadelphia, the upper sand unit is about 35 to 50 ft thick. Throughout most of its area of occurrence, the upper sand unit forms a hydraulically continuous unit with overlying deposits of Pleistocene sand and gravel. In New Jersey, the upper aquifer is the least extensive unit of the PRM. It is composed predominantly of quartzose sand and silt with clayey layers and lenses. The upper aquifer is as much as 100 ft thick.

In Pennsylvania, the middle clay unit consists of a tough, red and white clay, which is uniformly massive. It commonly contains relatively little sandy material. The surface of the clay is characterized by several elongated depressions caused

<table>
<tr><th rowspan="2">SYSTEM</th><th rowspan="2">SERIES</th><th colspan="4">HYDROGEOLOGIC UNIT</th></tr>
<tr><th colspan="2">PENNSYLVANIA[1]</th><th colspan="2">NEW JERSEY[2]</th></tr>
<tr><td rowspan="7">Cretaceous</td><td rowspan="6">Upper Cretaceous</td><td rowspan="7">Potomac-Raritan-Magothy aquifer system</td><td>Upper clay unit</td><td></td><td>Confining unit</td></tr>
<tr><td>Upper sand unit</td><td rowspan="6">Potomac-Raritan-Magothy aquifer system</td><td>Upper aquifer</td></tr>
<tr><td>Middle clay unit</td><td>Confining unit</td></tr>
<tr><td>Middle sand unit</td><td>Middle aquifer</td></tr>
<tr><td>Lower clay unit</td><td>Confining unit</td></tr>
<tr><td rowspan="2">Lower sand unit</td><td rowspan="2">Lower aquifer</td></tr>
<tr><td>Lower Cretaceous</td></tr>
</table>

[1] From Paulachok (1991, p. 13).

[2] From Zapecza (1989, p. 4).

Figure 2. Generalized hydrogeologic section of the Potomac-Raritan-Magothy aquifer system in Pennsylvania and New Jersey.

by erosion, which are oriented parallel to the trend of the underlying bedrock channels. The base of the middle clay unit is marked by a conspicuous bed of lignite. However, where the middle clay unit lies directly on the lower clay unit, as it does in much of Philadelphia, it is difficult to differentiate the two units. In New Jersey, the confining unit between the middle and upper aquifers consists of discontinuous, alternating layers and lenses of clay, silt, and sand. It is about 50-150 ft thick but locally may be less than 20 ft thick, and in some places, it may be absent.

In Pennsylvania, the middle sand unit fills shallow channels in the lower clay unit but is not areally extensive in south Philadelphia. The middle sand unit consists of a sequence of light colored, very fine to coarse sand beds and a few beds of light gray clay. The sediments are fairly well sorted, and grain size decreases away from the heads of the depositional channels. The middle sand unit is as much as 25 ft thick in Philadelphia, and it commonly is less than 20 ft thick. In New Jersey, the middle aquifer primarily consists of medium to coarse quartzose sand and gravel with a few interbedded layers and lenses of silty clay. It is as much as 150 ft thick. In and near the outcrop area near the Delaware River, sand makes up 60 to 100 percent of the middle aquifer.

In Pennsylvania, the lower clay unit consists of a tough clay containing beds of softer, well-stratified clay and thin lenses of fine sand. It unconformably overlies either the lower sand unit or the residual clay of the underlying crystalline bedrock. The lower clay unit occurs in the same bedrock channels as the lower sand unit but its distribution differs. Along the margins of the troughs, the lower clay unit overlies the lower sand unit, but it is absent at the heads of the troughs where it was removed by stream erosion. The lower clay unit is up to 61 ft thick but generally is about 20 to 40 ft thick. In New Jersey, the confining unit between the lower and middle aquifers consists primarily of red, white, and gray silty clay with some interbedded clayey silt and sand. It is less than 50 ft thick over half of its mappable area but can exceed 100 ft in thickness.

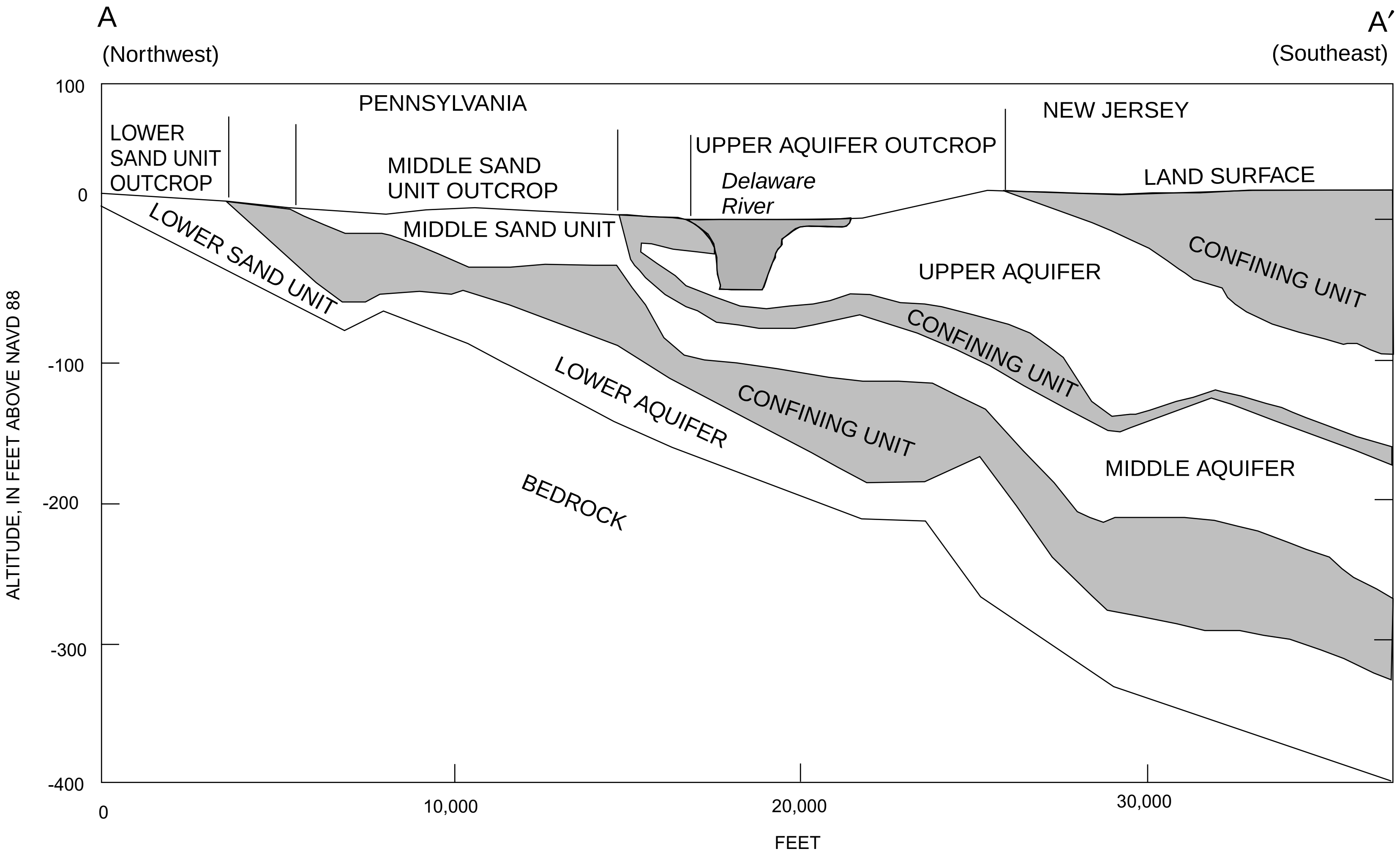


Figure 3. Hydrogeologic cross section through the Potomac-Raritan-Magothy aquifer system, Philadelphia, Pa., and Gloucester County, N.J. (modified from Navoy and Carleton,1995, pl. 1). Location of section shown on figure 1.

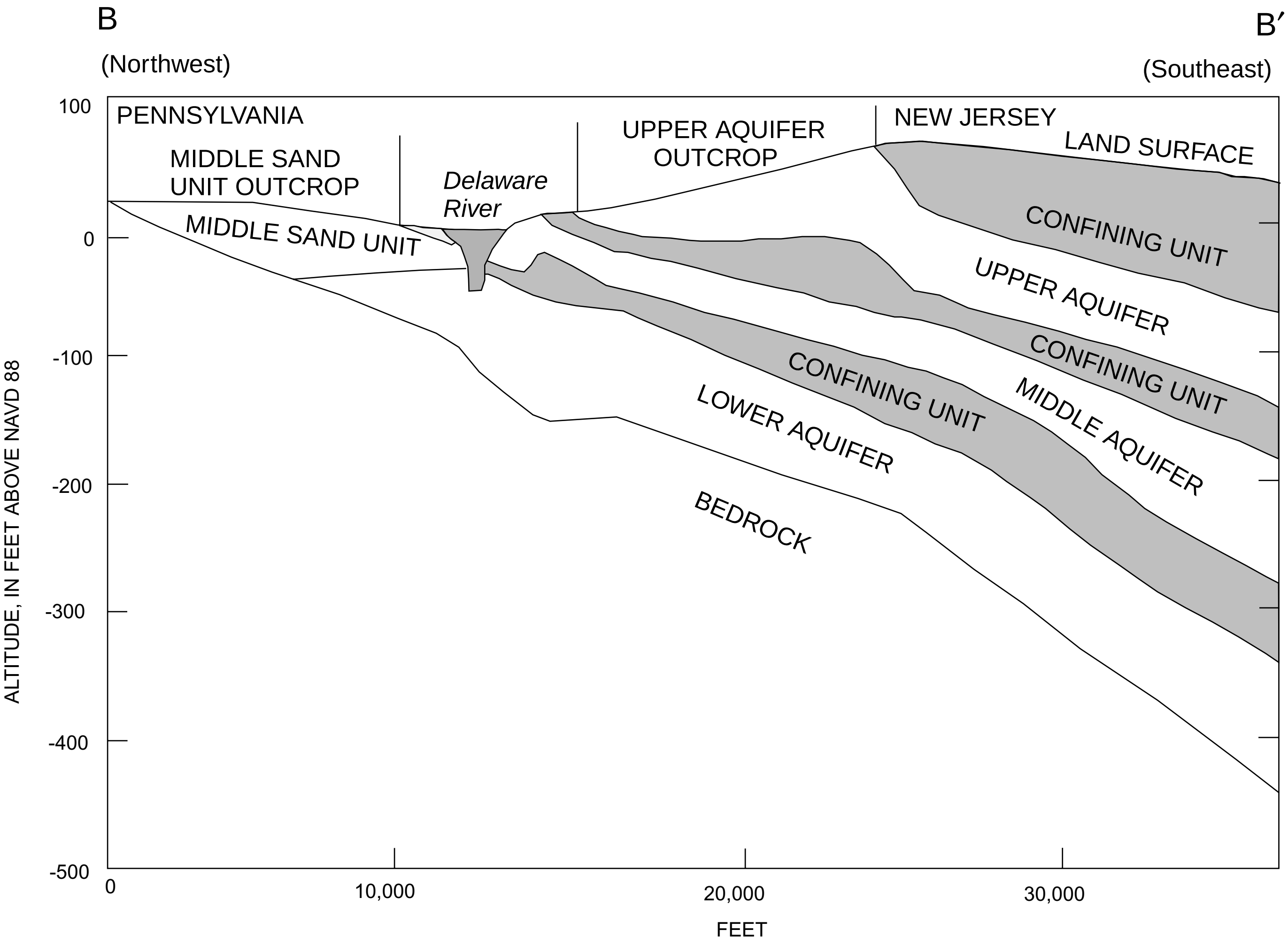


Figure 4. Hydrogeologic cross section through the Potomac-Raritan-Magothy aquifer system, Philadelphia, Pa., and Gloucester County, N.J. (modified from Navoy and Carleton,1995, pl. 1). Location of section shown on figure 1.

In Pennsylvania, the lower sand unit is the basal member of the PRM. It occupies channels carved into the underlying crystalline bedrock by a pre-Cretaceous drainage system; five troughs were mapped by Greenman and others (1961) in Philadelphia. The lower sand unit consists predominantly of fairly well-sorted coarse sand and fine gravel that grades upward into medium to fine sand containing a few beds of white clay. It is thickest in the axial parts of the troughs and thins rapidly toward the margins. The lower sand unit is as much as 90 ft thick, but rarely attains a thickness greater than 60 ft. In New Jersey, the lower aquifer primarily consists of medium to coarse quartzose sand and gravel with a few interbedded layers and lenses of silty clay. Because of the fluvial depositional environment, considerable amounts of silt and clay are interbedded locally with sand and gravel. Sand makes up more than 70 percent of the lower aquifer. It is greater than 250 ft thick in some places.

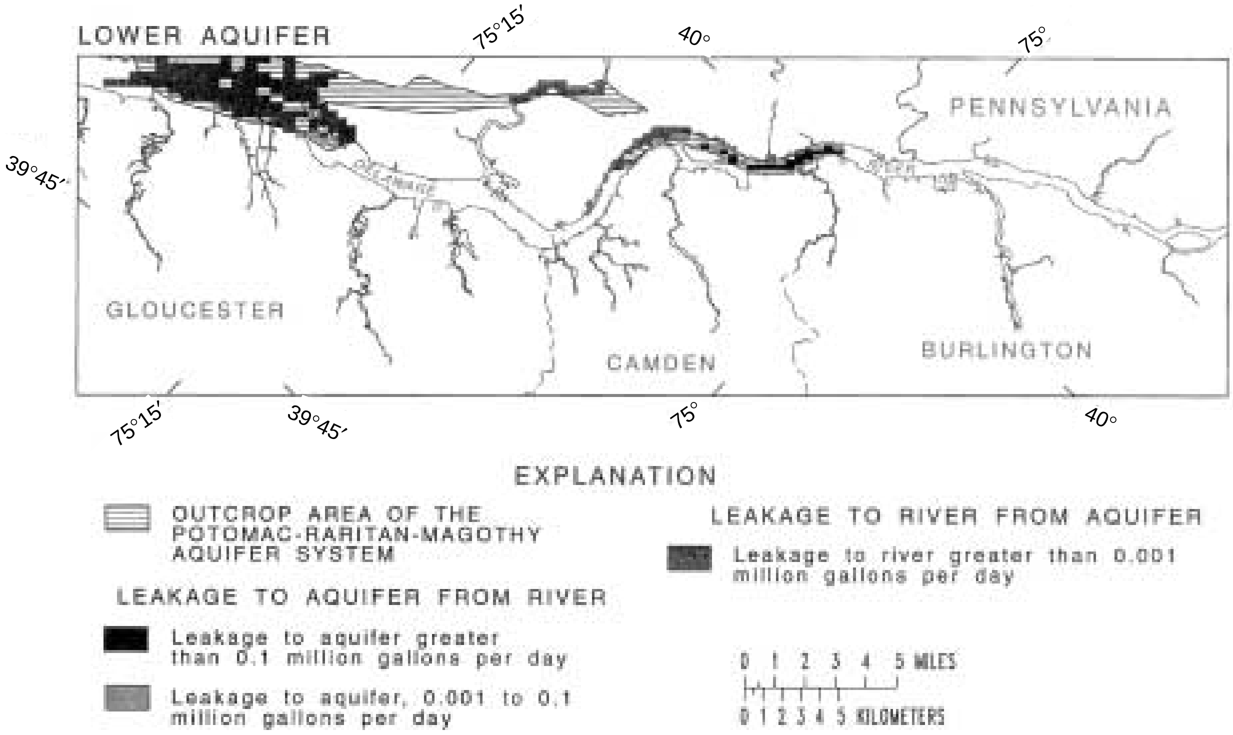
Hydraulic Connection Between Aquifers and the Delaware River

The interaction between the Delaware River and the aquifer system probably is the most important factor influencing movement of contaminated ground water from Pennsylvania to New Jersey. This interaction depends on the physical characteristics and orientation of the geologic material beneath the river and the hydraulic conditions controlling flow. The aquifer system and related confining units are laterally extensive and lie under or are adjacent to the river. The riverbed material, which is superimposed over these regional units, is composed of river deposits or reworked material, all modified by dredging operations. The riverbed material does not have a hydraulically significant contact with laterally adjacent regional geologic units, but it does have a significant vertical connection to the river. Given the aquifer system's physical contact with the river, the rate and magnitude of flow are controlled by the relative hydraulic potential across the connection and by the hydraulic conductivities of the aquifer system and riverbed (Navoy and Carleton, 1995, p. 35).

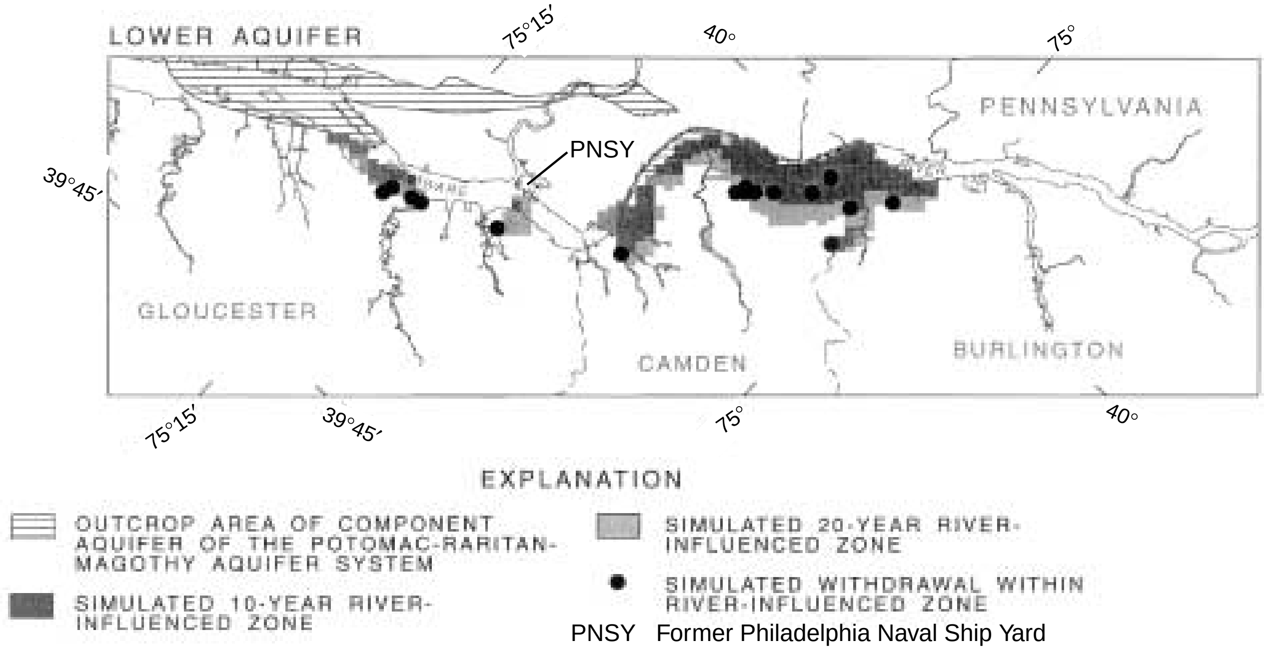
Where the course of the Delaware River crosses troughs in the bedrock surface, a significant thickness of the PRM aquifer system and hydraulically associated Cenozoic deposits fills the troughs and allows exchange of water with the river and flow under the river. Where bedrock highs exist under the riverbed, flow under the river is impeded, and interactions between the river and the aquifer are limited to lateral infiltration along the banks. Therefore, the hydrogeologic framework of the deposits within these troughs controls the interaction between the river and aquifer system and flow under the river (Navoy and Carleton, 1995, p. 35).

The Delaware River in the downstream area is in contact with the middle aquifer (fig. 4). The Delaware River in the upstream area is in contact with the middle and lower aquifers (fig. 3). Where a confining unit is present above the lower aquifer (fig. 3), ground water flows from Philadelphia beneath the Delaware River to New Jersey; this is the case in the area around the former PNSY. However, in areas northeast of the former PNSY along the Delaware River, the confining unit may be thin or absent, and the Delaware River may be in direct hydraulic contact with the lower aquifer (fig. 4). In these places, little or no ground water may flow from Pennsylvania to New Jersey.

Navoy and Carleton (1995) used a ground-water-flow model to determine areas of induced recharge from the Delaware River in the vicinity of Camden, N.J. Navoy and Carleton (1995, p. 104) determined that recharge induced from the Delaware River by pumping was a local process with recharge directed primarily toward wells or well fields proximal to the river rather than being distributed along the length of the river as a broad-scale process. Wells in cones of depression in regional potentiometric surfaces, caused by ground-water withdrawals far from the river, draw flow primarily from the aquifer's outcrop area on land, from intervening and overlying confining units, and from other parts of the aquifer system, but not from the river. The rate and magnitude of flow from the river to the aquifer system are controlled by the relative head difference across the aquifer-river interface and by the riverbed and aquifer-system hydraulic conductivities. Model simulations showed that the lower aquifer in New Jersey across the Delaware River from the former PNSY and the areas to the east and west of the former PNSY receive little recharge from the river (fig. 5).



A. SIMULATED FLOW BETWEEN THE DELAWARE RIVER AND THE LOWER AQUIFER OF THE POTOMAC-RARITAN-MAGOTHY AQUIFER SYSTEM



B. SIMULATED RIVER-INFLUENCED ZONES

Figure 5. Simulated (A) flow between the Delaware River and the lower aquifer of the Potomac-Raritan-Magothy aquifer system and (B) simulated river-influenced zones, 1983-88 (from Navoy and Carleton, 1995, p. 79 and 81).

Pre-Development Flow System

Before development of the Coastal Plain aquifers for water supply, water flowed in response to natural hydraulic gradients. Barksdale and others (1958, p. 108-111) theorized that before ground-water withdrawals began, regional ground-water flow in New Jersey was from topographically high outcrop areas east of Trenton, N.J., towards the Delaware River, the regional point of discharge. Ground-water flow in Pennsylvania was to the Delaware River. Most water that entered the aquifer discharged to local streams, but some water percolated downward through confining beds and moved to more distant points of discharge. Vertical hydraulic gradients were upward in the discharge area.

Development of Ground-Water Supplies

Development of the Coastal Plain aquifers as a source of water supply began before 1900. Bascom (1904) lists many wells tapping the unconsolidated deposits in Pennsylvania and New Jersey. A number of industrial wells are listed for Philadelphia. Schreffler (2001, p. 15) estimated and compiled pumpage from the PRM for 1904-95 for his modeled area in Philadelphia and adjacent parts of New Jersey (fig. 6). In Pennsylvania, ground-water withdrawals rose steadily from about 1900 until the peak of 7.4 Bgal/yr in 1949. By 1982, pumping from the PRM in Pennsylvania was negligible.

Prior to 1941, the former PNSY obtained its entire water supply from the city of Philadelphia. After the start of World War II, the demand of the PNSY exceeded the capabilities of the city pumping and distribution system. To meet increased demands, the PNSY drilled wells and began using ground water. Ground-water withdrawals from the PRM in Philadelphia, mainly from industrial wells, was 3.9 Bgal/yr in 1940. In 1943, the year of peak pumping at the PNSY, ground-water withdrawals rose to 6.6 Bgal/yr (fig. 6).

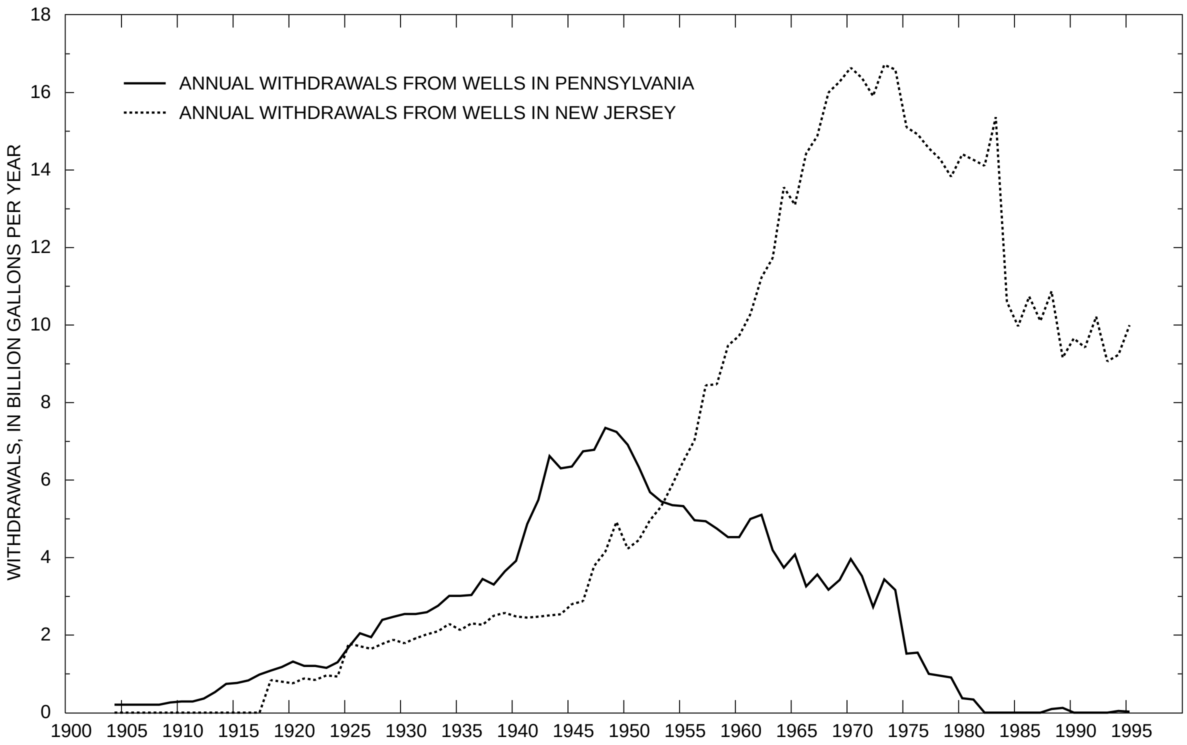


Figure 6. Estimated water withdrawal from the lower sand unit and lower aquifer of the Potomac-Raritan-Magothy aquifer system in Philadelphia and adjacent parts of New Jersey, 1904-95 (from Schreffler, 2001, p. 15).

Post-Development Flow System

By the 1920s, pumping in Philadelphia had changed the natural ground-water-flow patterns in the PRM aquifer system. The principal change in the direction of ground-water flow from pre-development to the 1920s was in the area near the Walt Whitman Bridge where the greatest withdrawals from the lower sand unit were made (Paulachok, 1991, p. 40). Withdrawals created cones of depression in this area, and ground water flowed toward the pumping centers. By 1940, continued and increased pumping from the lower sand unit near the Walt Whitman Bridge caused greater water-level declines in the lower sand unit with an even steeper hydraulic gradient towards the pumping centers (fig. 7). Lower heads in the lower sand unit relative to the heads in the alluvial and upper and middle sand units developed, which created a downward vertical ground-water-flow component. Recharge areas changed from the topographically high areas east of Trenton, N.J., to the outcrop area. The Delaware River was no longer a point of ground-water discharge. Because of increasing withdrawals from the unconfined alluvium and the confined PRM units, hydraulic heads were lowered below the levels of the Delaware and Schuylkill Rivers. Barksdale and others (1958) and Greenman and others (1961) documented induced recharge from these rivers.

Ground-water development for supply at the former PNSY started in 1940, and large withdrawals at the facility continued until the mid-1960s. Pumping at the PNSY created a large cone of depression in the lower sand unit that was documented by Greenman and others (1961). Potentiometric-surface maps presented by Greenman and others (1961), however, do not appear to have taken water levels in New Jersey into account. By 1954, the cone of depression at the PNSY exceeded 50 ft below NGVD 29 (fig. 8). Between 1943 and 1960, vertical leakage was the most important source of recharge to the lower sand unit in the vicinity of the PNSY (Paulachok, 1991).

Because of poor water quality, mainly highly elevated concentrations of iron (as high as 166 mg/L) and manganese (as high as 3.2 mg/L) (Paulachok and others, 1984), ground-water withdrawals at the PNSY were discontinued in the mid-1960s. The decrease in pumping allowed water levels to recover in Pennsylvania. This facilitated the flow of ground water from Philadelphia to New Jersey under the Delaware River, making Philadelphia a recharge area for the PRM aquifer system in parts of Camden and Gloucester Counties where the lower aquifer is not in direct hydraulic connection with the Delaware River.

Ground-water withdrawals from the PRM on the New Jersey side of the Delaware River began to increase sharply beginning about 1951. Although pumping stopped at the PNSY and water levels in the lower sand unit recovered, the increased pumping in New Jersey maintained downward vertical gradients. Total annual pumpage from the PRM in New Jersey in 1956 was 120 Mgal/d and increased to 195 Mgal/d by 1966 (Vowinkel, 1984). A generalized regional potentiometric-surface map for the PRM aquifer system for 1968 was presented by Gill and Farlekas (1976). The map shows six cones of depression in the PRM in New Jersey with water levels as deep as 70 ft below NGVD 29. The direction of ground-water flow was from Philadelphia to New Jersey.

Regional potentiometric-surface maps for the lower and upper aquifers of the PRM for 1978 were presented by Walker (1983). The map for the lower aquifer shows a large cone of depression with water levels as deep as 80 ft below NGVD 29 and a smaller cone of depression with water levels as deep as 60 ft below NGVD 29 (fig. 9). The map for the upper aquifer shows one large cone of depression with water levels as deep as 80 ft below NGVD 29 containing smaller cones of depression with water levels as deep as 70 ft below NGVD 29.

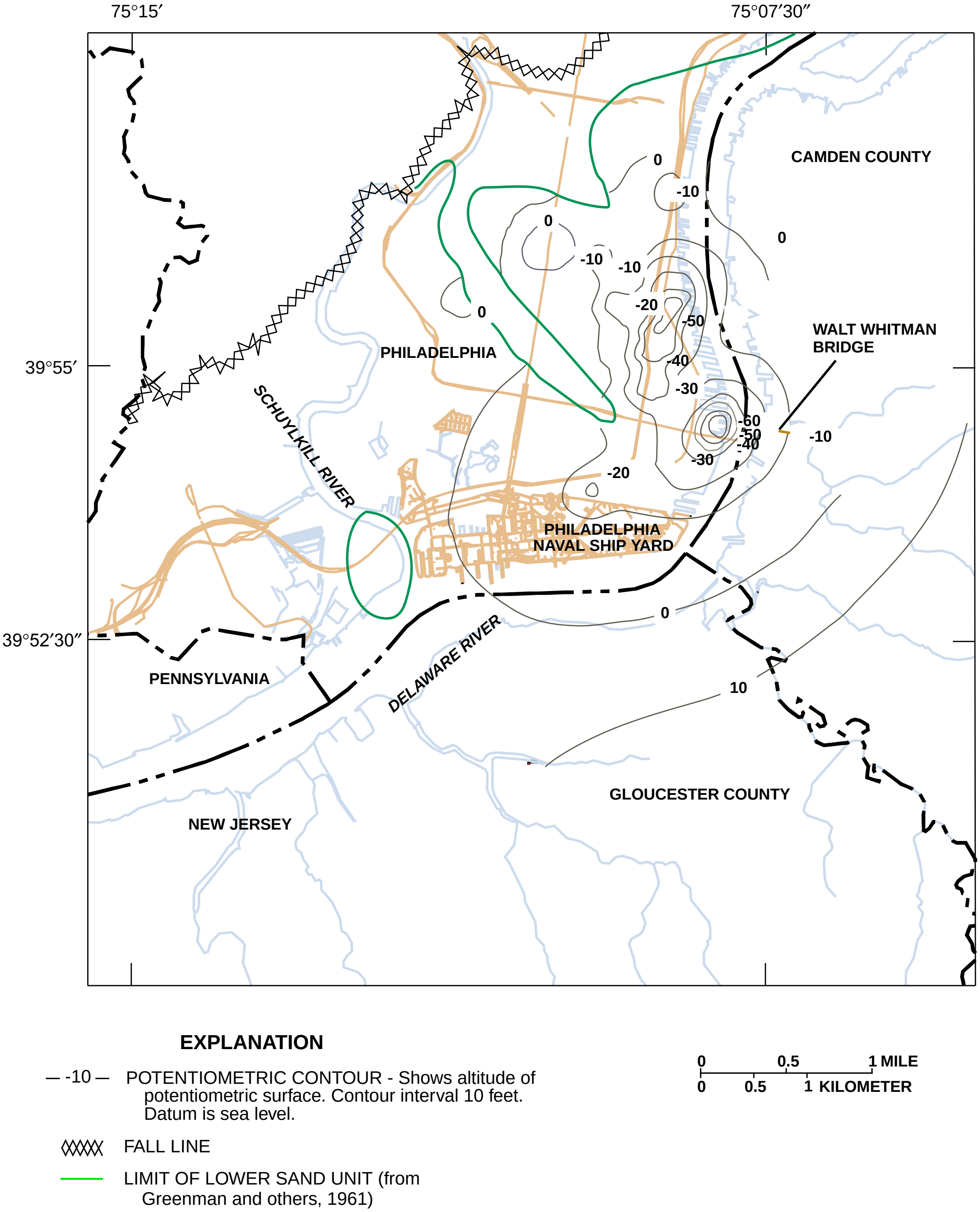


Figure 7. Potentiometric surface of the lower sand unit of the Potomac-Raritan-Magothy aquifer system in south Philadelphia, 1940 (modified from Greenman and others, 1961, figure 15).

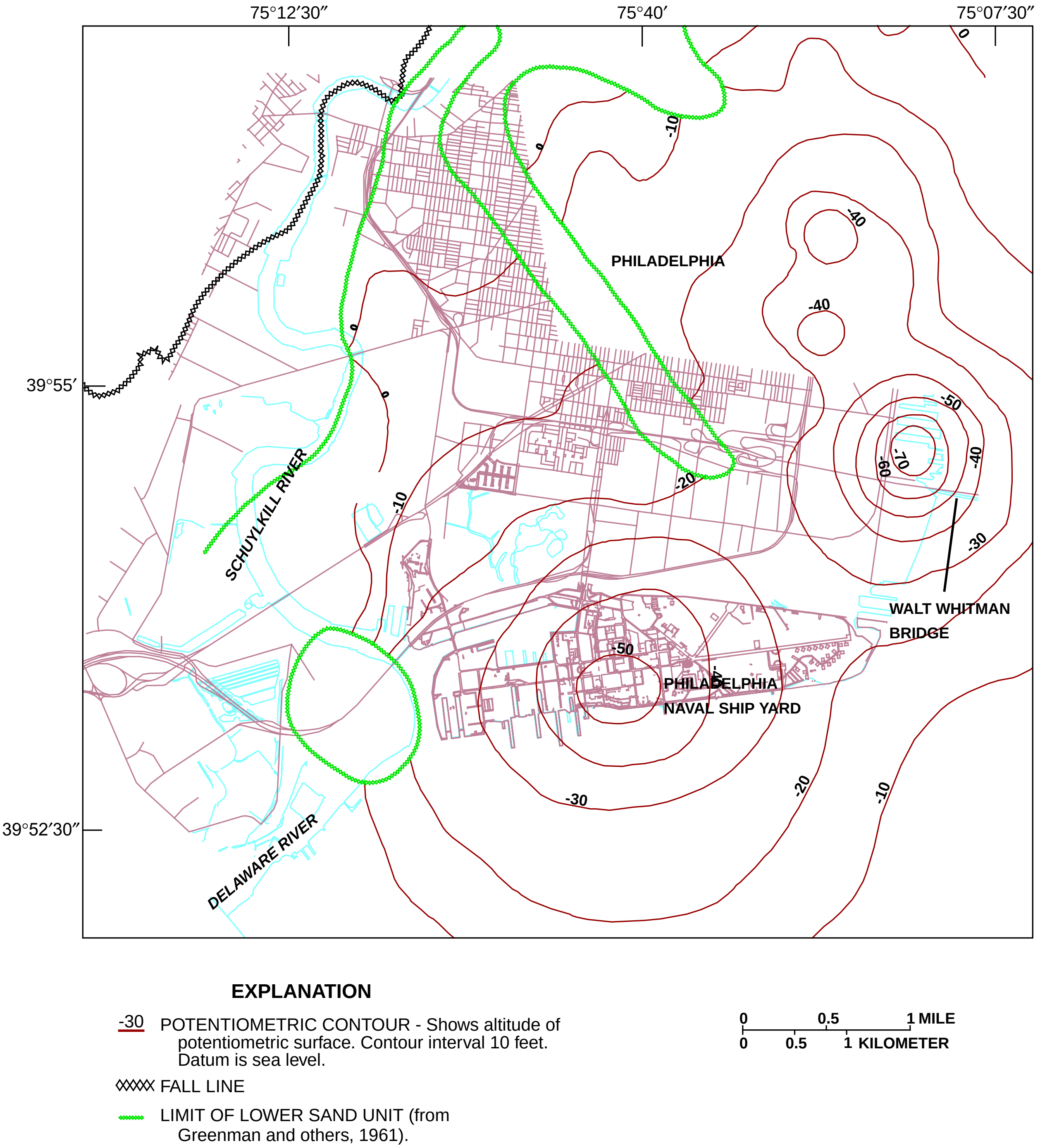
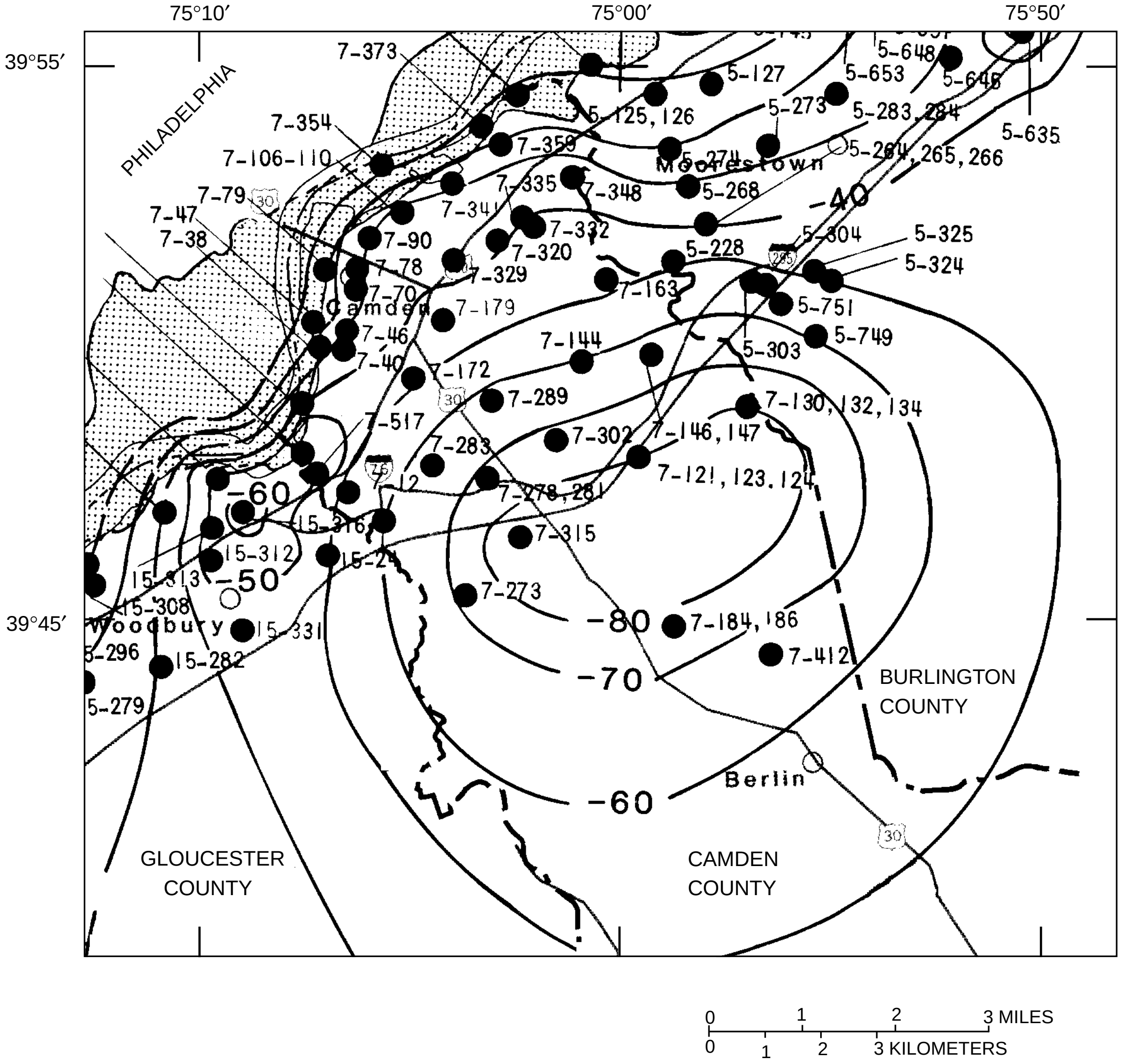


Figure 8. Potentiometric surface of the lower sand unit of the Potomac-Raritan-Magothy aquifer system in south Philadelphia, March 24, 1954 (modified from Greenman and others, 1961, figure 17 by Schreffler, 2001, p. 20).



EXPLANATION

▨ OUTCROP AREA OF THE LOWER AQUIFER

—— -70 — POTENTIOMETRIC CONTOUR - Shows altitude of the potentiometric surface. Contour interval is 10 feet. Datum is NGVD 29.

7-315 ● WATER-LEVEL MEASUREMENT SITE AND IDENTIFICATION NUMBER

Figure 9. Regional potentiometric surface of the lower aquifer of the Potomac-Raritan-Magothy aquifer system, 1978 (from Walker, 1983, pl. 1).

Ground-water pumpage data for 1978-97 presented by Lacombe and Rosman (2001) for southern New Jersey counties indicate that withdrawals peaked and then began to decline in 1981 in the middle aquifer, in 1983 in the lower aquifer, and in 1989 in the upper aquifer (fig. 10). Regional potentiometric-surface maps for the PRM aquifer system for 1988 were presented by Rosman and others (1995). The map for the lower aquifer (Rosman and others, 1995, pl. 8) shows that water levels were as deep as 103 ft below NAVD 88 in New Jersey and 8 ft below NAVD 88 in Philadelphia (fig. 11). The map for the middle and undifferentiated aquifer shows a large cone of depression with water levels as deep as 107 ft below NAVD 88 in New Jersey and 6 ft below NAVD 88 in Philadelphia (Rosman and others, 1995, pl. 7). The map for the upper aquifer shows a large cone of depression with water levels as deep as 88 ft below NAVD 88 in New Jersey and 7 ft below NAVD 88 in Philadelphia (Rosman and others, 1995, pl. 6).

In 1994, the New Jersey Department of Environmental Protection designated Water Supply Critical Area Number 2, which identified the PRM aquifer system in parts of Camden and Gloucester Counties as depleted and reduced water-supply allocations by an average of 22 percent in that area (New Jersey Department of Environmental Protection, 2002). In response, surface-water supplies are being developed and brought into the area.

More detailed potentiometric-surface maps for the PRM aquifer system for 1996 in the vicinity of the PNSY were presented by Rosman (1997). The map for the lower aquifer (Rosman, 1997, sheet 4) shows water levels in Philadelphia as deep as 13 ft below NAVD 88 and cones of depression directly south of the PNSY in New Jersey with water levels as deep as 57 ft below NAVD 88 (fig. 12).

Regional potentiometric-surface maps for the PRM aquifer system for 1998 were presented by Lacombe and Rosman (2001). The map for the lower aquifer (Lacombe and Rosman, 2001, sheet 10) shows a large cone of depression with water levels recovering to 62 ft below NAVD 88 in New Jersey but declining to 16 ft below NAVD 88 in Philadelphia (fig. 13). This reflects a rise in water level of 41 ft at the center of the cone of depression in New Jersey. The map for the middle and undifferentiated aquifer (Lacombe and Rosman, 2001, sheet 9) shows a large cone of depression with water levels recovering to 66 ft below NAVD 88 and a smaller cone of depression with water levels recovering to 61 ft below NAVD 88; water levels in Philadelphia are as deep as 4 ft below NAVD 88. The map for the upper aquifer (Lacombe and Rosman, 2001, sheet 8) shows a large cone of depression containing two smaller cones of depression with water levels as deep as 102 ft below NAVD 88 in New Jersey and 6 ft below NAVD 88 in Philadelphia.

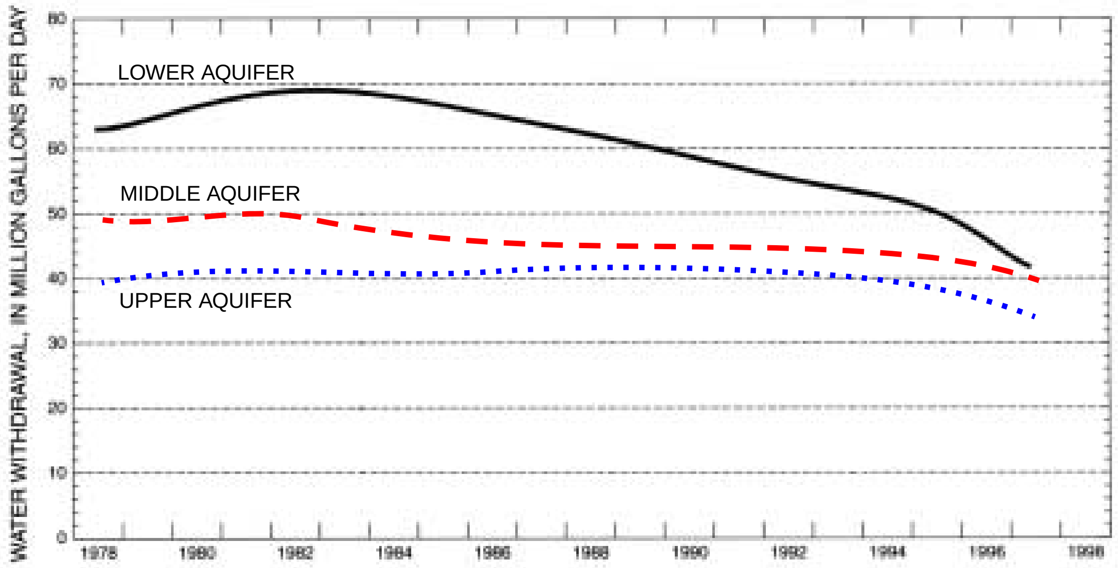
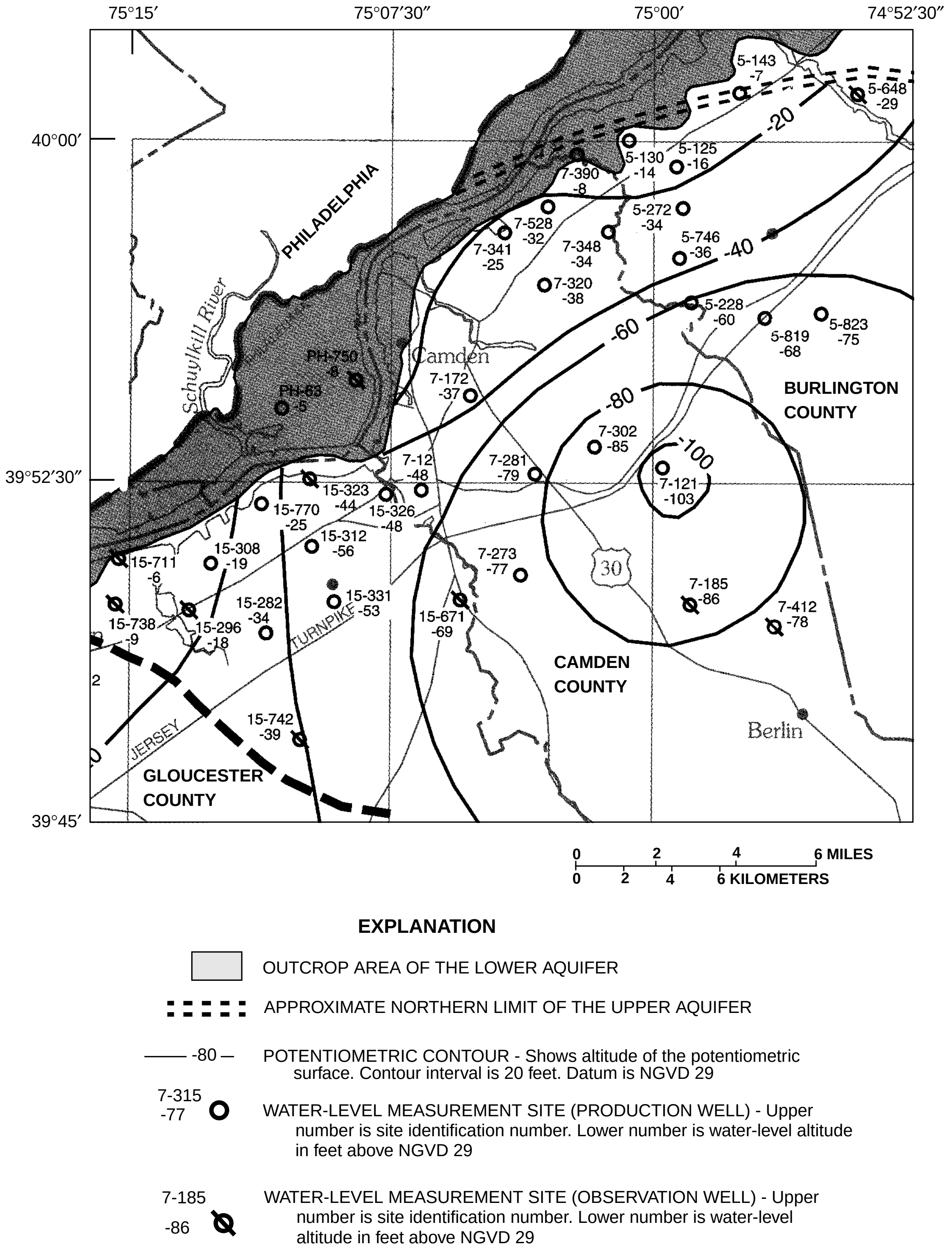


Figure 10. Estimated water withdrawals from the Potomac-Raritan-Magothy aquifer system, southern New Jersey counties, 1978-97 (modified from Lacombe and Rosman, 2001).



EXPLANATION

▨ OUTCROP AREA OF THE LOWER AQUIFER

APPROXIMATE NORTHERN LIMIT OF THE UPPER AQUIFER

-80 POTENTIOMETRIC CONTOUR - Shows altitude of the potentiometric surface. Contour interval is 20 feet. Datum is NGVD 29

7-315 -77 WATER-LEVEL MEASUREMENT SITE (PRODUCTION WELL) - Upper number is site identification number. Lower number is water-level altitude in feet above NGVD 29

7-185 -86 WATER-LEVEL MEASUREMENT SITE (OBSERVATION WELL) - Upper number is site identification number. Lower number is water-level altitude in feet above NGVD 29

Figure 11. Regional potentiometric surface of the lower aquifer of the Potomac-Raritan-Magothy aquifer system, 1988 (from Rosman and others, 1995, pl. 8).

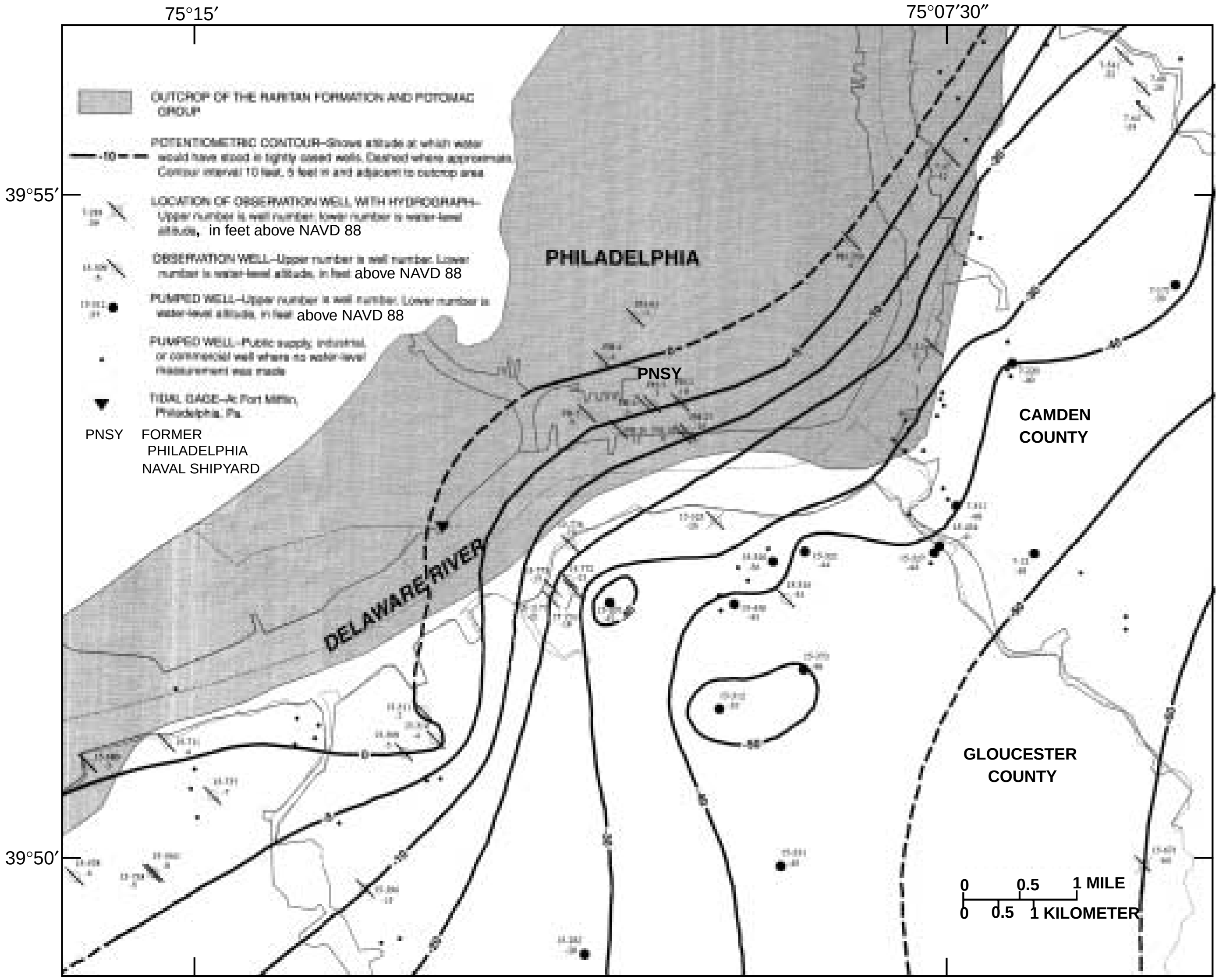
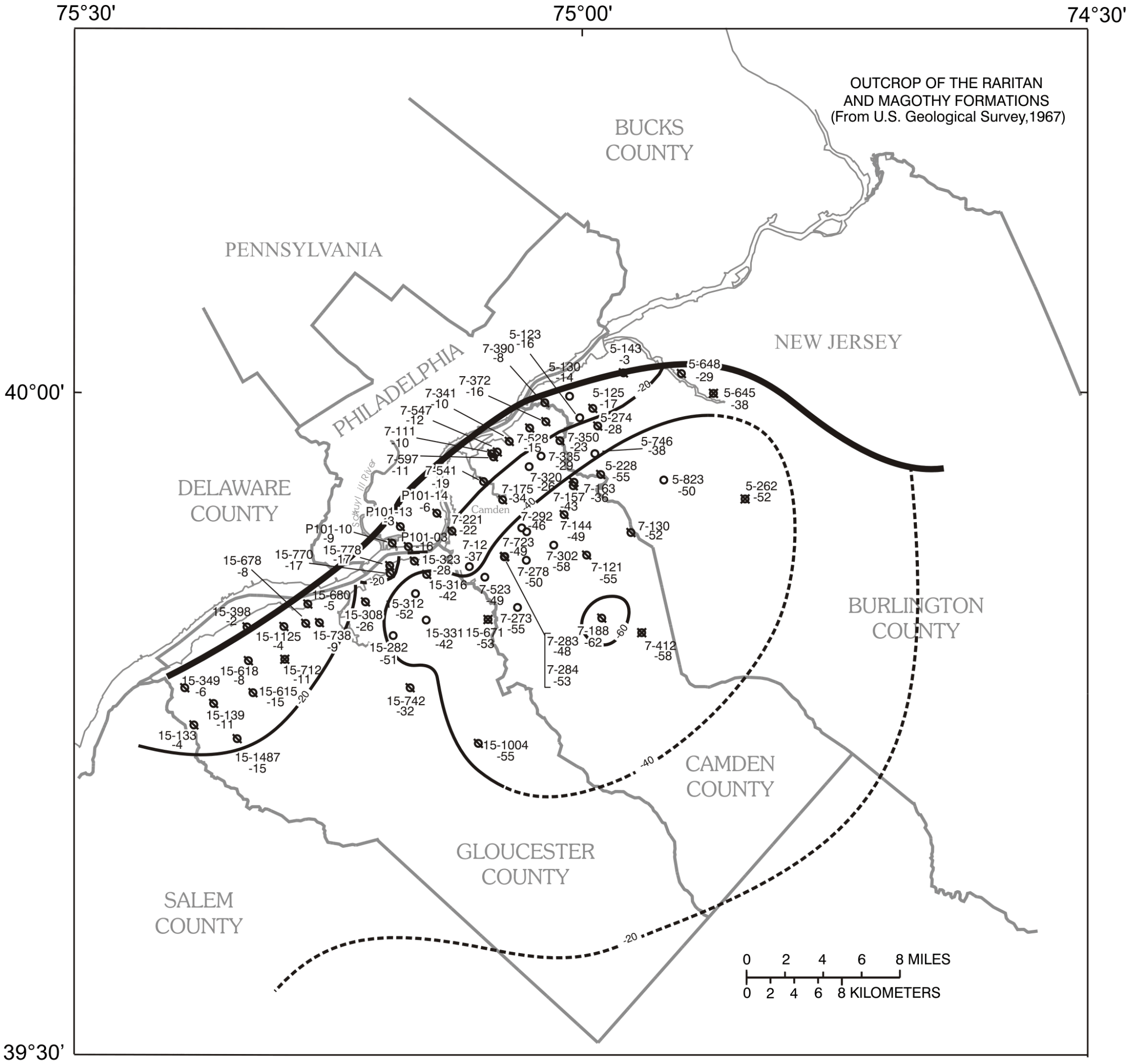


Figure 12. Regional potentiometric surface of the lower aquifer of the Potomac-Raritan-Magothy aquifer system, 1996 (modified from Rosman, 1997, sheet 4).



EXPLANATION

—-20— —	POTENTIOMETRIC CONTOUR - Shows altitude at which water would have stood in a tightly cased well. Dashed where approximate. (Dashed modified from Martin, 1984, 1990). Contour interval 20 feet
━━━	APPROXIMATE NORTHWESTERN LIMIT OF THE CONFINED AQUIFER (From Martin, 1984, 1998)
☒ 7-412 -57	OBSERVATION WELL WITH HYDROGRAPH - Upper number is well number; lower number is water-level altitude, in feet above NAVD 88
⊘ 33-458 -33	OBSERVATION WELL - Upper number is well number; lower number is water-level altitude, in feet above NAVD 88. Well was not pumped during the 24 hours before water-level measurement
○ 7-188 -62	PRODUCTION WELL - Upper number is well number; lower number is water-level altitude, in feet above NAVD 88. Well may have been pumped during the preceding 24 hours, but not during the hour before water-level measurement

Figure 13. Regional potentiometric surface of the lower aquifer of the Potomac-Raritan-Magothy aquifer system, 1998 (modified from Rosman, 1997, sheet 10).

IRON, MANGANESE, AND SULFATE CONCENTRATIONS

The outcrop area of the PRM aquifer system is densely populated and intensely developed. Thus, the area is highly susceptible to contamination from human point and nonpoint sources. The spread of contamination in the subsurface has been exacerbated by changes in the ground-water-flow system as a result of the withdrawal of large quantities of ground water.

Barksdale and others (1958, p. 121) noted in the late 1950s that "*the heaviest pumping and lowest water levels or artesian pressures are on the Pennsylvania side of the river, and water of good quality is being drawn across the river from the New Jersey side, beneath the aquiclude. Thus, in effect, the heavy pumping at the Naval Base has shielded the wells on the New Jersey side of the river from the mineralized water. If the pumping at the Naval Base should be greatly curtailed, the highly mineralized waters would tend to move past the wells there and beneath the river to the wells in New Jersey, creating a situation similar to that now existing in southern Camden.*"

Barksdale and others (1958, p. 118) also noted that "*The mineral content of the water from some wells in southern Camden is now also higher than that of the river waters or of any surrounding ground water except that in southern Philadelphia. These data seem to indicate that the highly mineralized water originating in southeastern Philadelphia may have spread to the area of heavy pumping in southern Camden. They are, however, inadequate for a positive conclusion, and the question should receive further study. They do serve to emphasize the fact that it is possible to draw water under the river from one side to the other, depending upon the gradients created by the pumping.*"

Elevated iron concentrations are responsible for the most persistent water-quality problems associated with ground water from the PRM aquifer system (Ervin and others, 1994, p. 59). Iron concentrations in ground water can be increased directly by contamination or indirectly by processes that cause dissolution of iron minerals. Microbial decomposition of organic wastes from sources such as leaky sewers, septic systems, landfills, and municipal and industrial wastewater disposal consumes oxygen and leads to reducing conditions in ground water; under these conditions, dissolved iron concentrations can be as high as 1,000 mg/L (Langmuir, 1969, p. 21). The decomposition process also can release protons (H^+) into the ground-water system, lowering the pH and thereby promoting leaching of iron from iron-bearing minerals in the aquifer matrix.

The subsurface environment in the vicinity of large water-supply wells can vary from aerobic (oxidizing) to anaerobic (reducing) with resultant variations in mineral stability and dissolved constituent concentrations (fig. 14). Aerobic conditions may be facilitated by pumping or other stresses that remove water from the aquifer or draw shallow oxygenated water to deeper zones. Reducing or anaerobic conditions can develop because of sustained organic loading associated with municipal waste, leaking sewer pipes, and industrial or chemical discharges that deplete oxygen.

Elevated concentrations of sulfate generally are a consequence of oxidation processes, whereas elevated concentrations of dissolved iron and manganese can be a consequence of oxidation and (or) reduction processes. The oxidation processes typically are acid-forming reactions that can consume bicarbonate and cause pH to decrease. For example, the introduction of oxygenated water or air into shallow zones (aerobic zone in figure 14) can facilitate the oxidation of organic compounds (eqn. 1) and inorganic compounds such as pyrite (eqn. 2), producing sulfate (SO_4^{2-}), iron (Fe^{2+}), protons (H^+), and carbon dioxide (CO_2).

$$CH_2O + O_2 \rightarrow CO_2 + H_2O \qquad (1)$$

$$FeS_2 + 3.5\ O_2 + H_2O \rightarrow Fe^{2+} + 2\ SO_4^{2-} + 2\ H^+ \qquad (2)$$

$$Fe^{2+} + 0.25\ O_2 + 2.5\ H_2O \rightarrow Fe(OH)_3\ (s) + 2\ H^+ \qquad (3)$$

In equation 1, "CH_2O" is a simplified representation of organic compounds; the accumulation of CO_2 would tend to lower the pH of the system. In equation 2, only pyritic sulfur is oxidized; dissolved ferrous iron (Fe^{2+}) is a product. At near-neutral pH, the solubility of Fe^{2+} is many orders of magnitude greater than that of oxidized, ferric iron (Fe^{3+}). The oxidation of Fe^{2+} to Fe^{3+} can be catalyzed by iron-oxidizing bacteria that are native or introduced to the subsurface environment (Ehrlich, 1990). In equation 3, the Fe^{2+} ions oxidize and hydrolyze forming solid Fe(III) oxyhydroxide. The Fe(III) compounds accumulate, forming encrustations on well screens where O_2 and Fe^{2+} are locally available.

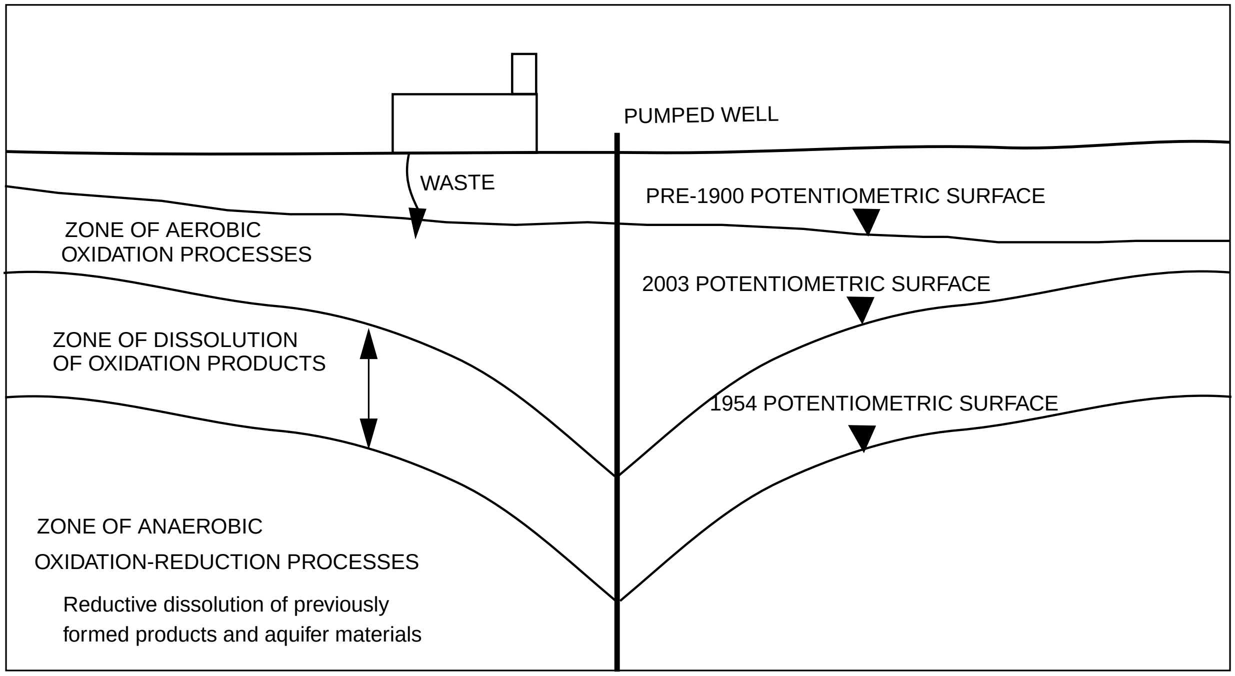


Figure 14. Conceptual section illustrating geochemical regimes in the aquifer affected by lowering and recovery of water levels.

Under anoxic conditions (anaerobic zone in figure 14), facultative bacteria may use other terminal electron acceptors (ions or compounds containing oxygen molecules) such as NO_3^-, NO_2^-, SO_4^{2-}, Mn(IV), or Fe(III) oxides to oxidize organic compounds. For example, the reduction of previously oxidized iron compounds such as ferrihydrite (eqn. 4) or goethite (eqn. 5) can produce elevated concentrations of dissolved iron.

$$4\ Fe(OH)_3 + CH_2O + 7\ H^+ \rightarrow 4\ Fe^{2+} + HCO_3^- + 10\ H_2O \qquad (4)$$

$$4\ FeOOH + CH_2O + 7\ H^+ \rightarrow 4\ Fe^{2+} + HCO_3^- + 6\ H_2O \qquad (5)$$

The reductive dissolution of Fe(III) oxide, coupled with the oxidation of organic matter, can increase alkalinity and pH. Similar reactions can be written for the reductive dissolution of Mn(III-IV) oxyhydroxide compounds and the consequent release of manganous ions (Mn^{2+}).

The overall reactions given above will proceed spontaneously, yielding energy for the organisms involved. Generally, in addition to elevated concentrations of Fe^{2+} and Mn^{2+}, environments favoring reductive dissolution of Fe(III) and Mn(IV) compounds may have elevated concentrations of CO_2 and other reduced species, such as ammonia (NH_4^+, NH_3) and hydrogen sulfide (H_2S, HS^-). Aeration of these solutions can promote the exsolution of the dissolved gases and a consequent increase in pH. For example, the exsolution of CO_2 can cause pH to increase in the vicinity of a pumped well (eqn. 6).

$$HCO_3^- \rightarrow CO_2\ (g) + OH^- \qquad (6)$$

Hence, aeration introduces O_2 and can increase pH, both of which favor the formation of Fe(III) and Mn(IV) oxides. Sustained or pulsed pumping can cause aeration in the vicinity of a well and lead to localized well-screen encrustation where Fe^{2+} and Mn^{2+} are abundant in the pumped water and insoluble iron and manganese hydroxides are formed.

Changes in Iron, Manganese, and Sulfate Concentrations With Time

Historical ground-water-quality data for wells screened in the lower aquifer of the PRM collected by the USGS are available for south Philadelphia beginning in 1943, for the adjacent part of Camden County beginning in 1949, and for the adjacent part of Gloucester County beginning in 1950 (fig. 15). Data presented in this section were retrieved from the USGS National Water Information System (NWIS) database. However, the historical data are sparse and temporally and spatially discontinuous and are not sufficient to permit a complete picture of changes in iron, manganese, and sulfate concentration.

Major ground-water withdrawals at the former PNSY began in 1941. The USGS collected the first samples for water-quality analysis in 1943, the peak year for pumping. In 1943, dissolved iron concentrations ranged from 0.07 to 0.6 mg/L. By 1945, dissolved iron concentrations exceeded 1 mg/L, and by 1956, dissolved iron concentrations exceeded 9 mg/L. In 1967, when the wells at the PNSY were abandoned, dissolved iron concentrations had reached 46 mg/L (fig. 16).

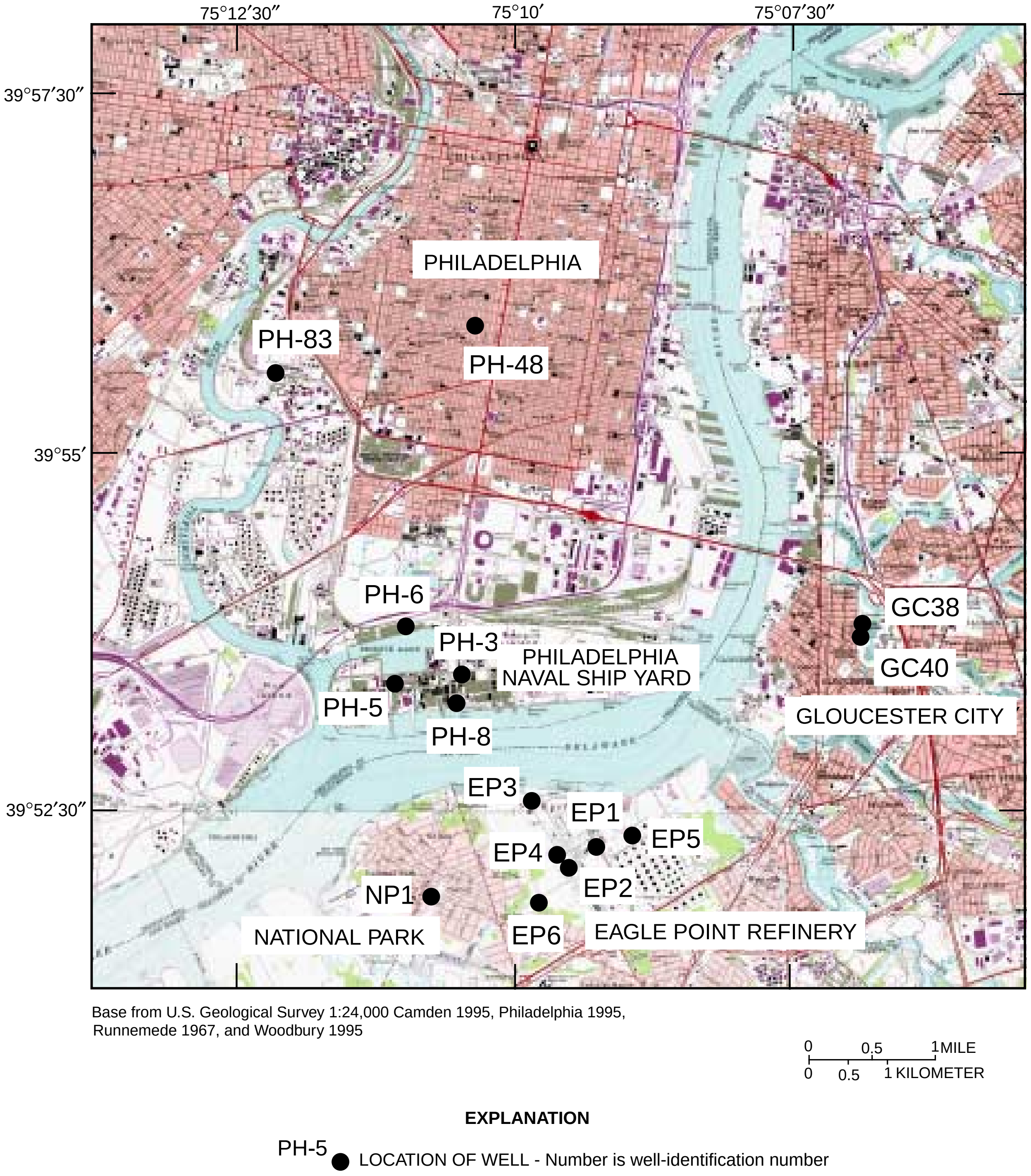
Each of the wells at the PNSY (except for well PH-5) produced water of acceptable quality for a period of about 1 to 5 years. This time probably represents the amount of time required by each well to discharge the original water of good quality in storage in the aquifer and to start yielding water from surface recharge areas. Well PH-8, situated the farthest downdip and partially shielded from the surface recharge area by the other PNSY wells, produced water of good quality from 1944 to 1950. In July 1950, the mineral concentration in the water from well PH-8 increased sharply. It is probable that this rapid change was due in part to the shutdown of several wells to the north, thereby permitting more surface-recharge water with a higher concentration of dissolved minerals to reach well PH-8 by moving past the idle wells (Graham and Kammerer, 1952, p. 69-70).

Data for dissolved iron concentrations for water samples from industrial wells in Philadelphia prior to 1946 are not available. Water samples collected by USGS in 1947 from two industrial wells screened in the lower sand unit had a dissolved iron concentration of 0.17 mg/L. By 1979, the dissolved iron concentration in water from well PH-83 was 19 mg/L (fig. 17).

Dissolved iron concentrations in water samples from wells screened in the lower aquifer in New Jersey sampled by USGS in 1949-50 ranged from 0.02 to 0.73 mg/L. Water samples collected from four wells screened in the lower aquifer at the Eagle Point Refinery, which is directly across the Delaware River from the former PNSY, had dissolved iron concentrations ranging from 0.11 to 0.73 mg/L. Iron concentrations in water samples from wells at the Eagle Point Refinery have increased with time (fig. 18).

The concentration of dissolved iron in water samples from other wells screened in the lower aquifer in New Jersey also increased with time. By 1966-67, dissolved iron concentrations were as high as 4.8 mg/L for Gloucester City wells (fig. 19), and 1.4 mg/L for Eagle Point Refinery wells. By 1985, dissolved iron concentrations were as high as 16 mg/L for Eagle Point Refinery wells. Current (2002) iron concentrations reported by water purveyors in water from production wells in New Jersey commonly exceed 1 mg/L and are as high as 16 mg/L.

Ervin and others (1994, p. 74) presented a map of dissolved iron concentrations in water from the lower aquifer for 1980-86 (fig. 20). The map shows dissolved iron concentrations greater than 25 mg/L in Philadelphia and greater than 10 mg/L in New Jersey south of the former PNSY.



Base from U.S. Geological Survey 1:24,000 Camden 1995, Philadelphia 1995, Runnemede 1967, and Woodbury 1995

Figure 15. Location of wells screened in the lower aquifer of the Potomac-Raritan-Magothy aquifer system with historical dissolved iron concentrations.

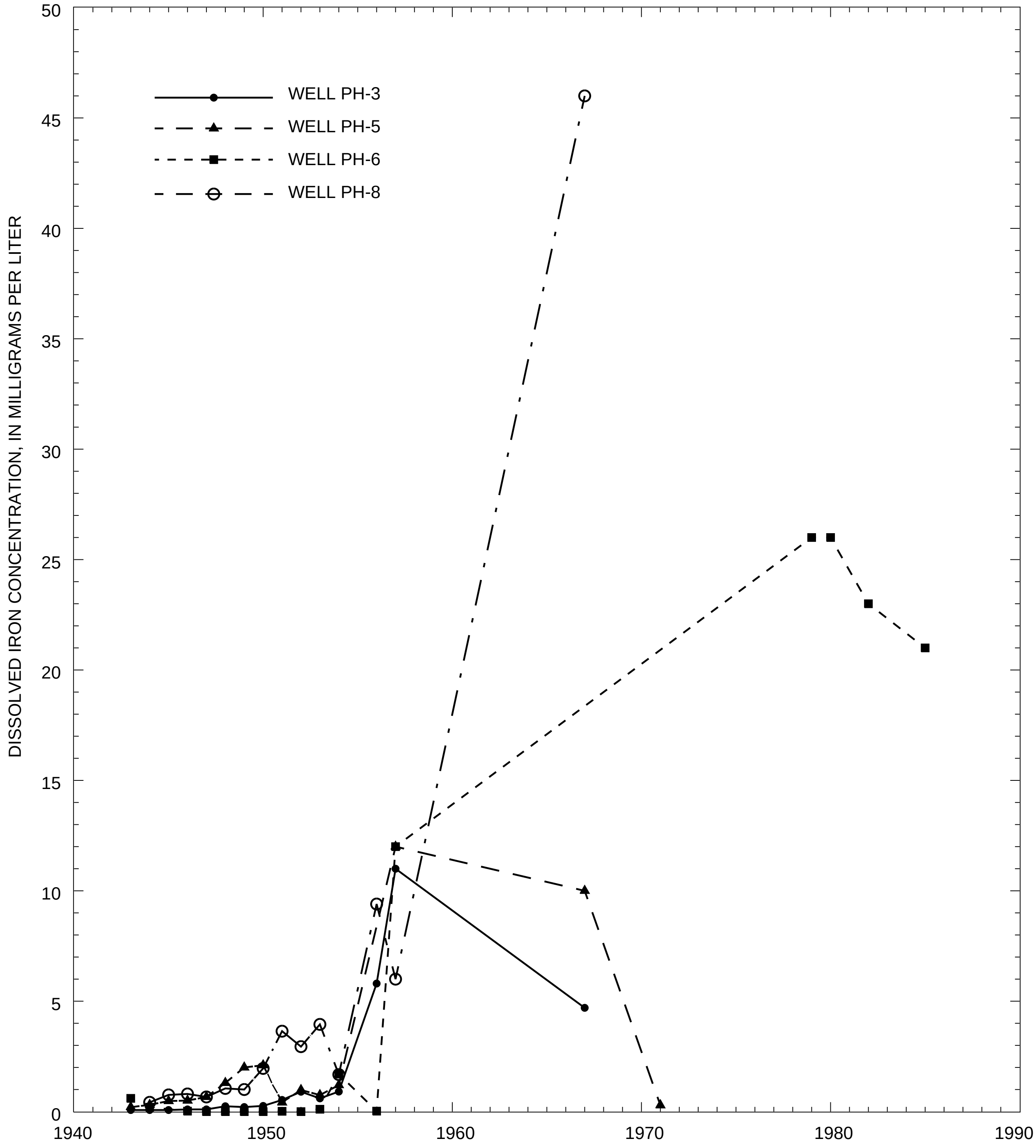


Figure 16. Concentrations of dissolved iron in water from wells screened in the lower sand unit of the Potomac-Raritan-Magothy aquifer system at the former Philadelphia Naval Ship Yard, 1943-85. Well locations are shown on figure 15. (Data from U.S. Geological Survey National Water Information System.)

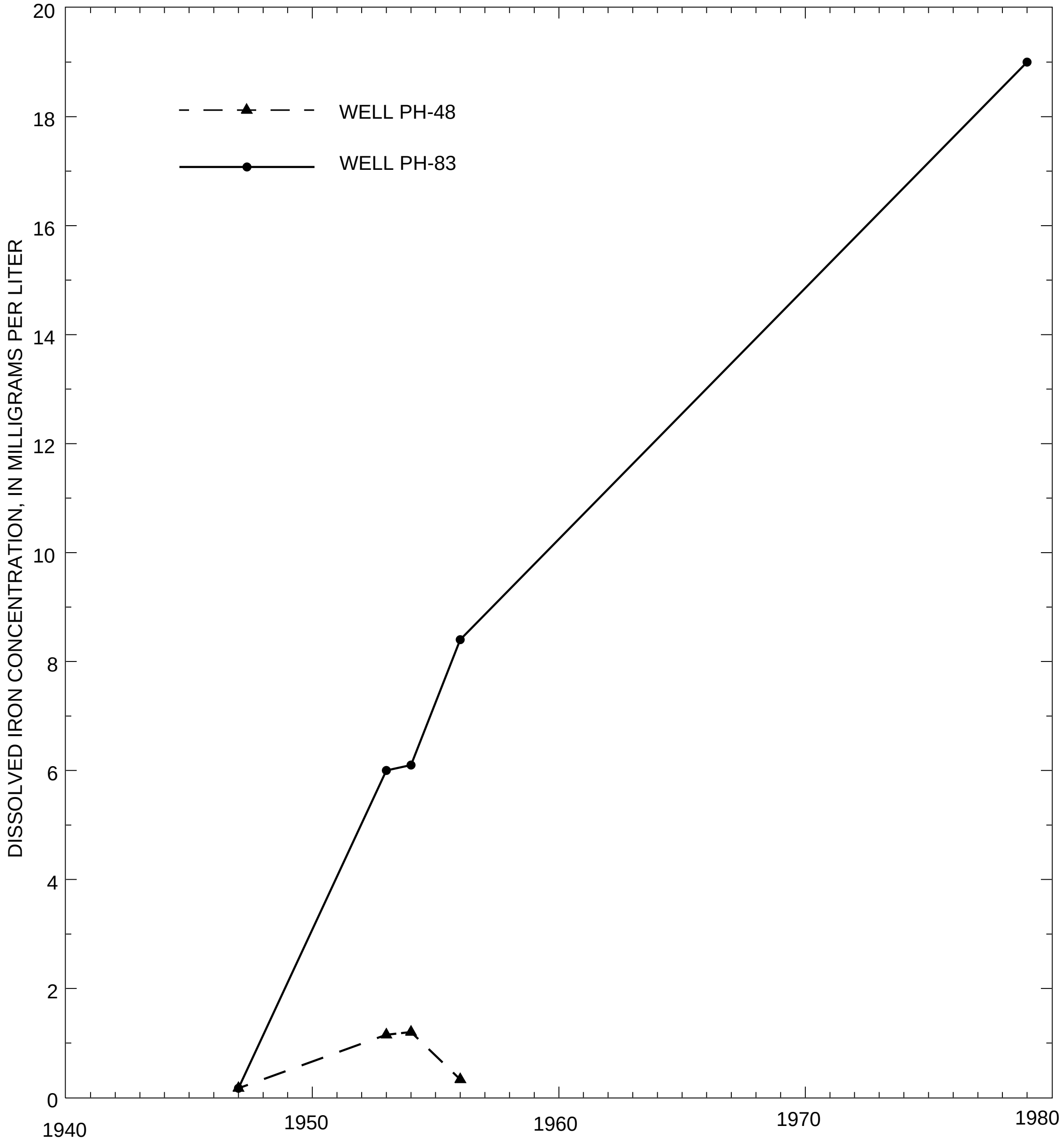


Figure 17. Concentrations of dissolved iron in water from industrial supply wells screened in the lower sand unit of the Potomac-Raritan-Magothy aquifer system in Philadelphia, 1947-79. Well locations are shown on figure 15. (Data from U.S. Geological Survey National Water Information System.)

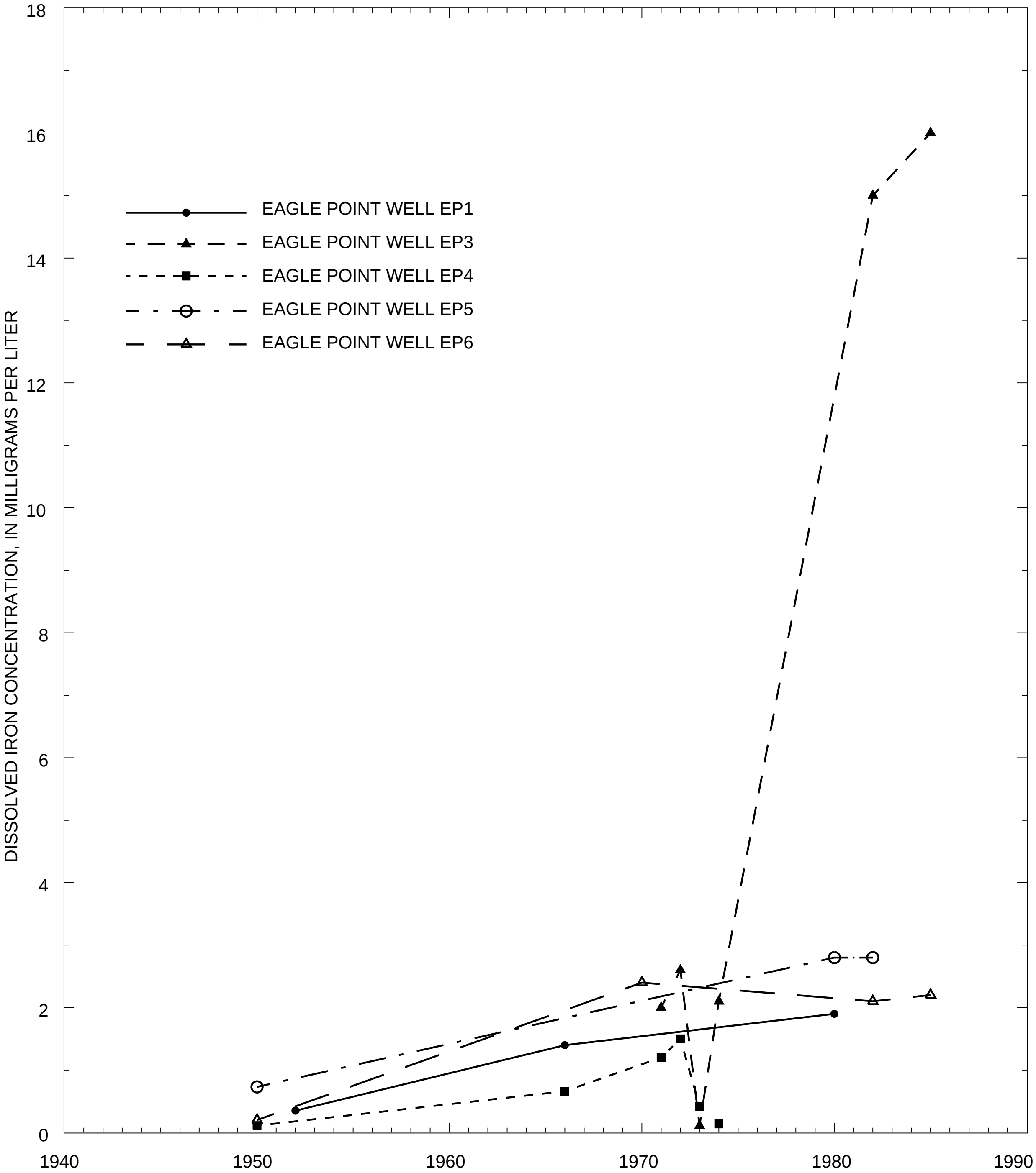


Figure 18. Concentrations of dissolved iron in water from wells screened in the lower aquifer of the Potomac-Raritan-Magothy aquifer system at the Eagle Point Refinery, Gloucester County, N.J., 1950-85. Well locations are shown on figure 15. (Data from U.S. Geological Survey National Water Information System.)

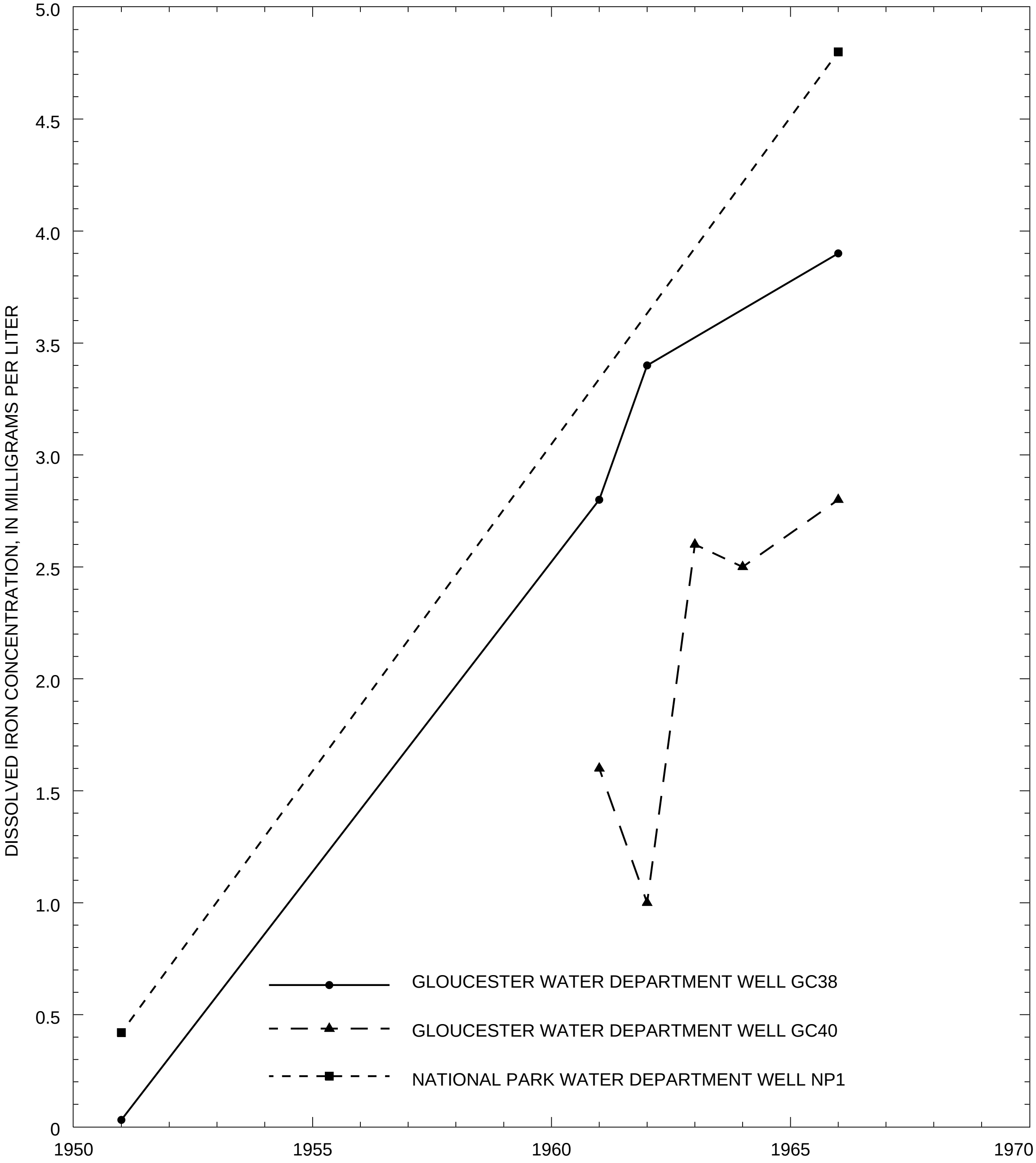


Figure 19. Concentrations of dissolved iron in water from wells screened in the lower aquifer of the Potomac-Raritan-Magothy aquifer system in Gloucester County, N.J., 1951-66. Well locations are shown on figure 15. (Data from U.S. Geological Survey National Water Information System.)

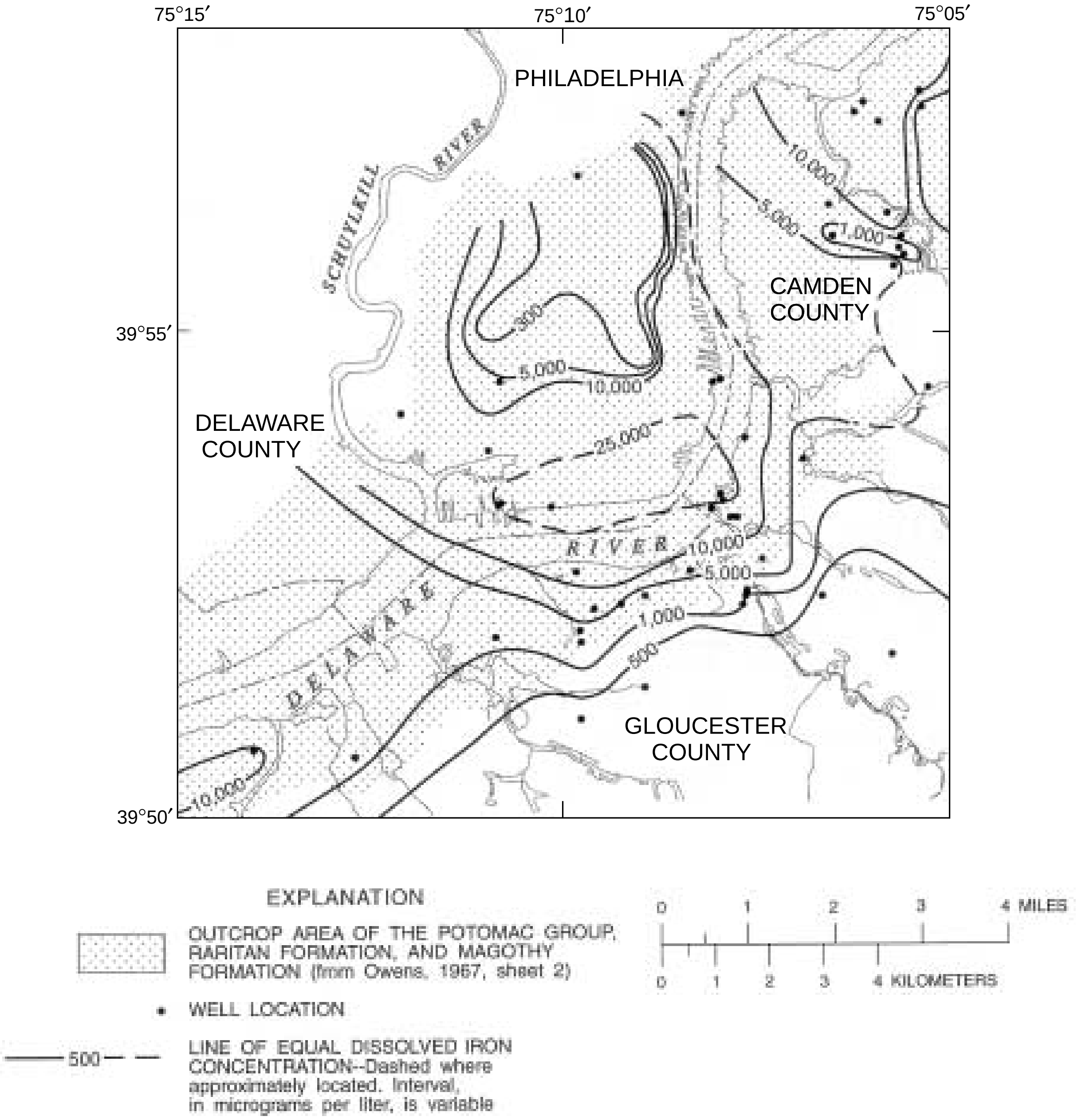


Figure 20. Concentrations of dissolved iron in water from the lower aquifer of the Potomac-Raritan-Magothy aquifer system, Philadelphia, Pa., and Camden and Gloucester Counties, N.J., 1980-86 (from Ervin and others, 1994, p. 74).

In addition to the increase in iron concentration with time, concentrations of manganese and sulfate in ground water in the PRM aquifer system also are increasing with time. Unfortunately, few data are available for manganese and sulfate concentrations. Paulachok (1991, p. 59 and 62) presented graphs of manganese and sulfate concentrations in water from wells screened in the lower sand unit at the PNSY collected between 1945 and 1982 that showed concentrations increasing with time (figs. 21 and 22). Ervin and others (1994, p. 75) presented a map of dissolved manganese concentrations in water from the lower aquifer for 1980-86 (fig. 23). The map shows dissolved manganese concentrations greater than 5 mg/L in Philadelphia and greater than 0.25 mg/L in New Jersey southeast of the former PNSY. Ervin and others (1994, p. 77) also presented a map of dissolved sulfate concentrations in water from the lower aquifer for 1980-86 (fig. 24). The map shows dissolved sulfate concentrations greater than 100 mg/L in Philadelphia and greater than 50 mg/L in New Jersey south of the former PNSY.

Role of Bacteria

Iron-related well-screen incrustation, aquifer biofouling, and subsequent loss in well yield are costly problems that are a concern locally and nationally. Iron-related yield declines are common in wells screened in unconsolidated sediments, such as those underlying the Pennsylvania-New Jersey Coastal Plain. Iron-related well-screen incrustation is an oxidation-reduction process that involves the oxidation of ferrous iron to ferric iron and its rapid precipitation as insoluble iron hydroxide. The rate of oxidation of ferrous iron in ground water is strongly dependent on pH and dissolved oxygen concentration. Iron-oxidizing bacteria can catalyze the oxidation of ferrous iron, and biological oxidation of ferrous iron can be substantial in low-pH waters. Well-screen incrustation and aquifer

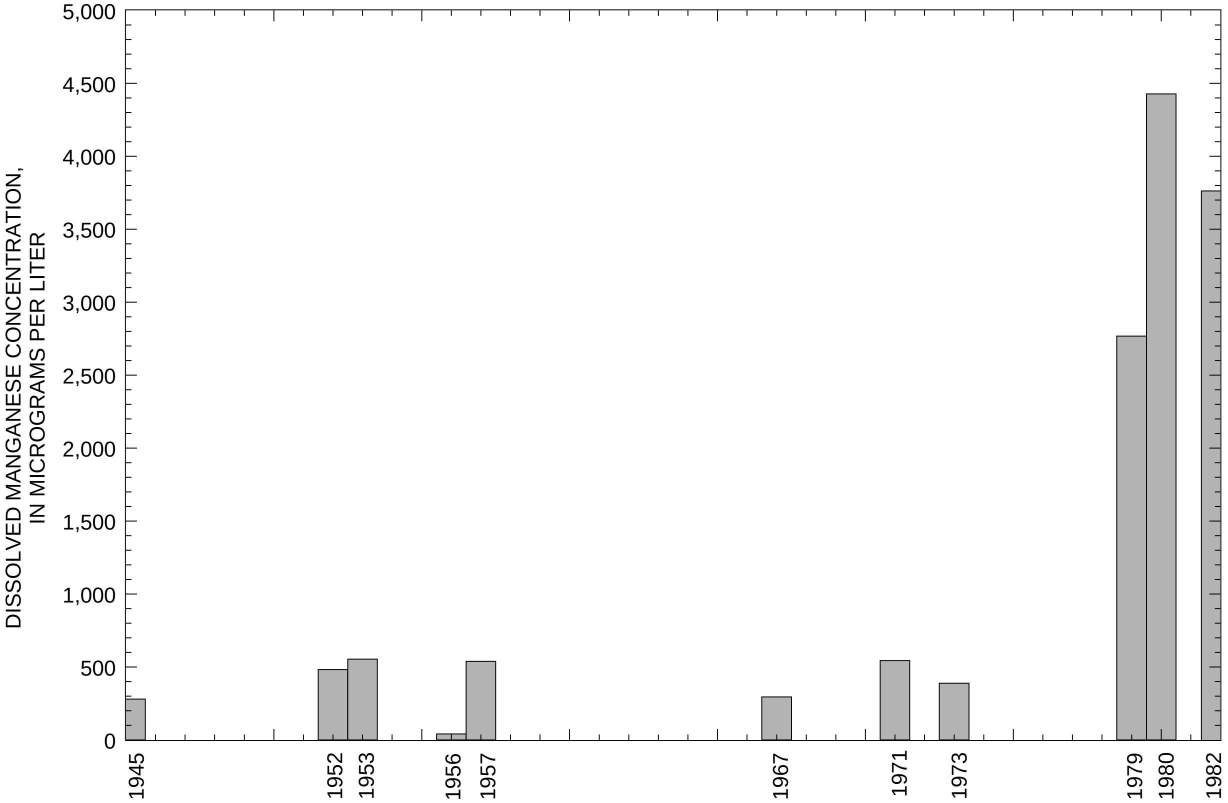


Figure 21. Concentrations of dissolved manganese in water from wells screened in the lower sand unit of the Potomac-Raritan-Magothy aquifer system at the former Philadelphia Naval Ship Yard, 1945-82 (from Paulachok, 1991, p. 59).

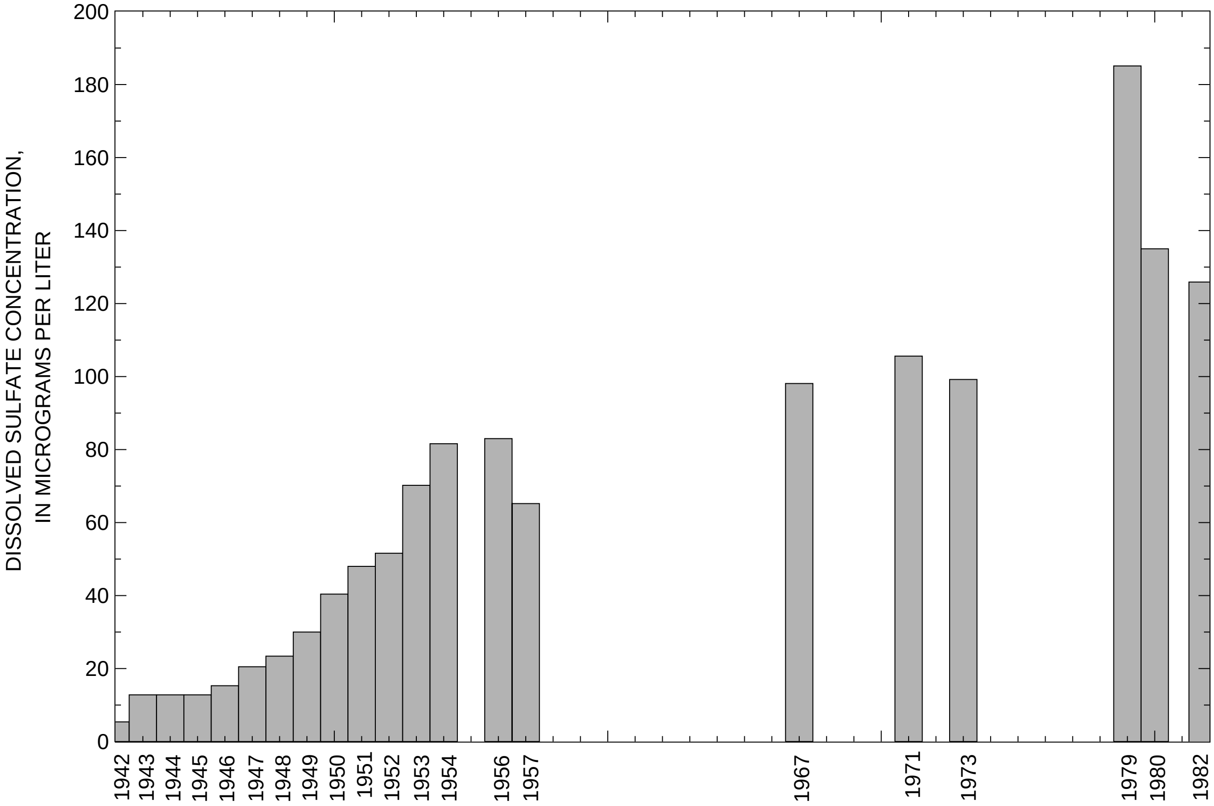


Figure 22. Concentrations of dissolved sulfate in water from wells screened in the lower sand unit of the Potomac-Raritan-Magothy aquifer system at the former Philadelphia Naval Ship Yard, 1942-82 (from Paulachok, 1991, p. 62).

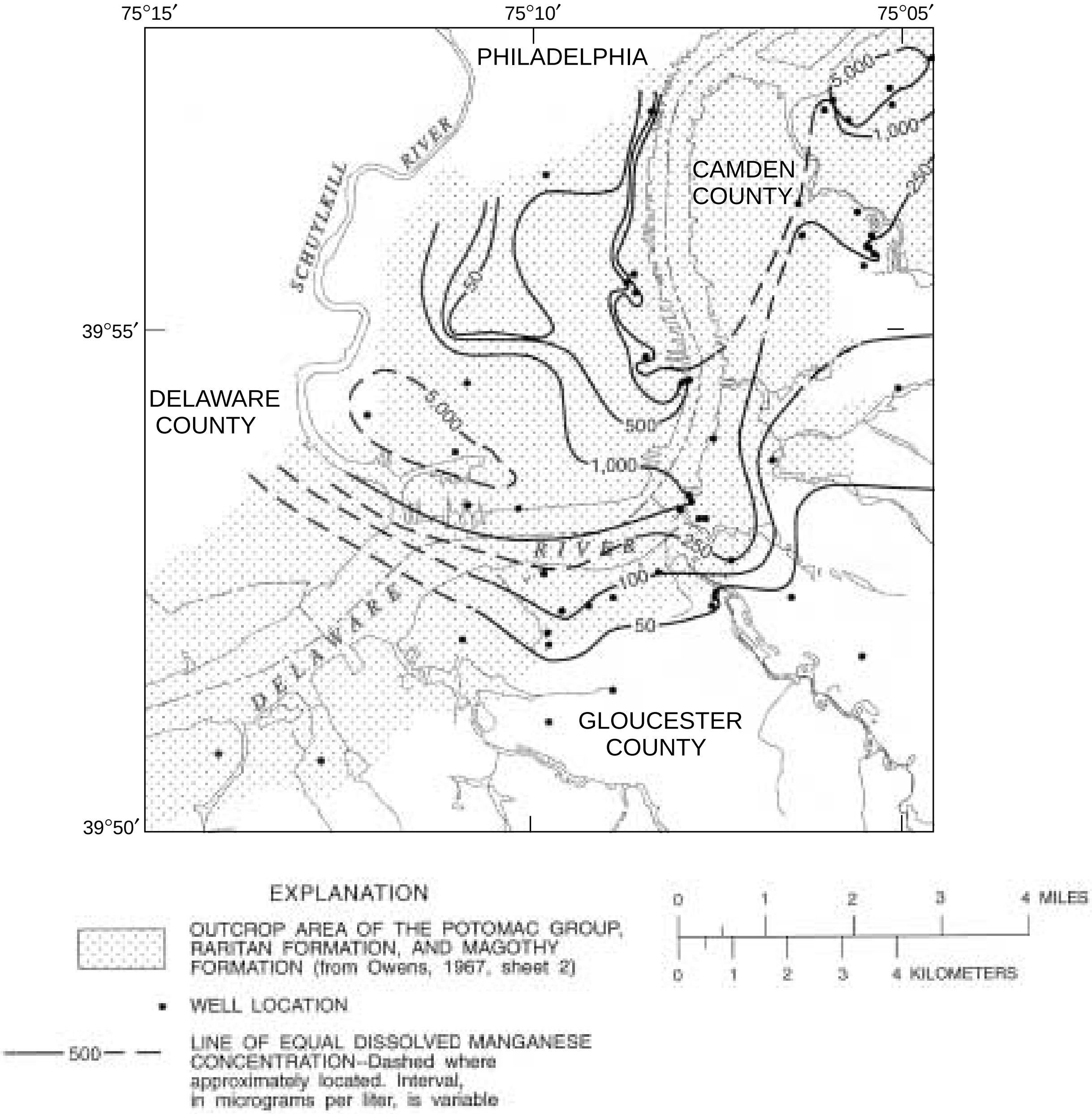


Figure 23. Concentrations of dissolved manganese in water from the lower aquifer of the Potomac-Raritan-Magothy aquifer system, Philadelphia, Pa., and Camden and Gloucester Counties, N.J., 1980-86 (from Ervin and others, 1994, p. 75).

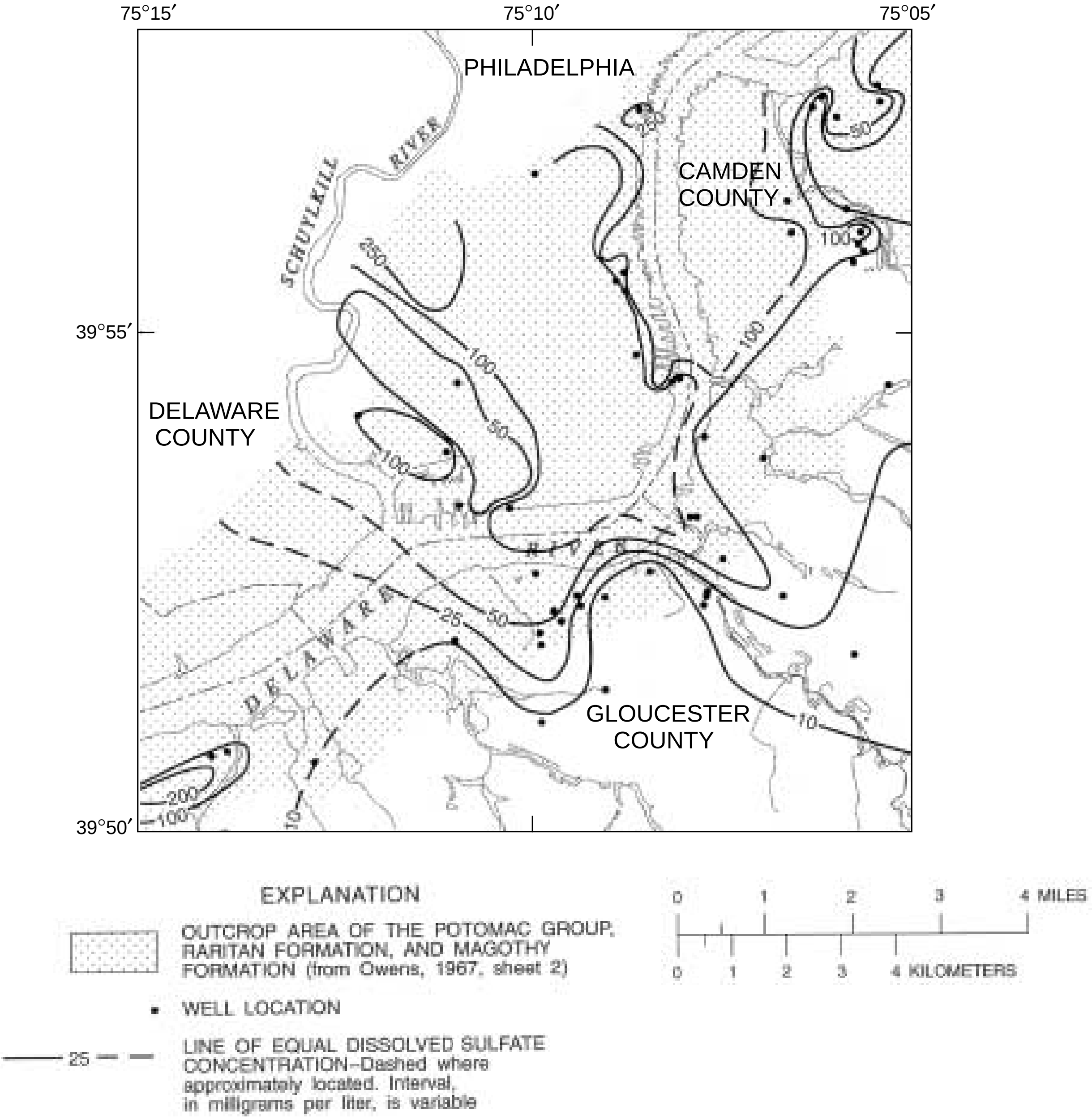


Figure 24. Concentrations of dissolved sulfate in water from the lower aquifer of the Potomac-Raritan-Magothy aquifer system, Philadelphia, Pa., and Camden and Gloucester Counties, N.J., 1980-86 (from Ervin and others, 1994, p. 77).

biofouling occur when filamentous iron bacteria produce large extracellular filaments that become coated with iron oxyhydroxides. This combination of ferric oxyhydroxides and extracellular material can clog not only well screens but pore spaces in the surrounding aquifer (Ghiorse, 1986). The growth of iron-oxidizing bacteria on well screens and in the surrounding aquifer begins when nonfilamentous iron-related bacteria colonize the surfaces of well screens and sediment grains. This organic substrate allows filamentous iron bacteria to form extensive biofilms. A typical biofilm consists of a consortium of organisms that represent several species of iron bacteria. Iron bacteria also can catalyze the oxidation of manganese. Manganese-related biofouling can occur in environments with high pH and high manganese concentrations.

The role of iron bacteria in well-screen incrustation, aquifer biofouling, and increasing iron concentration has not been investigated in the Pennsylvania-New Jersey Coastal Plain. A study by Walter (1997) in the Coastal Plain sediments of the Magothy Formation on Long Island, N.Y., indicated that iron bacteria play an important role in the incrustation and biofouling process and that iron bacteria biofilms can alter ground-water chemistry by removing iron, manganese, and sulfate from solution and increasing pH. Walter (1997) found that the most common species of iron bacteria was *Gallionella ferruginea*, an effective biofouling agent that prefers water with low, but detectable, dissolved oxygen concentrations and high dissolved iron concentrations.

Walter (1997) found that lignite in aquifer materials could act as a carbon source for heterotrophic iron bacteria, which could accelerate the formation of iron-bacteria biofilms in wells screened in some parts of the Magothy Formation. The PRM aquifer system contains lignite (Bascom and others, 1909, p. 9; Barksdale and others, 1958, p. 93). Lignin forms the base of microbial food chains in ground-water systems. Walter (1997) found that the presence of lignite near a well screen can accelerate the formation of iron-bacteria biofilms. The growth of heterotrophic iron bacteria such as *Pseudomonas* forms the organic substrate necessary for the growth of filamentous bacteria such as *Gallionella* and allows the bacteria to colonize the surface of the well screen.

Sulfate-reducing bacteria and iron-sulfide mineral phases were observed by Walter (1997) in some samples of incrusting material, indicating that these bacteria could contribute to well-screen incrustation in some geochemical environments. Bacterially mediated reduction of sulfate to sulfide and the precipitation of iron sulfide on well screens could contribute to the incrustation process. Pyrite in the PRM aquifer system (Barksdale and others, 1958, p. 93) may have formed where conditions were sufficiently reducing.

SUGGESTIONS FOR FURTHER STUDY

Further study of the controls on ground-water movement and aquifer geochemistry would help to provide a better understanding of the potential sources, extent, and spread of contaminated ground water in the PRM aquifer system. The current knowledge of the geologic framework includes the relation among the hydrogeologic units of the Coastal Plain on a regional scale but lacks necessary local detail. More detailed knowledge of the framework is needed in the area beneath and near the Delaware River where the hydrogeologic units may not fit the regional model of the Coastal Plain. A more detailed geologic framework model could be developed from available drilling, boring, and geophysical logs and possibly additional drilling. This would help to identify areas where the confining bed above the lower aquifer is present and ground-water flow is occurring beneath the Delaware River. It also may identify areas where the confining bed above the lower aquifer is missing and ground-water flow beneath the Delaware River is unlikely. It may help to identify areas in New Jersey where confining units are thin or absent and where vertical pathways exist for water and contaminant movement.

A ground-water-flow model could be used with forward and backward particle-tracking techniques to determine the contributing area for supply wells and time-of-travel of water and conservative solutes from source areas to wells. Particle tracking is a process where hypothetical particles are simulated as if they are carried along with ground-water flow. Particles are tracked through a flow field explicitly by computing the directional components of velocity at a particle's current position and moving the particle to a new location that is determined by multiplying those velocity components by a finite time step to obtain the incremental changes in the particle's coordinates over that interval of time. As this process is repeated, a series of coordinates are produced that trace the path of a particle through the flow field as a function of time (Pollock, 1988). Backward particle tracking introduces particles at a supply well and tracks them backward to determine the source areas contributing water to the well. Forward particle tracking introduces particles at the recharge area and tracks them along ground-water-flow paths. Affected areas could be identified, and travel-time contours could be generated.

Age dating of ground-water samples using tritium (^3H) and tritium/helium-3 ($^3H/^3He$) methods could be used to calibrate and (or) confirm simulated ground-water-flow model flow rates. ^3H is the radioactive isotope of hydrogen with a half-life of 12.43 years and is an excellent indicator of ground water recharged since 1952. Production of ^3H in the atmosphere naturally occurs by cosmic-ray spallation, but the principal source was the atmospheric testing of thermonuclear weapons that began in 1953. The explosions of nuclear devices produced peak ^3H concentrations in precipitation during 1963-64 and resulted in a large input of ^3H to the ground-water system. Atmospheric concentrations have declined gradually since 1964. Pumping at the former PNSY stopped in the mid-1960s, and around that time the reversal of hydraulic gradients caused water to start moving from Philadelphia toward New Jersey. Because the reversal of hydraulic gradients occurred around the mid-1960s, the $^3H/^3He$ method is an excellent tool to trace the movement of contaminated ground water in the PRM aquifer system that originated as recharge. ^3H and ^3He are virtually inert in ground water, unaffected by other substances in water, and unaffected by contamination from most anthropogenic sources. Apparent age estimates from the $^3H/^3He$ method can be extremely accurate (within months) for confined ground water containing high ^3H concentrations (waters recharged since 1963 that have not mixed with older water). Unlike other dating methods, such as using chlorofluorocarbons, $^3H/^3He$ is a valid technique for areas contaminated with organic compounds.

Wells in Philadelphia were last sampled in 1985, and no water-quality data have been collected since then. A resampling of available wells in Philadelphia could allow assessment of current conditions in the PRM aquifer system, show how the concentration of chemical constituents has changed since the last sampling took place, and help to estimate the mass of contaminants. Sampling recently drilled monitor wells in Philadelphia could provide additional data points to supplement historical data. In addition, active and unused supply wells and monitor wells in New Jersey in the area south and southeast of the former PNSY could be sampled to supplement data collected for Philadelphia. Chemical constituents analyzed could include $^3H/^3He$ for age determination; inorganic constituents including carbon, nitrogen, and sulfur species; major cations; trace metals; organic compounds, especially volatile organic compounds (VOCs) and their degradation products; and radionuclides.

Geochemical-reaction modeling may help to develop an understanding of the geochemical controls on the movement and precipitation of iron, manganese, and sulfate in the PRM aquifer system. A reactive-transport model capable of simulating chemical reactions of contaminants in ground water could be used to simulate aerobic and anaerobic degradation of organic chemicals and degradation pathways including reduction of Mn^{+4}, Fe^{+3}, and SO_4. Chemical-equilibria modeling may show which mineral phases in ground water would be thermodynamically favored to precipitate or dissolve.

To determine the types and sources of iron and sulfur bacteria associated with aquifer biofouling and well-screen incrustation, core samples from several locations within the PRM aquifer system could be tested. Analysis of cored aquifer sediments collected in the vicinity of public-supply wells could provide data on types of bacteria, biofilms, and changes to aquifer mineralogy. Evaluation of Fe(III)-reducing and SO_4-reducing activity of sediment slurries may indicate the zones of greatest potential for such reactions. The analyses could help define geochemical processes occurring in the aquifer and in screen incrustations.

SUMMARY

This study, which was prepared in cooperation with the U.S. Environmental Protection Agency, documents ground-water-flow patterns and water-quality trends in the lower aquifer of the Potomac-Raritan-Magothy (PRM) aquifer system. The sole-source PRM aquifer system is the largest and most productive of the Coastal Plain aquifers and is an important water-supply source in New Jersey. Most of the withdrawals from the lower aquifer of the PRM are in Camden and Gloucester Counties, and these supplies commonly contain elevated iron concentrations. Elevated iron concentrations are responsible for the most persistent and emerging water-quality problems associated with the use of ground water from the PRM aquifer system. Iron-related well-screen incrustation, aquifer biofouling, and well-yield loss are costly problems that are a concern to public water suppliers and industrial users. Much of the outcrop area of the PRM aquifer system is densely populated and intensely developed and is highly susceptible to contamination from point and nonpoint sources. The spread of contamination in the subsurface has been exacerbated by changes in the ground-water-flow system as a result of the withdrawal of large quantities of ground water.

The PRM no longer is usable as a source of water supply in Philadelphia because of highly elevated concentrations of iron, manganese, and sulfate. A strong reducing environment in the PRM in south Philadelphia causes these constituents to be remobilized by reductive dissolution of the aquifer matrix. Elevated concentrations of sulfate generally are a consequence of oxidation processes, whereas elevated concentrations of dissolved iron and manganese can be a consequence of oxidation and (or) reduction processes. The oxidation processes typically are acid-forming reactions that can consume bicarbonate and cause pH to decrease. The oxidation of Fe^{2+} to Fe^{3+} can be catalyzed by iron-oxidizing bacteria that are native or introduced to the subsurface environment. Fe^{2+} ions oxidize and hydrolyze forming solid Fe(III) oxyhydroxide. The Fe(III) compounds accumulate forming encrustations on well screens where O_2 and Fe^{2+} are locally available. Many wells in Philadelphia, including those at the former Philadelphia Naval Ship Yard (PNSY), were abandoned primarily because of problems associated with the precipitation of Fe(III) oxyhydroxides.

Development of the Coastal Plain aquifers as a source of water supply began before 1900. Prior to development for water supply, the Delaware River was the point of regional ground-water discharge from the PRM in Philadelphia and New Jersey. By the 1920s, pumping in Philadelphia changed the natural ground-water-flow patterns. Withdrawals in the area near the Walt Whitman Bridge created cones of depression, and ground water flowed toward these pumping centers. By 1940, continued and increasing pumping from the lower sand unit near the Walt Whitman Bridge caused greater water-level declines in the lower sand unit with an even steeper hydraulic gradient towards the pumping centers. Lower heads in the lower sand unit relative to the heads in the alluvial and upper and middle sand units developed, which created a downward ground-water-flow component. Recharge areas changed from the topographically high areas east of Trenton to the outcrop area. The Delaware River was no longer a point of ground-water discharge.

Ground-water development for supply at the former PNSY started in 1940, and large withdrawals at the facility continued until the mid-1960s. Pumping at the PNSY created a large cone of depression in the lower sand unit. By 1954, the cone of depression exceeded 50 ft below NGVD 29. Between 1943 and 1960, vertical leakage was the most important source of recharge to the lower sand unit in the vicinity of the PNSY. In 1943, dissolved iron concentrations in water samples from wells at the PNSY ranged from 0.07 to 0.6 mg/L. By 1945, dissolved iron concentrations exceeded 1 mg/L, and by 1956, dissolved iron concentrations exceeded 9 mg/L. In 1967, when the wells at the PNSY were abandoned, dissolved iron concentrations had reached 46 mg/L. Other wells in Philadelphia exhibited a similar pattern.

Ground-water withdrawals from the PRM in New Jersey began to increase sharply beginning about 1951, which caused the lateral head gradient to reverse and facilitated the flow of ground water from Philadelphia to New Jersey under the Delaware River. Although pumping stopped at the PNSY and water levels in the lower sand unit in Pennsylvania recovered, the increased pumping in New Jersey maintained downward vertical gradients in Philadelphia and made the outcrop area of the PRM in Philadelphia a recharge area for the PRM aquifer system in parts of Camden and Gloucester Counties. Where a confining unit is present above the lower aquifer, ground water

flows from Philadelphia beneath the Delaware River to New Jersey; this is the case in the area around the former PNSY. However, in areas northeast of the former PNSY along the Delaware River, the confining unit may be thin or absent, and the Delaware River may be in direct hydraulic contact with the lower aquifer. In these areas, little or no ground water may flow from Pennsylvania to New Jersey. Model simulations showed that the lower aquifer in New Jersey across the Delaware River from the former PNSY and the areas to the east and west of the former PNSY received little recharge from the river.

By 1968, cones of depression developed in the PRM in New Jersey with water levels as deep as 70 ft below NGVD 29. The direction of ground-water flow was from Philadelphia to New Jersey. By 1988, water levels in the lower aquifer were as deep as 103 ft below NAVD 88 in New Jersey and 8 ft below NAVD 88 in Philadelphia. In 1994, the New Jersey Department of Environmental Protection designated Water Supply Critical Area Number 2, which identified the PRM aquifer system in parts of Camden and Gloucester Counties as depleted and reduced water-supply allocations by an average of 22 percent in that area. In response to decreased pumping, water levels in 1998 in the lower aquifer recovered to 62 ft below NAVD 88 in New Jersey but declined to 16 ft below NAVD 88 in Philadelphia, reflecting a rise in water level of 41 ft at the center of the cone of depression in New Jersey.

Water samples collected in 1949-50 from wells screened in the lower aquifer at the Eagle Point Refinery, which is directly across the Delaware River from the former PNSY, had dissolved iron concentrations ranging from 0.11 to 0.73 mg/L. Iron concentrations in water samples from wells at the Eagle Point Refinery have increased with time. The concentration of dissolved iron in water samples from other wells screened in the lower aquifer in New Jersey also increased with time. By 1966-67, dissolved iron concentrations were as high as 4.8 mg/L for Gloucester City wells, and 1.4 mg/L for Eagle Point Refinery wells. By 1985, dissolved iron concentrations were as high as 16 mg/L for Eagle Point Refinery wells. Current (2002) iron concentrations reported by water purveyors in water from production wells in New Jersey commonly exceeded 1 mg/L and were as high as 16 mg/L. In addition to the increase in iron concentration with time, concentrations of manganese and sulfate in ground water in the PRM aquifer system also are increasing with time.

Although ground-water withdrawals in New Jersey have declined since the 1980s, water of poor quality still may be moving under the Delaware River from Pennsylvania toward wells in New Jersey in certain areas in response to pumping. In addition, sources of contamination in New Jersey also may be contributing to the elevated iron problem by vertical migration. Ground-water flow from areas of contamination in south Philadelphia to adjacent downgradient areas of New Jersey has the potential to affect supply wells drawing water from the lower aquifer of the PRM. Under present pumping conditions, the quality of water in the PRM aquifer system in New Jersey is likely to degrade with time.

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