SIMULATION OF GROUND-WATER FLOW IN THE LOWER SAND UNIT OF THE POTOMAC-RARITAN-MAGOTHY AQUIFER SYSTEM, PHILADELPHIA, PENNSYLVANIA

By Ronald A. Sloto

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FACTORS FOR CONVERTING INCH-POUND UNITS TO METRIC UNITS

Multiply inch-pound unit	By	To obtain metric unit
	Length	
inch (in.)	2.540	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per day (ft/d)	0.3048	meter per day (m/d)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	0.003785	cubic meter (m^3)
	Flow	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.01081	cubic meter per second (m^3/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

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, formely called "Sea Level Datum of 1929."

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ABSTRACT

Ground-water flow in the lower sand unit of the Potomac-Raritan-Magothy aquifer system in Philadelphia was simulated with a two-dimensional finite-difference ground-water model. The modeled 133-square-mile area also includes parts of Delaware County, Pennsylvania, and Camden and Gloucester Counties, New Jersey. The lower sand unit is Cretaceous in age and consists of well-sorted coarse sand and fine gravel that grades upward into medium to fine sand containing a few thin beds of clay. The modeled aquifer consists of the lower sand unit in Philadelphia and the lowermost sand unit of the Potomac-Raritan-Magothy aquifer system in New Jersey. Throughout most of the area, the lower sand unit is overlain by a clay confining unit. Where the clay is absent, the lower sand unit is unconfined. A hydraulic conductivity of 1.6×10^{-3} foot per second and a storage coefficient of 3.0×10^{-4} was assigned to the lower sand unit based on 15 aquifer tests, and a hydraulic conductivity of 4.0×10^{-8} foot per second was assigned to the upper confining unit based on transient-flow sensitivity analysis. Water levels were not sensitive to changes in the value for specific storage of the upper confining unit, indicating that most vertical leakage occurs as steady leakage. Changes in the potentiometric surface of the lower sand unit for 1904-78 were simulated. Differences between simulated and observed head generally were less than 10 feet.

Simulations were made to determine the effects on hydraulic head of increases in industrial pumpage of 5 and 10 Mgal/d (million gallons per day) and of an emergency 60 Mgal/d municipal water supply in Philadelphia. A 5- and 10-Mgal/d increase in industrial pumpage would lower heads in the lower sand unit by as much as 33 and 66 feet, respectively. Pumping 60 Mgal/d for 30 days for an emergency municipal supply would lower heads in the lower sand unit by as much as 121 feet.

INTRODUCTION

Purpose and Scope

This report presents the results of a study to simulate ground-water flow in the lower sand unit of the Potomac-Raritan-Magothy aquifer system in the Philadelphia area using a digital model and to evaluate the effects of potential future ground-water withdrawals on hydraulic heads in the lower sand unit in south Philadelphia. The modeled area includes parts of New Jersey where ground-water withdrawals have affected water levels in south Philadelphia. This report discusses the hydrogeology of the Philadelphia area and describes the construction and calibration of the model used to simulate ground-water flow in the lower sand unit of the Potomac-Raritan-Magothy aquifer system. It describes the effects of different pumping strategies on heads in the Philadelphia area.

Location and Physiography

The 133 mi^2 (square mile) modeled area includes the southern part of the City of Philadelphia, a small part of Delaware County, Pennsylvania, and parts of Camden and Gloucester Counties, New Jersey (fig. 1). The modeled area is in the Coastal Plain physiographic province, which is underlain by unconsolidated sediments of Cretaceous to Holocene age. The land surface has a relatively flat slope, with altitudes ranging from 0 to 140 feet above sea level.

The area is drained by the Delaware River and its tributaries. The Delaware River is tidal in the modeled area. The Schuylkill River is the principal tributary to the Delaware and is confluent to the Delaware River at south Philadelphia (fig. 2).

The annual normal precipitation at the Philadelphia International Airport (1951-80) was 39.93 inches. The average monthly temperature (1951-80) was 54.7°F and (12.6°C) and ranged from 32.4°F (0.2°C) in January to 76.8°F (24.9°C) in July.

The Philadelphia area is densely populated and, in some areas, is extensively industrialized. The 1980 population of Philadelphia was 1.7 million, with a density of 12,600 persons per mi^2. The area modeled in south Philadelphia includes areas of dense urban development, an industrialized area bordering the Delaware and lower Schuylkill Rivers, and the U.S. Naval Base at Philadelphia.

Previous Investigations

The water resources of the Philadelphia area were first described by Bascom (1904). Hall (1934) described general ground-water conditions in a report on the ground-water resources of southeastern Pennsylvania. Graham and Kammerer (1952) discussed the ground-water resources of the U.S. Naval Base at Philadelphia. Greenman and others (1961) published a comprehensive report on the geology and ground-water resources of the Coastal Plain of southeastern Pennsylvania. Paulachok and Wood (1984) presented a water-table map of Philadelphia. Hydrologic data for aquifers in Philadelphia are given by Paulachok, Wood, and Norton (1984).

In New Jersey, the geology and ground-water resources of Gloucester County were described by Hardt and Hilton (1969). Farlekas and others (1976) described the geology and ground-water resources of Camden County. Gill and Farlekas (1976) presented geohydrologic maps of the Potomac-Raritan-Magothy aquifer system.

Barksdale and others (1958) described the ground-water resources of the tristate region adjacent to the lower Delaware River. The water resources of the Delaware River basin were summarized by Parker and others (1964).

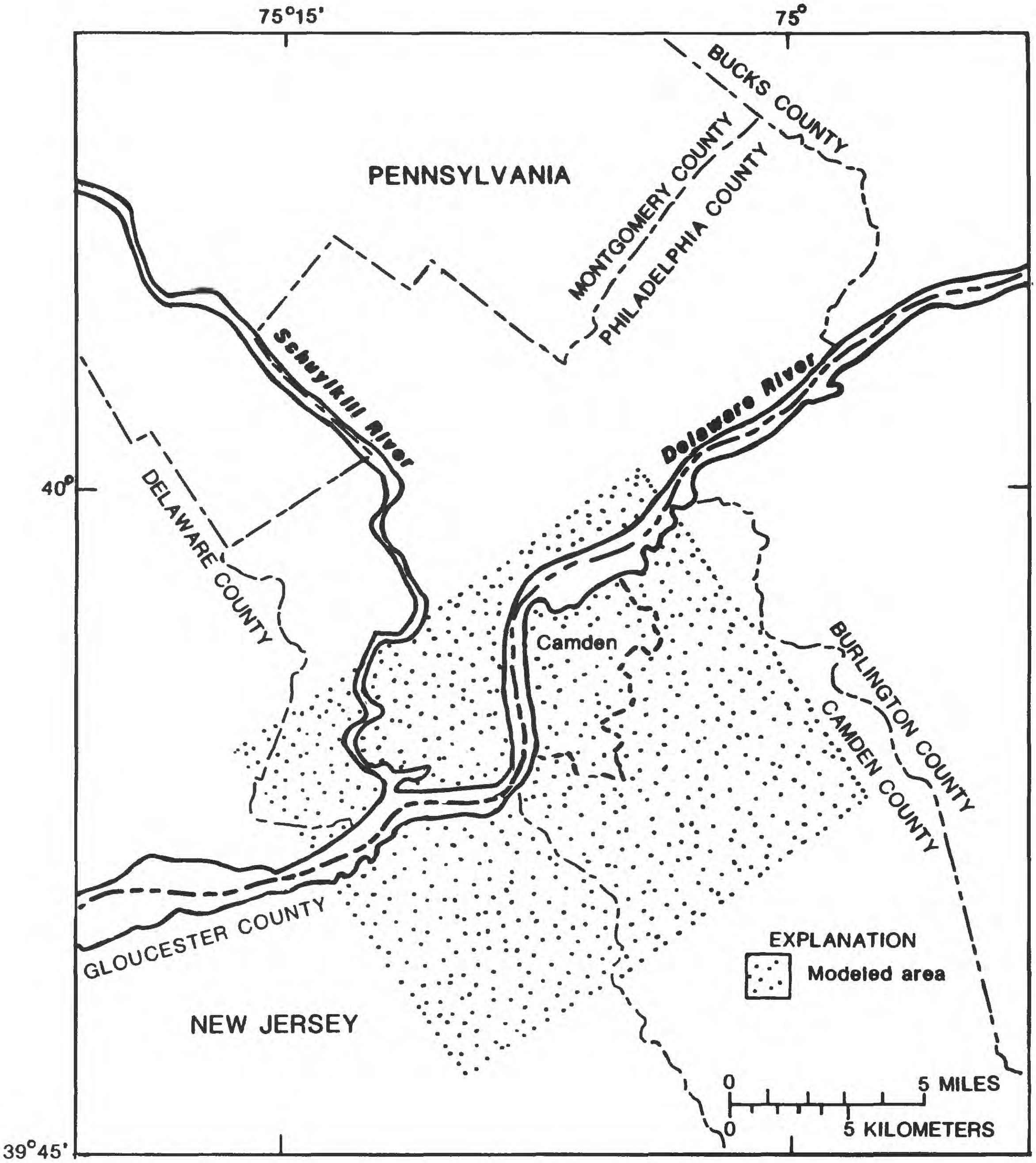


Figure 1.--Location of modeled area.

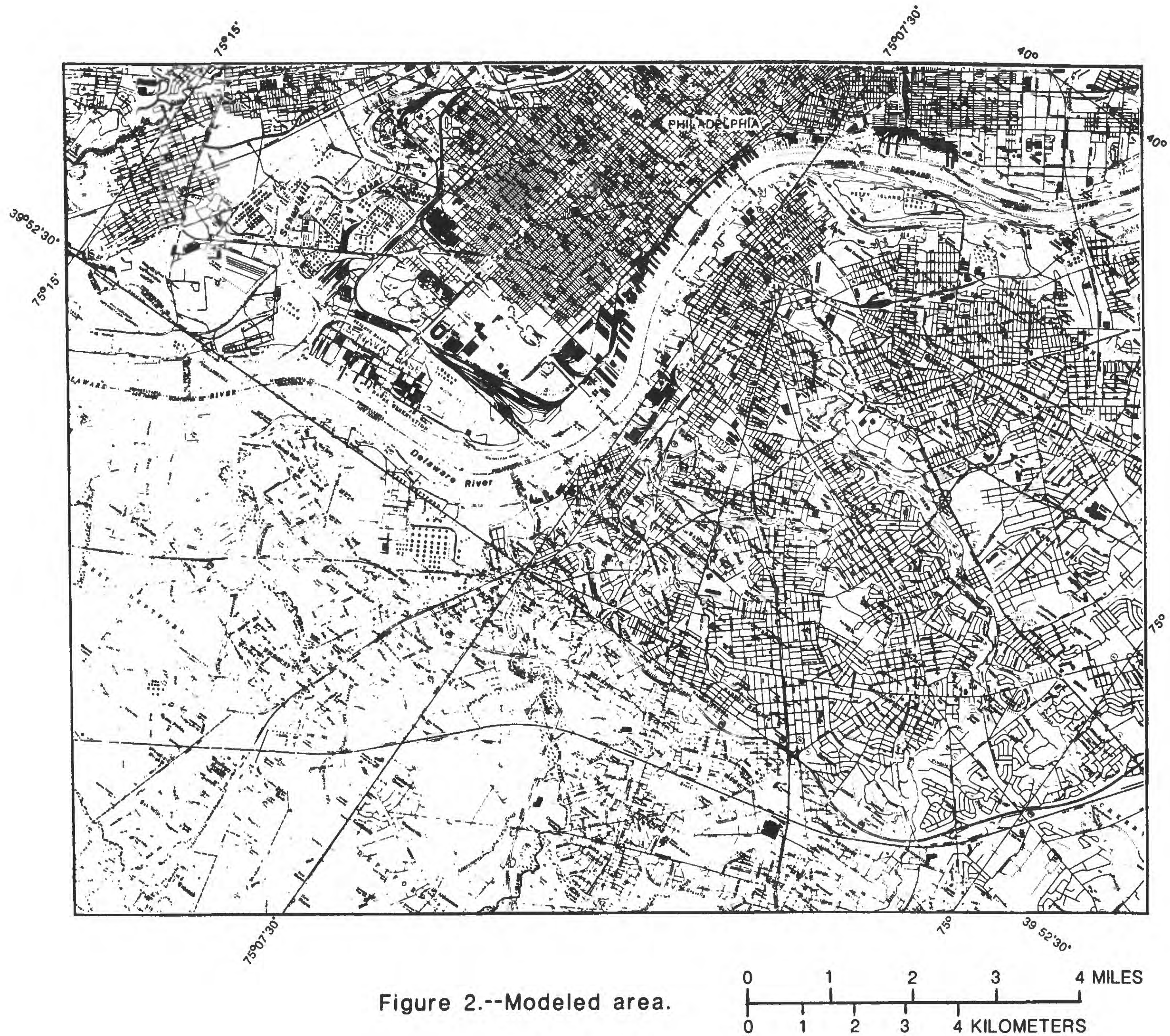


Figure 2.--Modeled area.

Luzier (1980) modeled the Potomac-Raritan-Magothy aquifer system in the Coastal Plain of New Jersey. This model was used by Harbaugh and others (1980) to evaluate the effects of supplementing ground water with water from the Delaware River.

HYDROGEOLOGY

The generalized stratigraphic section of the Coastal Plain in Philadelphia and the names of the hydrogeologic units used in this report and those of Greenman and others (1961, table 4) are given in table 1. Greenman and others (1961, p. 29) adopted the stratigraphic nomenclature of Barksdale and others (1943, p. 66) for beds of the Raritan Formation in northern New Jersey. However, this nomenclature is not accepted for the sediments in Philadelphia because these beds cannot be traced to the Delaware Valley. Although the nomenclature of Greenman and others (1961) is not used here, the descriptions of the sediments in each hydrogeologic unit are used.

Table 1.--Generalized stratigraphic section of the Coastal Plain of Philadelphia

<table>
<tr><th rowspan="2">SYSTEM</th><th rowspan="2">SERIES</th><th colspan="4">HYDROGEOLOGIC UNIT</th></tr>
<tr><th colspan="2">THIS REPORT</th><th colspan="2">GREENMAN AND OTHERS (1961)</th></tr>
<tr><td rowspan="2">QUATERNARY</td><td>HOLOCENE</td><td colspan="2">ALLUVIUM</td><td colspan="2">ALLUVIUM</td></tr>
<tr><td>PLEISTOCENE</td><td colspan="2">TRENTON GRAVEL (INFORMAL USAGE)</td><td colspan="2">CAPE MAY FORMATION
PENSAUKEN FORMATION</td></tr>
<tr><td>TERTIARY</td><td>MIOCENE</td><td colspan="2">BRIDGETON FORMATION</td><td colspan="2"></td></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 colspan="2">MAGOTHY FORMATION
UPPER CLAY MEMBER</td></tr>
<tr><td>UPPER SAND UNIT</td><td rowspan="5">RARITAN FORMATION</td><td>OLD BRIDGE SAND MEMBER</td></tr>
<tr><td>MIDDLE CLAY UNIT</td><td>MIDDLE CLAY MEMBER</td></tr>
<tr><td>MIDDLE SAND UNIT</td><td>SAYREVILLE SAND MEMBER</td></tr>
<tr><td>LOWER CLAY UNIT</td><td>LOWER CLAY MEMBER</td></tr>
<tr><td rowspan="2">LOWER SAND UNIT</td><td>FARRINGTON SAND MEMBER</td></tr>
<tr><td>LOWER CRETACEOUS</td><td colspan="2"></td></tr>
<tr><td>PRE-CRETACEOUS</td><td></td><td></td><td>CRYSTALLINE ROCKS</td><td colspan="2">CRYSTALLINE ROCKS, GLENARM SERIES</td></tr>
</table>

Pre-Cretaceous Rocks

The basement rocks beneath the Coastal Plain are pre-Cretaceous mica and hornblende schists and gneisses, chiefly the Wissahickon Formation. These rocks crop out in the Piedmont physiographic province northwest of the Fall Line (fig. 3). The surface of the bedrock dips about 90 feet per mile southeast towards the Atlantic Ocean. The altitude of the bedrock surface in the modeled area is shown on figure 4. The contours were based on Greenman and others (1961, plate 5), geologic and geophysical log data from recently completed wells and borings in Pennsylvania, and hydrogeologic data from New Jersey (Zapecza, O. S., U.S. Geological Survey, written commun., 1981 and 1982).

A residual clay marks the buried upper surface of the crystalline rocks. This clay, formed by the weathering of the crystalline rock, is a few feet to tens of feet thick where present. It is a confining unit where it underlies the unconsolidated sediments. Where the clay is present, water levels in the crystalline rocks commonly differ from those in the overlying unconsolidated sediments. Where the clay is absent, water levels in the crystalline rock and the unconsolidated sediments are about the same (Greenman and others, 1961, p. 27-28).

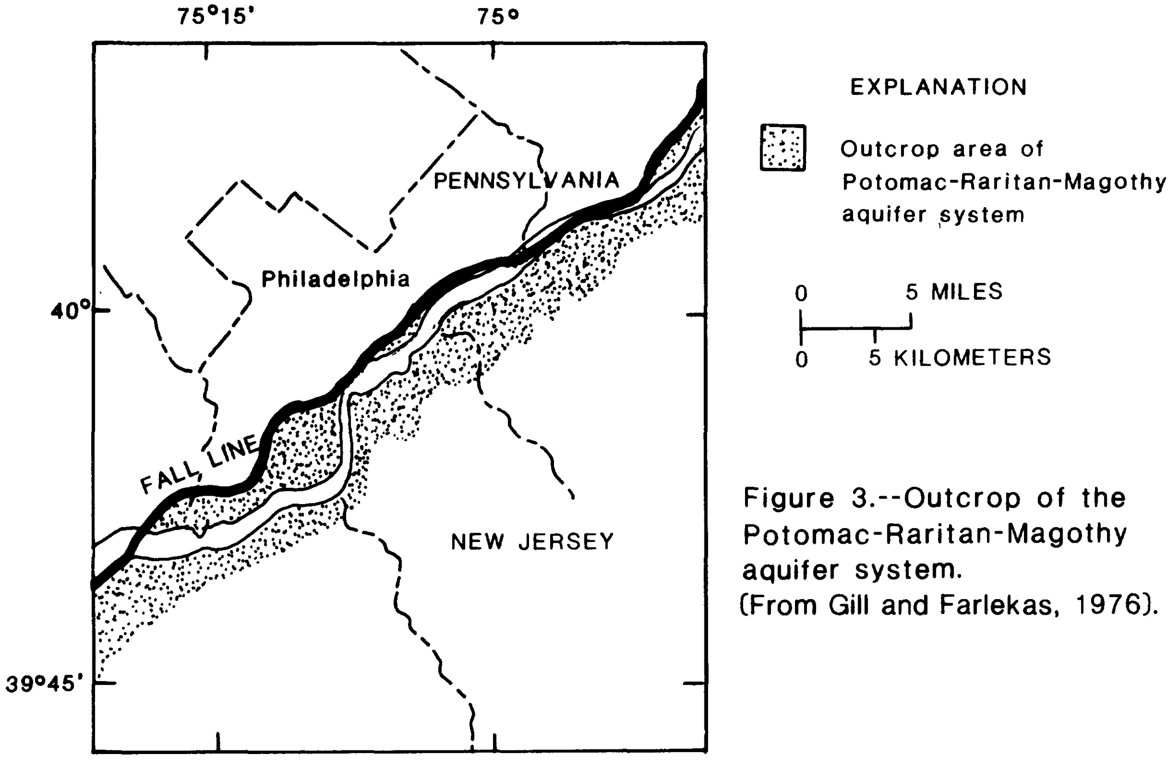
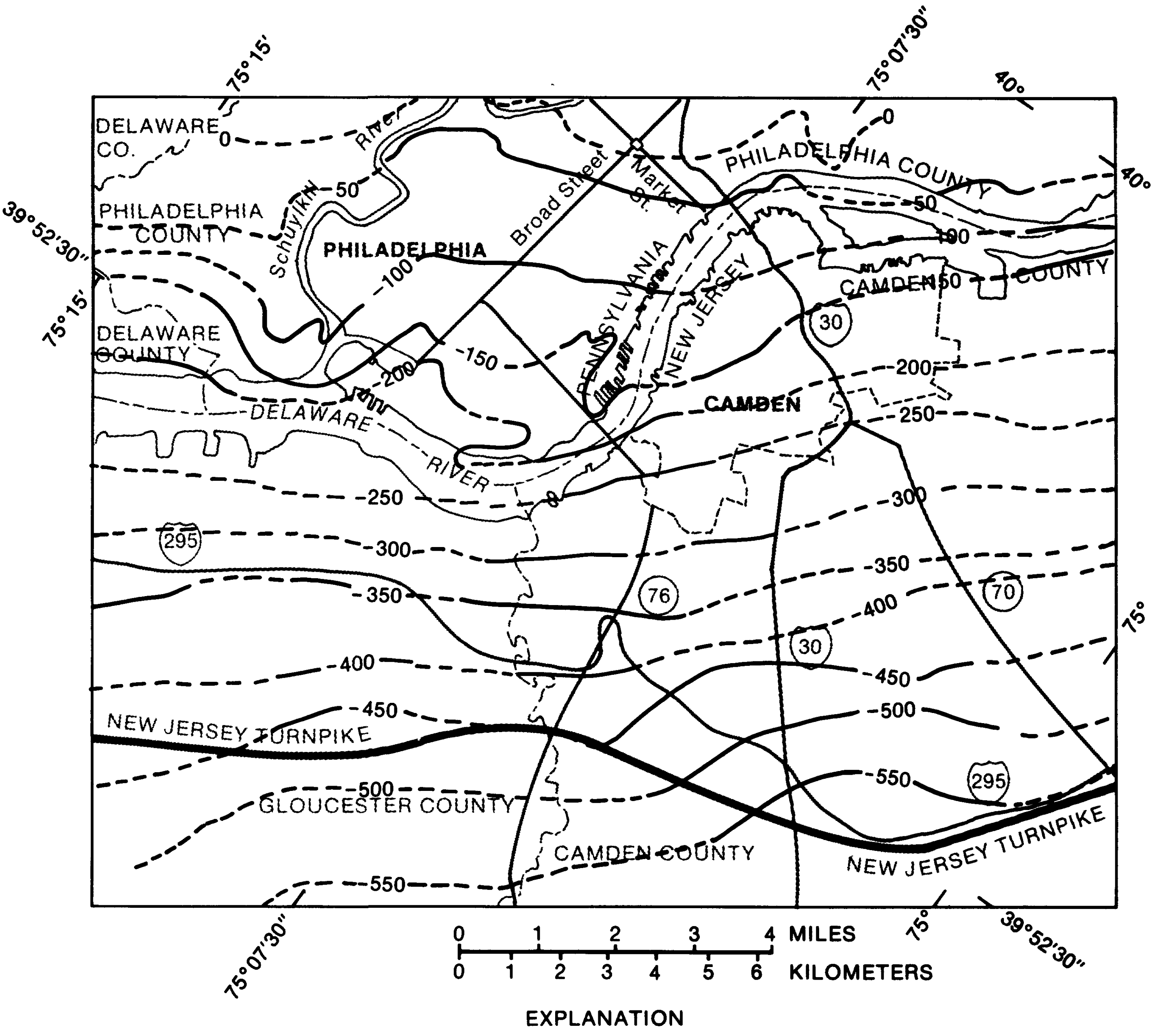


Figure 3.--Outcrop of the Potomac-Raritan-Magothy aquifer system. (From Gill and Farlekas, 1976).



EXPLANATION

——— -150 - - - BEDROCK CONTOUR-- shows altitude of top of bedrock surface. Dashed where approximately located. Contour interval 50 feet. Datum is sea level.

Figure 4.-- Generalized configuration of the bedrock surface beneath the Coastal Plain sediments.

Cretaceous Sediments

Cretaceous sediments unconformably overlie the crystalline rocks southeast of the Fall Line. These sediments dip from 40 to 80 feet per mile toward the southeast, forming a wedge that thickens toward the Atlantic Ocean. These sediments are regionally known as the Potomac-Raritan-Magothy aquifer system and consist of highly-permeable beds of sand and gravel separated by less-permeable layers of clay and silt. The sediments were deposited in a complex fluvial-deltaic environment (Owens and others, 1968) and are considered to be chiefly nonmarine in the Delaware Valley. In the Philadelphia area, the Potomac-Raritan-Magothy aquifer system has been divided into six informal units: lower sand, lower clay, middle sand, middle clay, upper sand, and upper clay (table 1). Detailed descriptions and geologic logs are given by Greenman and others (1961) and are summarized below with the stratigraphic nomenclature used in this study.

The lower sand unit (Farrington sand member of Greenman and others, 1961, p. 30-31) is the lowermost unit of the Potomac-Raritan-Magothy aquifer system in Philadelphia. The lower sand unit is the lower part of the Raritan Formation, but may include some Potomac Group sediments. Palynologic data indicate that Potomac Group sediments are present in Camden, New Jersey (Wolfe and Pakister, 1971, p. B38). The lower sand unit consists of fairly well-sorted coarse sand and fine gravel that grades upward into fine- to medium-grained sand containing a few thin beds of clay. The thickness of the lower sand unit ranges from less than 1 foot at the Fall Line to approximately 90 feet where it fills channels carved into the bedrock by the ancestoral Delaware and Schuylkill Rivers. However, the lower sand unit rarely exceeds 60 feet in thickness in Pennsylvania. Throughout most of its area of occurrence, the lower sand unit is overlain by a confining layer of either the lower clay unit, the middle clay unit, or both. Near the Fall Line, these confining clays are absent and the lower sand is directly overlain by the upper sand unit or Tertiary and Quaternary deposits and becomes part of the water-table-aquifer system.

The lower clay unit (lower clay member of Greenman and others, 1961, p. 37-38) consists of a tough clay containing beds of softer clay and thin lenses of fine-grained sand. The lower clay unconformably overlies the lower sand unit. It generally is from 20 to 40 feet thick but can be up to 60 feet thick in places.

The middle sand unit (Sayreville sand member of Greenman and others, 1961, p. 38-40) fills shallow channels in the lower clay unit and is not areally extensive in Philadelphia. The middle sand unit is present as valley fill deposited by shifting currents in lens-shaped masses separated by narrow bedrock divides. This unit consists of a sequence of very fine- to coarse-grained sand beds and a few thin beds of clay. The maximum thickness of the middle sand unit exceeds 40 feet but commonly is less than 20 feet.

The middle clay unit (middle clay member of Greenman and others, 1961, p. 40-41) is the most extensive clay of the Potomac-Raritan-Magothy aquifer system in Philadelphia. It consists of a tough clay with a uniformly massive texture and contains relatively little sandy material. It commonly exceeds 20 feet in thickness and may be up to 60 feet thick locally. Because the middle clay unit lies directly upon the lower clay unit in much of the Philadelphia area, it is difficult to differentiate the two units.

The upper sand unit (Old Bridge sand member of Greenman and others, 1961, p. 42-43) unconformably overlies the middle clay unit and consists of medium to coarse sand, gravel, and lenses of clay. Gravel beds are common, especially at the base. The upper sand unit is up to 50 feet thick but usually does not exceed 35 feet in thickness. In much of Philadelphia, the upper sand unit is part of the water-table-aquifer system.

The upper clay unit (upper clay member of Greenman and others, 1961, p. 43) is locally present in Philadelphia; where present, it overlies and confines the upper sand unit. This unit consists of a sequence of sandy, carbonaceous, and massive clays with a maximum thickness of 35 feet.

In Camden County, New Jersey, the Potomac-Raritan-Magothy aquifer system has been divided into three hydrogeologic units by Farlekas and others (1976, p. 22). The lower and middle units include the sands of the Potomac Group and the Raritan Formation. The upper unit consists mainly of the sands of the Magothy Formation. In the modeled area of Camden County, the thickness of the Potomac-Raritan-Magothy sediments ranges from 260 feet in the outcrop area to about 500 feet downdip (Farlekas and others, 1976, p. 16-18).

The lower aquifer consists of undifferentiated silt, clay, and sand of the Potomac Group and Raritan Formation. It is up to 120 feet thick, and is underlain by pre-Cretaceous basement rocks that form a lower confining unit. The middle aquifer consists of silt, clay, and sand of the Raritan Formation and ranges from 18 to 170 feet in thickness in the modeled area (Farlekas and others, 1976, p. 24-25). The upper aquifer consists mainly of alternating bands of dark clay and light sand of the Magothy Formation. The clays are, for the most part, distinctly laminated and commonly lignitic (Bascom and others, 1909, p. 86). The upper aquifer ranges from 57 to 170 feet in thickness in the modeled area. In the outcrop area, it is overlain by Pleistocene deposits and is part of the water-table-aquifer system (Farlekas and others, 1976, p. 22). Downdip, the upper aquifer is overlain by the Merchantville-Woodbury confining layer (Luzier, 1980, p. 5).

In Gloucester County, New Jersey, the Raritan and Magothy Formations can not be differentiated except locally because of similar lithology. The Raritan Formation is composed of clay, quartzose sand, and gravel. The Magothy Formation consists of beds of clay, commonly lignitic, alternating with micaceous fine sand. Hardt and Hilton (1969, p. 10-11) identify two water-bearing zones in the outcrop area. The upper zone is usually confined and is composed of all of the water-bearing beds in the upper 120 feet of the Raritan and Magothy Formations. The lower zone is confined everywhere it is present and consists of the water-bearing beds in the lower 200 feet of the formations. The upper and lower aquifers are separated by clay beds in the outcrop area, but their identification downdip is uncertain.

Post-Cretaceous Sediments

Deposits of Tertiary and Quaternary age unconformably overlie and completely cover the Cretaceous sediments. These terrace and valley-fill deposits consist of clay, silt, sand, and gravel. In Philadelphia, their maximum thickness is about 80 feet and the typical thickness is about 40 feet (Greenman and others, 1961, p. 44). These deposits form an extensive water-table aquifer. The post-Cretaceous deposits consist of the Bridgeton Formation, the "Trenton gravel," and Holocene sediments. The Cape May Formation, used by Greenman and others (1961, table 4), is now largely applied to the marine beds that crop out only in the lower Delaware River valley near the coast (Owens and Minard, 1979, p. D6). The Cape May Formation is not present at Philadelphia.

The Bridgeton Formation (Illinoian deposits of Greenman and others, 1961, p. 24) is a feldspathic quartz sand with local beds of fine gravel that crops out in a 3-mile-wide band northwest of the Fall Line (Owens and Minard, 1979, p. D9-D13). Owens and Minard (1979, p. D18) assigned a Miocene age to the Bridgeton Formation.

The informally-named "Trenton gravel" (Wisconsin deposits of Greenman and others, 1961, p. 24) crops out in a 4-mile-wide band southeast of the Fall Line (Owens and Minard, 1979, p. D40). The "Trenton gravel" has been informally subdivided by Owens and Minard (1979, p. D28) into the Spring Lake beds and the Van Sciver Lake beds. In Philadelphia, the Spring Lake beds are up to 45 feet thick and consist of silt-clay, sand, and gravel (Owens and Minard, 1979, p. D34-D35). Owens and Minard (1979, p. D46) assigned an early Sangamon age to the Spring Lake beds. In Philadelphia, the Van Sciver Lake beds are up to 55 feet thick and consist of silt-clay and sand (Owens and Minard, 1979, p. D34-D35). The Van Sciver Lake beds are considered to be late Sangamon in age based on palnologic studies and radiocarbon dating (Owen and Minard, 1979, p. D42). Owens and Minard (1979, p. D34-D35) present geologic sections of these deposits in Philadelphia.

Holocene sediments consisting of silt and fine sand underlie the channels and tidal flats of the Delaware River and its principal tributaries. These sediments are as much as 78 feet thick in parts of south Philadelphia near the Delaware and Schuylkill Rivers, but, elsewhere, the thickness rarely exceeds 28 feet and is typically less than 10 feet (Greenman and others, 1961, p. 48).

HYDROLOGY

Predevelopment Ground-Water Flow System

Before the development of ground-water supplies around 1900, the main source of recharge was precipitation on the high-altitude outcrop areas of the permeable beds east of Trenton, New Jersey. Regional ground-water flow was from this area toward the Delaware River, where the water was discharged (fig. 5). A complete description of this theoretical predevelopment flow pattern and the assumptions on which it is based is given by Barksdale and others (1958, p. 108-112). This theoretical predevelopment flow pattern has been accepted by Greenman and others (1961, p. 51), Parker and others (1964, p. 53), and Rush (1968, p. 33). The same flow pattern was reproduced by Back (1966, p. A10) with an electric analog model and by Luzier (1980, p. 45) with a digital model.

The Potomac-Raritan-Magothy aquifer system also was recharged in topographically high areas in downdip parts of the New Jersey Coastal Plain. In these areas, the prepumping potentiometric surface of each aquifer was higher than that of the aquifer below, causing downward movement of ground water through confining units (Farlekas and others, 1976, p. 26). Ground water discharged to the Delaware River where vertical flow was upward through confining units.

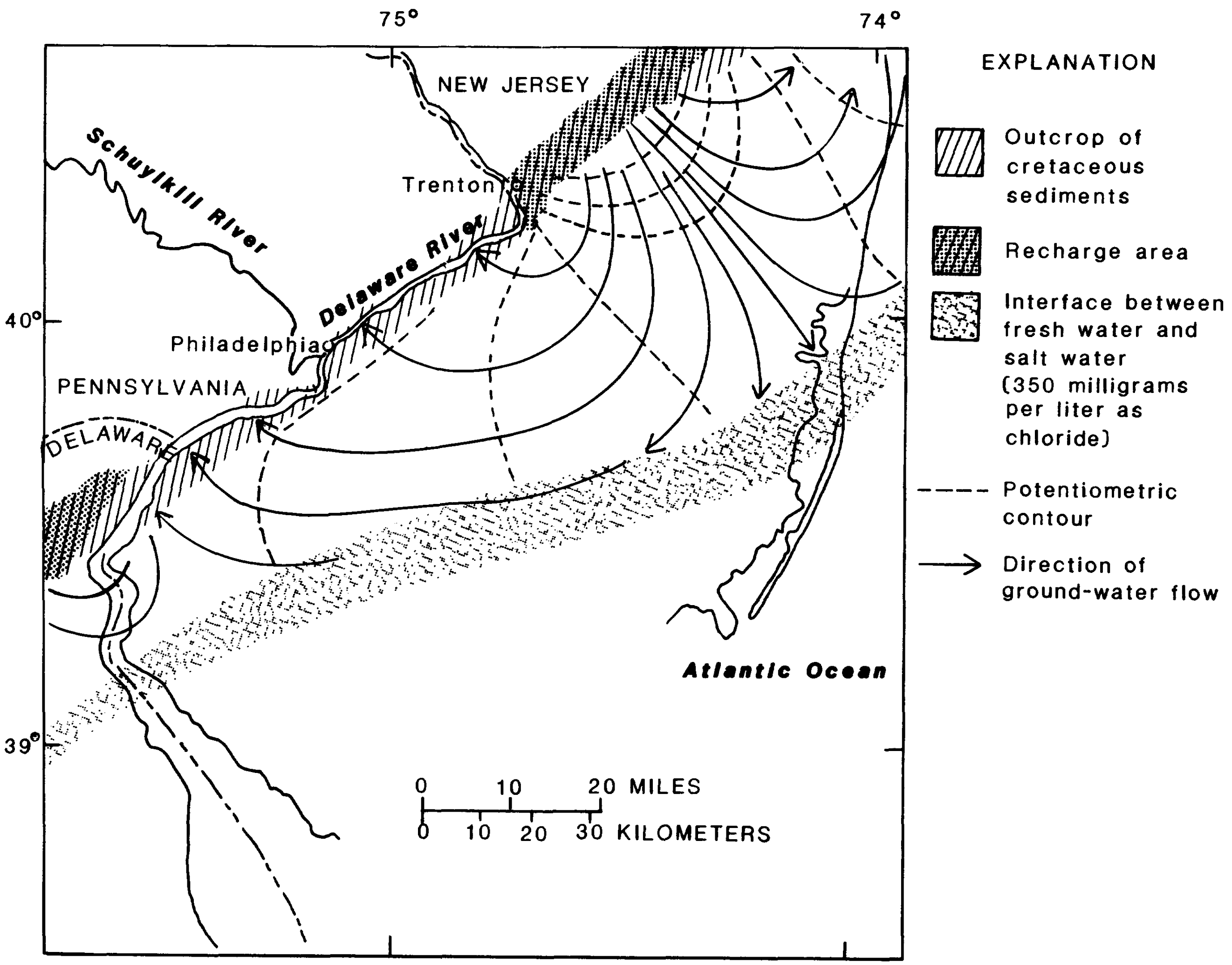


Figure 5.--Theoretical flow pattern in the Potomac-Raritan-Magothy aquifer system before the development of ground-water supplies.
(After Barksdale and others, 1958, figure 18)

The water-table system was recharged by precipitation on local outcrop areas and by upward leakage of water through underlying confining units and around confining units where they pinch out. Flow was local with discharge to nearby streams.

Post-Development Ground-Water Flow System

The development of the Coastal Plain aquifers for ground-water supplies has greatly altered the natural ground-water flow system. Pumping of large quantities of ground water has reversed head gradients in both the water-table and confined aquifers in the vicinity of the Delaware and Schuylkill Rivers. Reversal of head gradients has induced recharge from the Delaware and Schuylkill Rivers into the water-table aquifer. Evidence for induced recharge has been documented by Barksdale and others (1958, p. 106-108 and p. 115-123) and by Greenman and others (1961, p. 76-81).

Water levels in the water-table-aquifer system near the Delaware and Schuylkill Rivers in south Philadelphia are below river altitude (Paulachok and Wood, 1984). Flow in this area is from the Delaware and Schuylkill Rivers into the water-table aquifer. Heads in the lower sand unit are lower than those in the water-table aquifer (Paulachok, G. N., U.S. Geological Survey, oral commun., 1982). Downward leakage occurs through the confining unit into the lower sand unit. The head gradient in the lower sand unit is toward pumping centers in Camden and Gloucester Counties in New Jersey. As a consequence of ground-water development, the flow in south Philadelphia is from the Delaware and Schuylkill Rivers into the water-table aquifer, downward through the confining unit, and into the lower sand unit. Water in the lower sand unit flows downgradient beneath the Delaware River toward New Jersey.

Another source of recharge is leakage from the water distribution and sewer systems in Philadelphia. Most breaks in the water distribution system quickly become evident and are repaired. Many small leaks and probably some large leaks remain undetected. The sewer system in south Philadelphia is old. Where the sewer lines lie above the water table, considerable quantities of liquid sewage may be leaking to the subsurface.

The sources of recharge to the lower sand unit in Philadelphia after the development of ground-water supplies are: (1) precipitation on the outcrop area, (2) induced infiltration from the Delaware and Schuylkill Rivers, (3) downward leakage through confining units in downdip areas, and (4) leakage from water distribution and sewer systems.

Ground-Water Withdrawals

Ground-water withdrawals from the lower sand unit in Philadelphia began around 1904 and peaked at 19 Mgal/d (million gallons per day) in 1949 (fig. 6). The U.S. Naval Base, formerly the largest user of ground water in Philadelphia, began to develop a ground-water supply in 1941; peak pumpage was 5.7 Mgal/d in 1943. Naval Base wells were abandoned by 1966 because of degraded water quality. Withdrawal from the lower sand unit in 1980 was 2.6 Mgal/d and was chiefly for industrial and commercial use. The City of Philadelphia obtains water for public supply from the Delaware and Schuylkill Rivers.

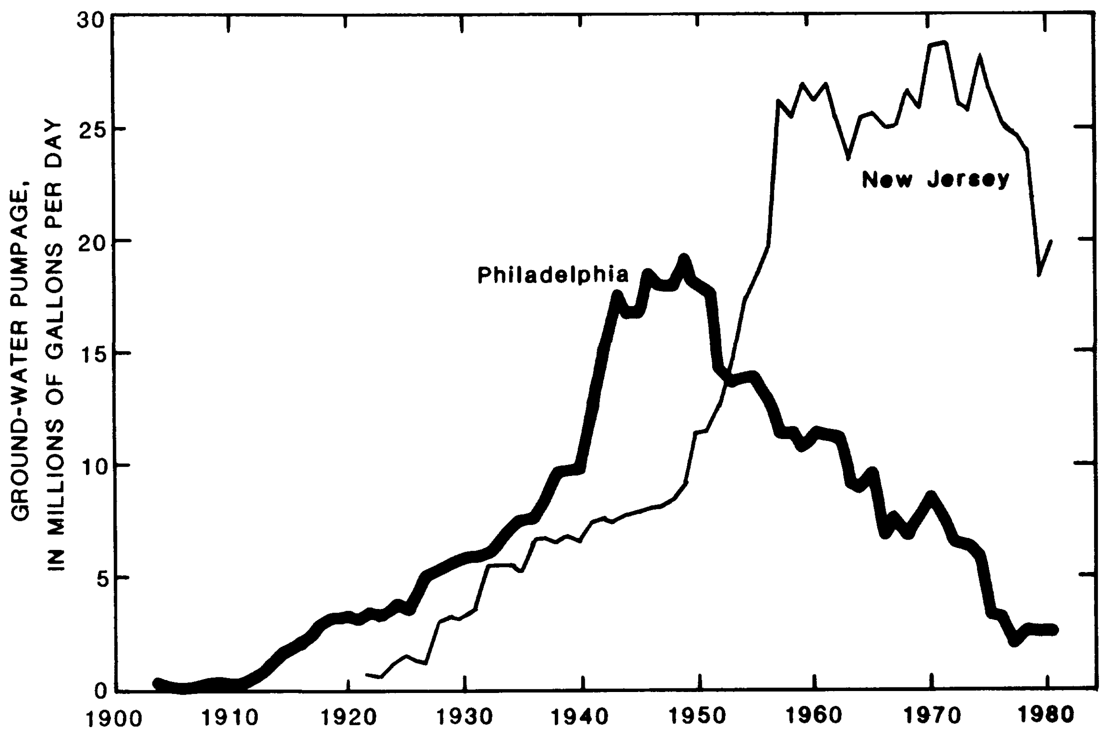


Figure 6.--Estimated withdrawals from the lower sand unit in the modeled area, 1904-80.

Ground-water-withdrawal data shown in figure 6 for Philadelphia are estimated. Because well owners rarely kept records on ground-water usage, early (1904-40) pumpage data generally are not available; however, dates when wells were abandoned generally are available. Pumpage was estimated based on later water-use data, pump capacity or well yield, and the length of time wells were known to have been pumped. Nearly complete pumpage data are available for wells at the U.S. Naval Base for 1941-53. Graham and Kammerer (1952, p. 125-129) give monthly withdrawals for each well for 1941-50. Industrial ground-water use surveys conducted in 1942, 1945, 1947, and 1953 also were used to estimate pumpage. Records of combined pumpage by Publicker Industries, Inc., from both the lower sand unit and the water-table aquifer, are available for 1961-80. Additionally, limited ground-water-use data are available for 1964, 1973, and 1977.

Ground-water withdrawals from the lower aquifer of the Potomac-Raritan-Magothy aquifer system in Camden County, New Jersey, began in 1922 (Thompson, 1932, p. 9). The peak pumpage in the modeled area in New Jersey was 28.7 Mgal/d in 1971. In 1980, pumpage was 20.9 Mgal/d. Early ground-water development was centered in the City of Camden. The increase in pumpage in New Jersey paralleled that in Pennsylvania until the 1940's. Suburban development expanded southeastward from Camden in the 1950's and 1960's, and many new public-supply wells were drilled. Most ground-water withdrawals in New Jersey are for public supply. Pumpage data for 1922-27 are given by Thompson (1932, p. 13). Pumpage data for some wells for 1925-55 and all major production wells for 1956-80 in Camden and Gloucester Counties were provided by O. S. Zapecza (U.S. Geological Survey, written commun., 1981). Pumpage data from other wells for 1928-55 were estimated based on data given by Thompson (1932), Farlekas and others (1976), later pumpage data, and well yields.

DESCRIPTION OF MODELED HYDROGEOLOGIC UNITS

Lower Confining Unit

The lower confining unit in Philadelphia consists of pre-Cretaceous bedrock or, where present, the layer of residual clay formed from the bedrock (fig. 7). The bedrock is considered to be impermeable relative to the overlying sediments. In New Jersey, the lower confining unit consists of pre-Cretaceous bedrock, the residual clay layer where present, or a clay layer that is locally present between the bedrock and the lowermost sands of the Potomac-Raritan-Magothy aquifer system. The geologic log for Camden City Water Works test well 1 (Donsky, 1963, p. 27) shows 23 feet of residual clay and 34 of hard clay between the bedrock and the lowermost sand.

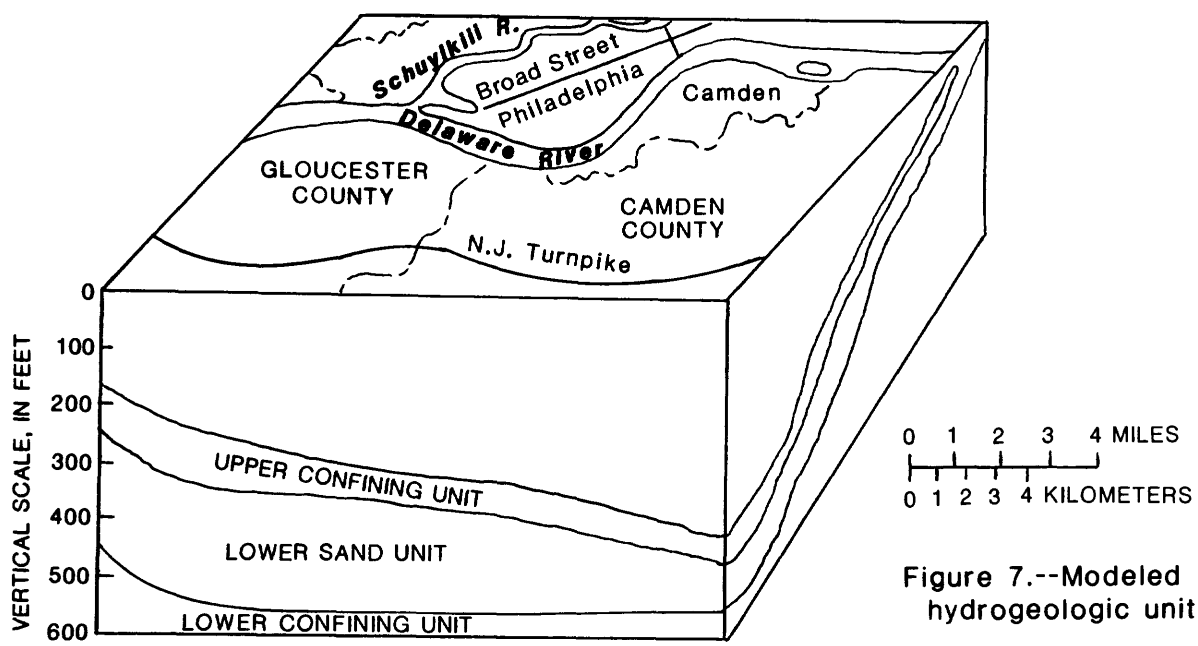


Figure 7.--Modeled hydrogeologic units.

Lower Sand Unit

The lower sand unit, also referred to as the modeled aquifer, is the hydrogeologic unit consisting of sand, gravel, and thin lenses of clay underlain by the lower confining unit. Updip, where it commonly is unconfined, the modeled aquifer consists of the lower sand unit and the overlying deposits in areas where no intervening confining unit is present. Downdip, where it is confined, the modeled aquifer consists of the lower sand unit in Philadelphia and the lowermost sand unit of the Potomac-Raritan-Magothy aquifer system in New Jersey. The lowermost sand unit generally is the lower aquifer of Farlekas and others (1976, p. 22) in Camden County and the lower part of the lower water-bearing zone of Hardt and Hilton (1969, p. 11) in Gloucester County.

The hydraulic continuity between the lower sand unit in Philadelphia and the lower aquifer of the Potomac-Raritan-Magothy aquifer system in Camden County, New Jersey, has been established using aquifer tests and water-level data. Heavy pumping on either side of the Delaware River in the south Philadelphia area affects water levels on the other side (Graham and Kammerer, 1952, p. 5). The geologic continuity between the lower sand unit in Philadelphia and the lowermost sand of the Potomac-Raritan-Magothy aquifer system in New Jersey was established by Graham and Kammerer (1952, p. 35) based on geological well logs (fig. 8).

Upper Confining Unit

In Philadelphia, the upper confining unit consists of the lower clay unit; the lower clay unit and the middle clay unit where the middle sand unit is absent; and the lower clay unit, middle sand unit, and middle clay unit where the middle sand unit is present. In New Jersey, the upper confining unit consists of the clay layer overlying the lower aquifer of the Potomac-Raritan-Magothy aquifer system.

In most of the modeled area, the Delaware and Schuylkill Rivers are above the upper confining unit. In some places, a ship channel has been dredged into or through the upper confining unit (U.S. Army Corps of Engineers, 1975). Where part of the upper confining unit has been removed by dredging, its thickness has been reduced at those nodes. Where the upper confining unit has been removed by dredging and the river and the modeled aquifer are in direct contact, a constant head of zero (mean sea level) was assigned to those nodes. Dredging of the ship channel has removed the upper confining unit at two nodes in the Delaware River and at 11 nodes in the Schuylkill River (fig. 9).

SIMULATION OF GROUND-WATER FLOW IN THE LOWER SAND UNIT

Ground-water flow in the lower sand unit was simulated with the computer program developed by Trescott and others (1976) for two-dimensional flow using finite-difference approximations. The strongly implicit procedure (SIP) numerical solution technique was used to solve the finite-difference equation of ground-water flow. Modifications made to the program are discussed in following sections. The lower sand unit was simulated as a combined confined and water-table aquifer. It was simulated as confined downdip where the upper confining unit is present, and as water table in the outcrop area where the upper confining unit is absent. Water-table conditions were also simulated when the head in a cell in the confined part of the aquifer was below the top of the aquifer.

A 133-mi^2 area was modeled. The area was divided into a rectangular grid of 28 rows and 37 columns of variable sized cells (fig. 9). The computer program requires the entire modeled area to be surrounded by a no-flow boundary (Trescott and others, 1976, p. 30); these cells are not shown on figure 9. Cells in the fine-grid area in south Philadelphia are 1,000 feet on each side or 0.036 mi^2 in area. Cell size increases away from the fine-grid area. Each cell is represented by a node at its center. Physical and hydraulic parameters are averaged over the area represented by the cell and assigned to the corresponding node.

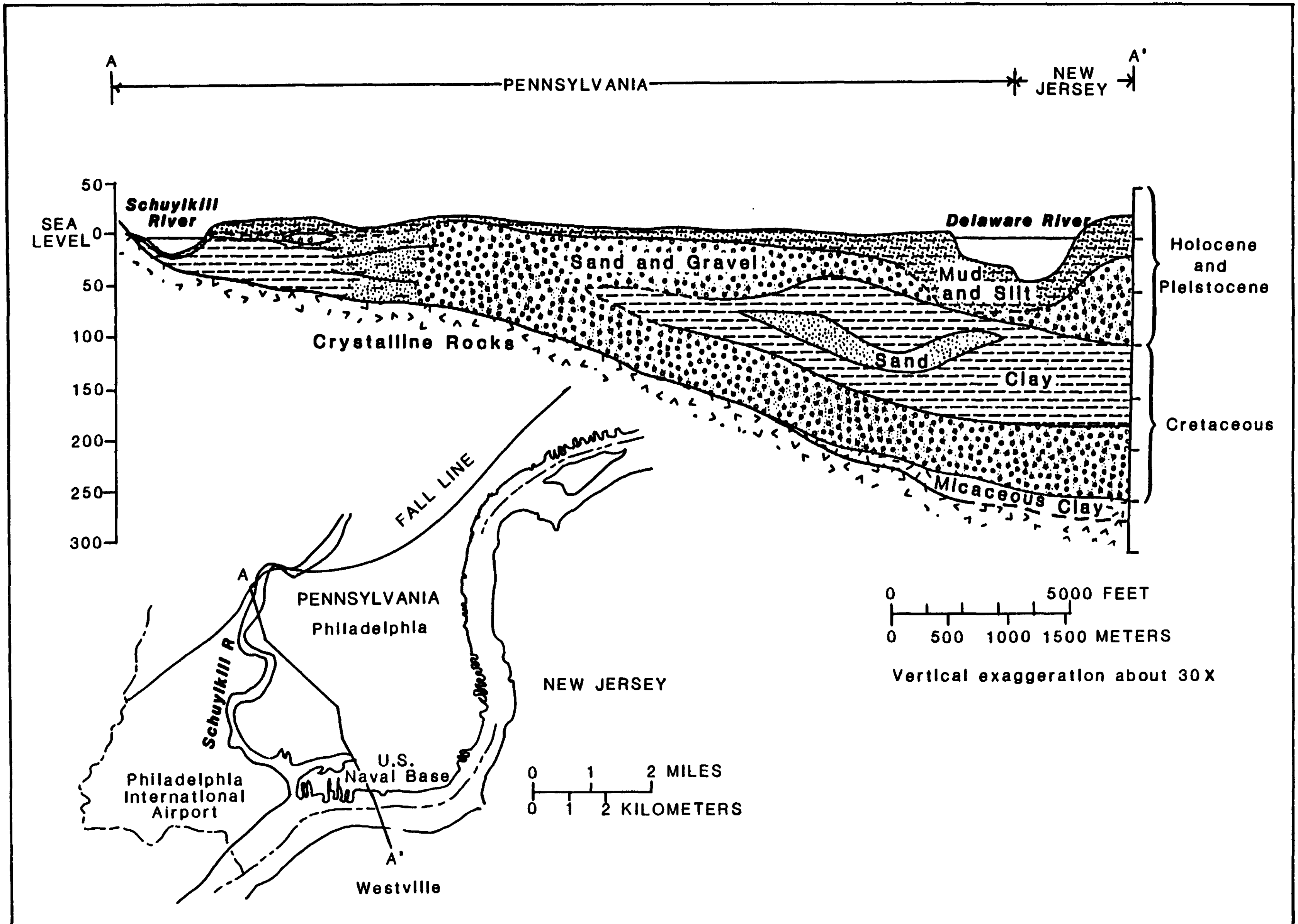


Figure 8.--Generalized geologic section, Philadelphia, Pennsylvania to Westville, New Jersey. (From Graham and Kammerer, 1952)

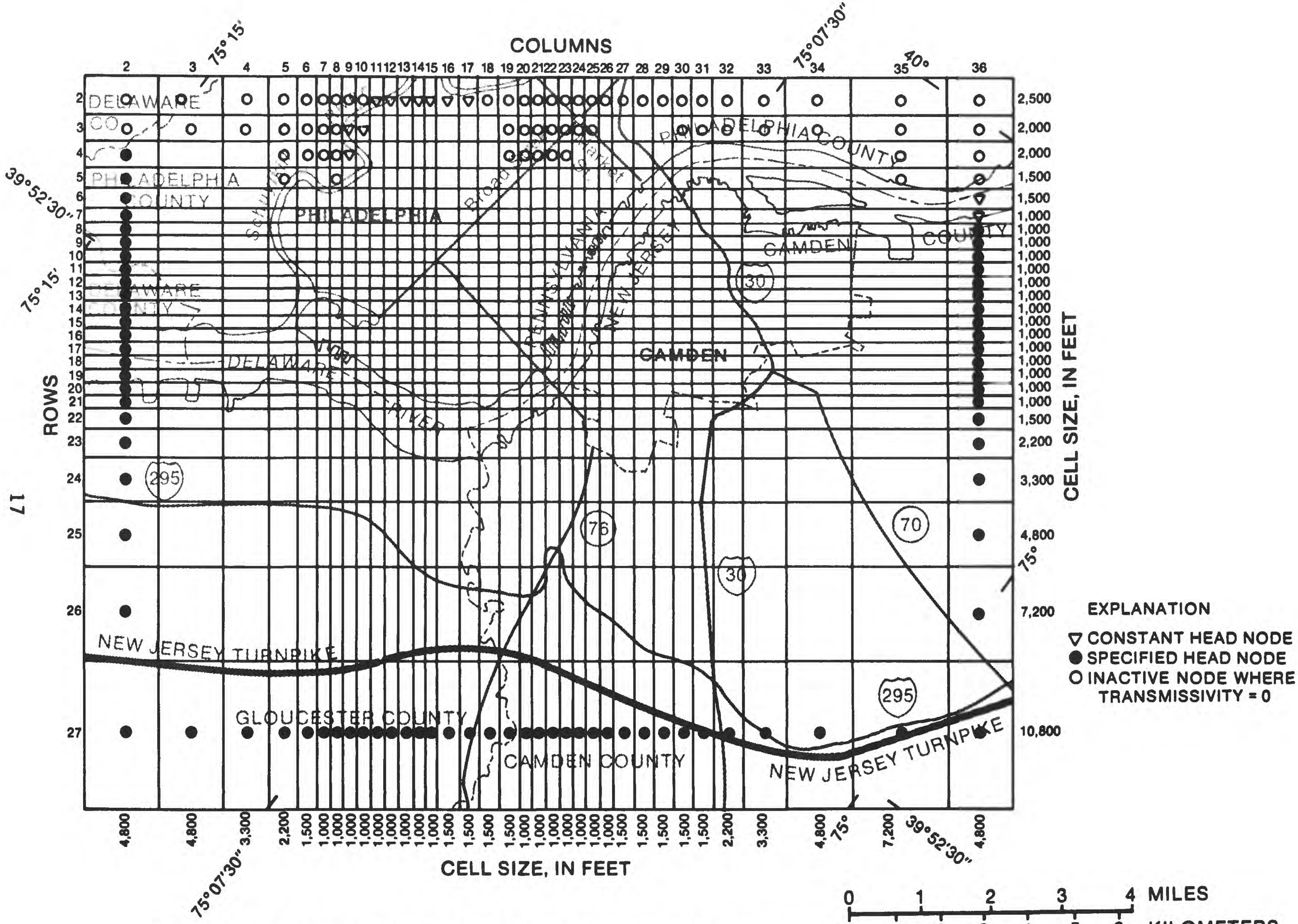


Figure 9.-- Finite-difference grid and lateral boundary conditions.

Boundary Conditions

Three types of boundaries are used in the model: (1) no flow, (2) constant head, and (3) specified head.

A no-flow boundary was used for most of the northwestern boundary, shown as inactive nodes in figure 9. The northwestern boundary of the model coincides with the physical boundary of the Cretaceous sediments. In this area, the Cretaceous sediments pinch out against relatively impermeable bedrock. An insignificant amount of flow is assumed to cross the contact.

A constant-head boundary was used for part of the northwestern boundary where the Schuylkill River is in direct contact with the modeled aquifer and for two nodes of the northeastern boundary where the Delaware River is in direct contact with the modeled aquifer (fig. 9).

The southeastern, southwestern, and most of the northeastern boundaries were represented as a specified-head boundary (fig. 9). A specified-head boundary allows the head to be specified and held constant for each stress period. These boundaries do not coincide with the physical boundaries of the lower sand unit. In the modeled area, the lower sand unit and the upper and lower confining units are distinct hydrogeologic units. However, at some distance from the modeled area, they probably lose their identity as distinct hydrogeologic units and become part of the regional Potomac-Raritan-Magothy aquifer system. The physical boundaries of the Potomac-Raritan-Magothy aquifer system are a considerable distance from Philadelphia and are uncertain. To the southeast, the aquifer system underlies New Jersey and extends seaward beneath the Atlantic Ocean. Luzier (1980, p. 5) estimates that it extends 100 miles to the continental slope. To the northeast, the physical boundary of the aquifer system also extends beneath the Atlantic Ocean beyond Long Island. To the southwest, the aquifer system extends beneath Delaware Bay and the Delmarva Peninsula.

Because the area of interest in south Philadelphia was only about 10 mi^2, it was necessary to arbitrarily truncate the aquifer system. Model boundaries were placed beyond major pumping centers in Camden and Gloucester Counties, New Jersey. Little pumping from the lower sand unit takes place beyond the model boundaries. These boundaries are located sufficiently far from the fine-grid area of the model in south Philadelphia so that stress caused by pumping beyond these boundaries has little effect on heads in the fine-grid area. To account for stress caused by pumping beyond these boundaries, and to avoid the effects of drawdown against an impermeable boundary from pumping in New Jersey, a specified-head boundary was used. Historical head data are available for 1900 (Gill and Farlekas, 1976), 1956 (Gill and Farlekas, 1976; Farlekas and others, 1976, p. 31), and 1978 (Walker, 1983, plate 1). The computer program was modified to accept two sets of head data, one for head at the beginning of the simulation and one for head at the end of the simulation, and to interpolate between them to compute a different head for each stress period. The computed head is held constant for that stress period. This modification allows a constant head at the boundary to change with time.

The underlying relatively impermeable bedrock is a no-flow boundary. Flow into or out of the bedrock is assumed to be insignificant.

Over most of the modeled area, the upper boundary is a leaky confining layer. The quantity of leakage is determined by the hydraulic conductivity, specific storage, and thickness of the upper confining unit and the difference between the head in the lower sand unit and the head in the aquifer above the upper confining unit.

Initial Conditions

Nonpumping conditions about 1900 were approximated by a steady-state simulation. Values for initial model variables were based on field data and estimated where field data were not available. The steady-state simulation produced a potentiometric surface (fig. 10) in good agreement with the hypothetical prepumping potentiometric surface of Greenman and others (1961, fig. 7) shown in figure 11. Simulated heads were generally within 2 feet of observed or hypothetical prepumping heads. Head gradients were toward the Delaware River. The simulated regional potentiometric surface was similar to that of Gill and Farlekas (1976) and Barksdale and others (1958, p. 114). This simulated potentiometric surface was used as the initial potentiometric surface for subsequent transient simulations.

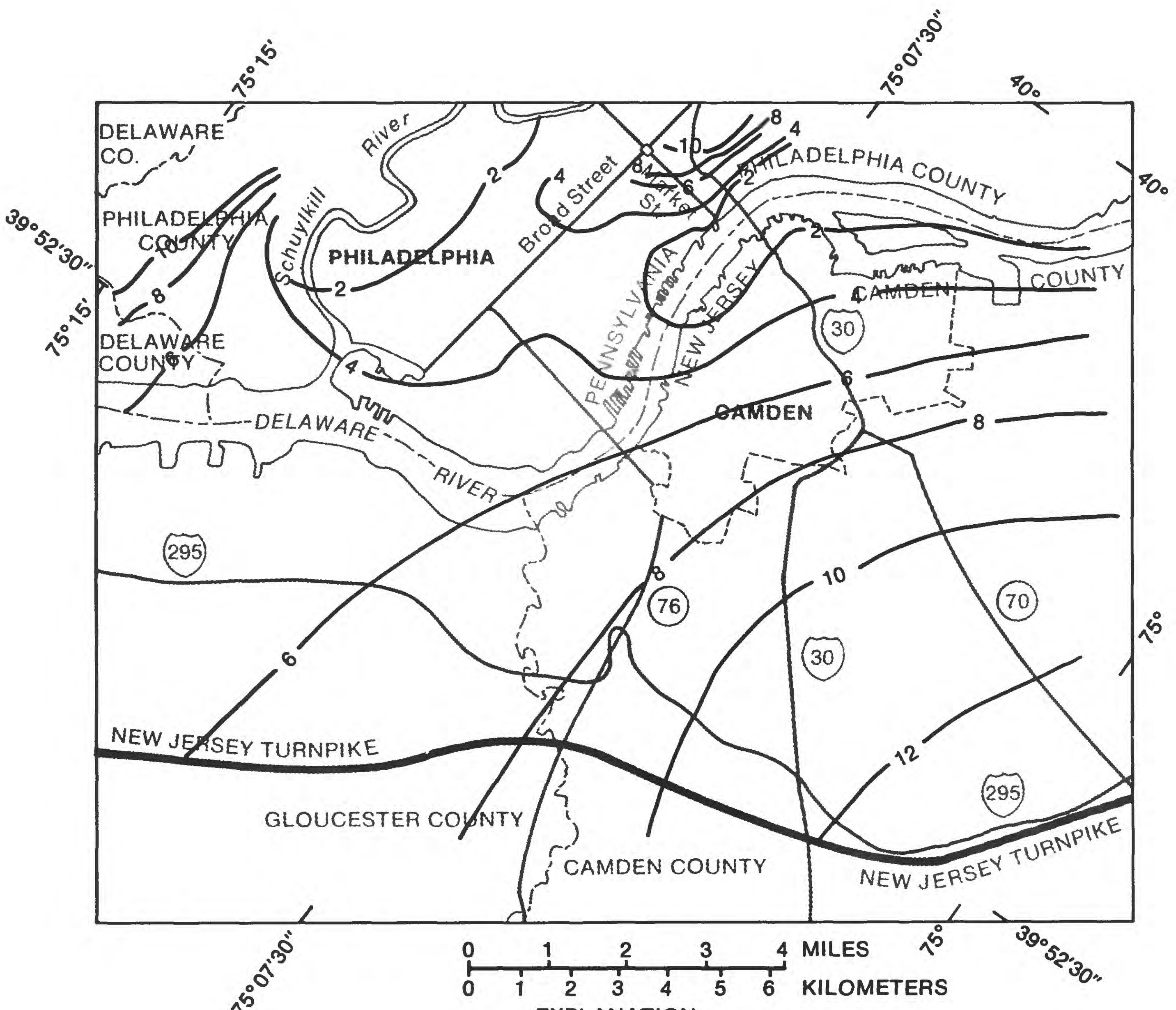
Transient-Simulation Time Discretization

Transient flow in the lower sand unit was simulated for 1904-78. This period was divided into three parts based on the availability of pumpage and head data.

The initial calibration period, 1904-45, consisted of 12 stress periods. Early (1904-40) stress periods were 4 to 8 years long and were chosen so that pumpage was relatively constant during each. Later stress periods (1941-45) were 1 year each. The initial calibration period was used for model calibration and sensitivity analysis because of the availability of nearly complete pumpage and head data for the U.S. Naval Base wells and head data for other wells.

The final calibration period, 1946-56, consisted of 11 stress periods of 1 year each and was used for final adjustments of model variables.

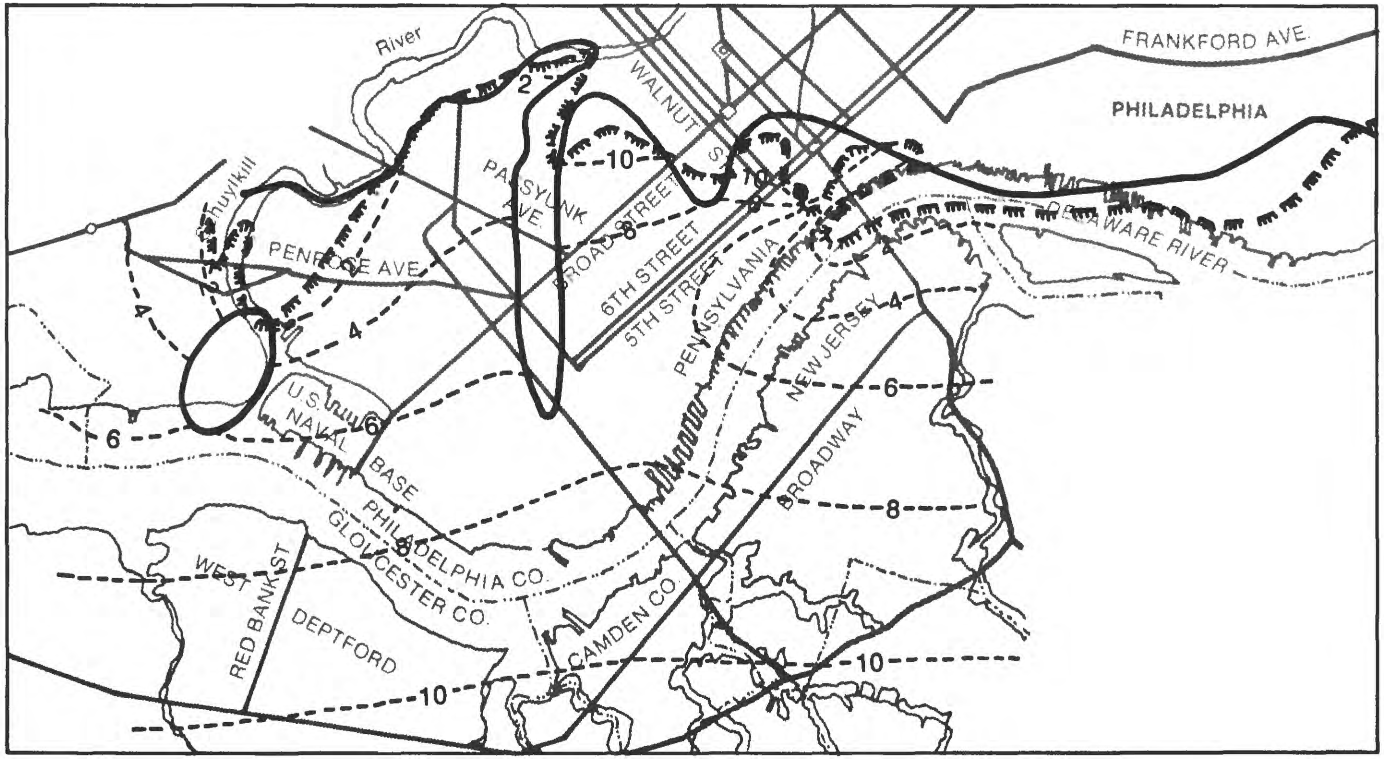
The period 1957-78 was simulated without adjusting the final model variables obtained from calibration. This period consisted of 13 stress periods. Early stress periods (1957-70) were 2 or 3 years long; later stress periods (1971-78) were 1 year each.



EXPLANATION

—— 2 —— POTENTIOMETRIC CONTOUR-- shows altitude of the potentiometric surface. Contour interval 2 feet. Datum is sea level.

Figure 10.-- Simulated prepumping potentiometric surface of the lower sand unit.



0 1 MILE
0 1 KILOMETER

EXPLANATION

---6--- POTENTIOMETRIC CONTOUR--SHOWS EQUAL ALTITUDE OF THE POTENTIOMETRIC SURFACE. CONTOUR INTERVAL 2 FEET.

LINE SHOWING THE LIMIT OF THE LOWER SAND UNIT.

EDGE OF THE UPPER CONFINING UNIT.

Figure 11.--Hypothetical prepumping potentiometric surface in Philadelphia. (From Greenman and others 1961, figure 7)

Sensitivity Analysis

A sensitivity analysis was made of boundary conditions and of each model variable to (1) determine the effects of using a specified-head boundary, (2) to determine the change in simulated heads in response to changes in the value of each variable, (3) to estimate the values of variables for which no field data were available, and (4) to aid in the choice of final variable values. Transient flow was simulated for 1904-45, and changes in head at particular nodes, the potentiometric surface, and the water budget were compared to determine sensitivity. Change in head for 1945 at node 14,10, which corresponds to well PH-6 at the U.S. Naval Base, is presented to show how changes in boundary conditions and in the values of model variables affect the head at a node in an area of heavy pumping. Node 14,10 was chosen because it is in an area where pumpage and head data were available (fig. 12).

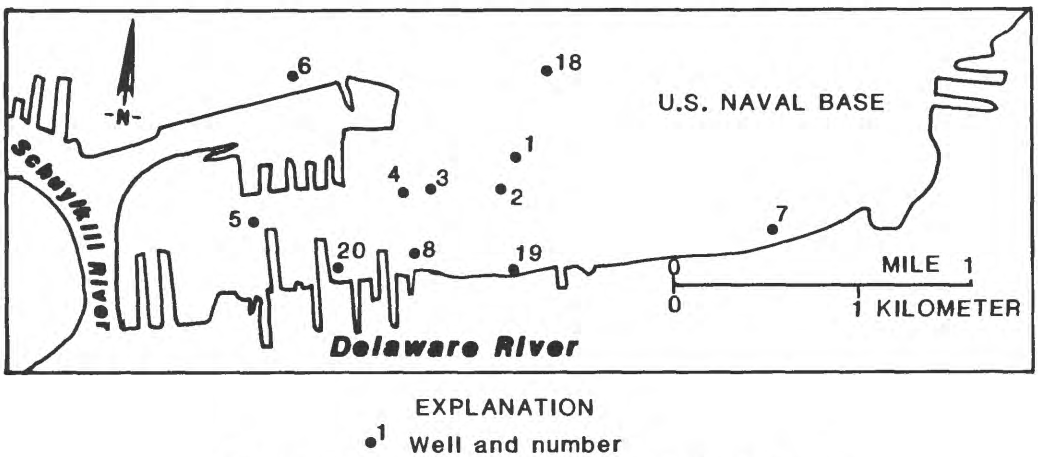


Figure 12.--Wells at the U.S. Naval Base

To test the sensitivity of heads in Philadelphia to boundary conditions, a no-flow boundary and constant-head boundaries were substituted for the specified-head boundary. With the specified-head boundary, the simulated head at node 14,10 for 1945 was -23.2 feet. When the specified-head boundary was replaced with a no-flow boundary, the simulated head at node 14,10 for 1945 was -22.9 feet, or 0.3 feet higher. A constant-head boundary was simulated with the heads held constant at (1) the prepumping heads, and (2) the heads in 1946. With the prepumping heads held constant at the boundaries, the simulated head at node 14,10 for 1945 was -21.3 feet, or 1.9 feet higher than the simulation using specified heads. This is because of the higher prepumping heads at the boundaries maintaining a steeper hydraulic gradient and allowing more water to flow toward south Philadelphia. With the 1946 heads held constant at the boundaries, the simulated head at node 14,10 in 1945 was -23.2 feet--the same as for the simulation using the specified-head boundary. The no-flow boundary and specified-head boundary produced nearly the same heads in south Philadelphia, indicating little sensitivity of heads in south Philadelphia to boundary conditions.

Sensitivity analysis of model variables involves changing the value of a single input in the model and making another simulation. To determine how changing the value of a particular model variable affects head, the value of the variable being tested was varied over a reasonable range while the values of the rest of the variables remained set at their initial values (table 2).

Any changes in results (model-generated potentiometric surface) are then caused only by the change in that variable. If the changes in results are great when a change is made to an input variable, the model is said to be sensitive to that variable. Conversely, slight changes in the results indicate model insensitivity to that variable. Results of sensitivity analyses are presented in following sections.

Table 2.--Initial and final model variable values

Model variable	Initial value	Final value
Lower sand unit		
Hydraulic conductivity	1.74×10^{-3} ft/s	1.60×10^{-3} ft/s
Storage	3.0×10^{-4}	3.0×10^{-4}
Recharge rate	1.37×10^{-8} ft/s	1.37×10^{-8} ft/s
Upper confining unit		
Hydraulic conductivity	1.0×10^{-8} ft/s	4.0×10^{-8} ft/s
Specific storage	1.0×10^{-5}/ft	1.0×10^{-5}/ft

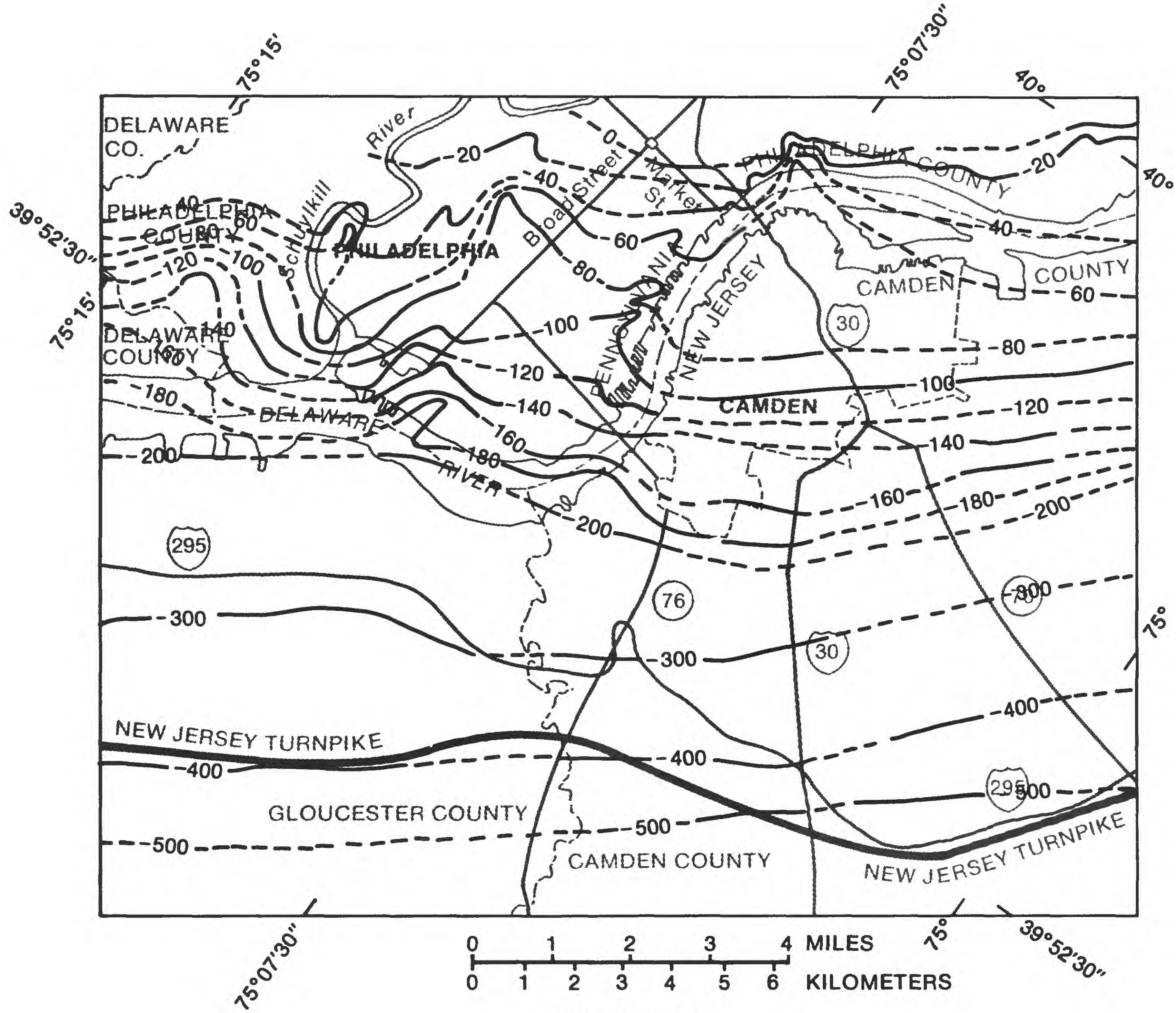
Modeled Hydraulic and Physical Characteristics

Lower Sand Unit

Model variables include altitudes of the top and bottom of the aquifer, hydraulic conductivity, storage coefficient, specific yield, and recharge rate.

Altitude of the top of the modeled aquifer was taken from figure 13. Figure 13 combines data from Greenman and others (1961, plate 7), geologic and geophysical log data from recently completed wells and borings in Pennsylvania, and hydrogeologic data from New Jersey (Zapecza, O. S., U.S. Geological Survey, written commun., 1982).

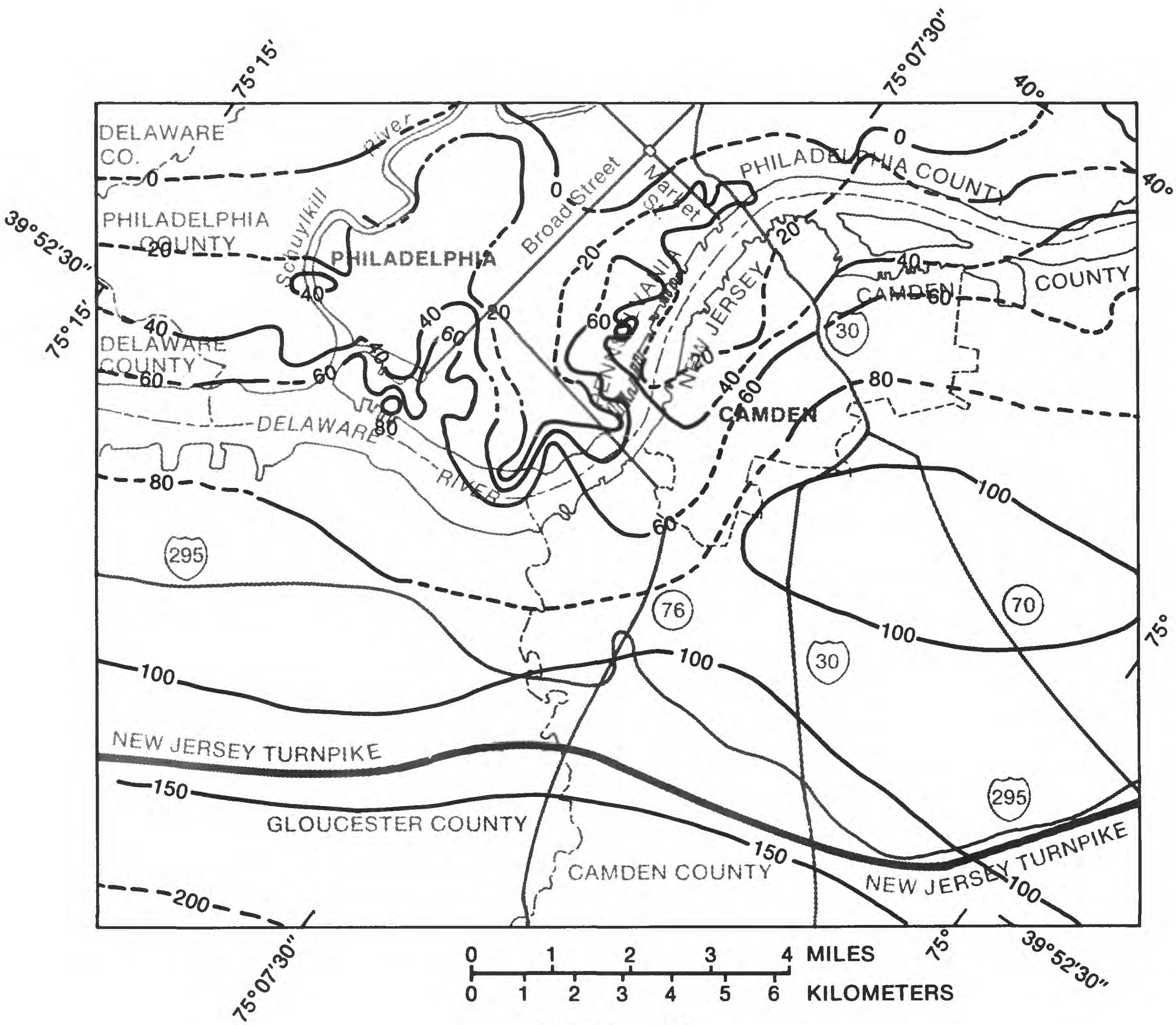
The altitude of the bottom of the lower sand unit was calculated by subtracting its thickness (fig. 14) from the altitude of the top of the aquifer (fig. 13). Figure 14 combines data from Greenman and others (1961, plate 9), geologic and geophysical log data from recently completed wells and borings in Pennsylvania, and hydrogeologic data from New Jersey (Zapecza, O. S., U.S. Geological Survey, written commun., 1982).



EXPLANATION

—— -100 —— STRUCTURE CONTOUR--shows altitude of top of lower sand unit. Dashed where approximately located. Contour intervals 20 and 100 feet. Datum is sea level.

Figure 13.-- Altitude of the top of the lower sand unit.



EXPLANATION

—— 100 —— LINE OF EQUAL THICKNESS-- dashed where approximately located. Intervals 20 and 50 feet. Datum is sea level.

Figure 14.-- Thickness of the lower sand unit.

Hydraulic conductivity

The hydraulic conductivity of the lower sand unit was determined from analysis of 15 aquifer tests conducted in Philadelphia and Camden and Gloucester Counties, New Jersey. Hydraulic conductivity values ranged from 1.1×10^{-3} to 2.4×10^{-3} ft/s, with an average value of 1.6×10^{-3} ft/s. More than half the values were in the range of 1.5×10^{-3} to 1.8×10^{-3} ft/s. A transient-flow sensitivity analysis for 1904-45 showed that simulated heads were very sensitive to changes in aquifer hydraulic conductivity (fig. 15). A 20-foot range in head at node 14,10 was produced by varying the hydraulic conductivity of the lower sand unit from 1.1×10^{-3} to 2.4×10^{-3} ft/s. The hydraulic conductivity of the upper confining unit was 1.0×10^{-8} ft/s for these simulations. The final value for hydraulic conductivity of the lower sand unit used in model simulations was the average value, 1.6×10^{-3} ft/s, which is consistent with average values given by Barksdale and others (1958, p. 98), Greenman and others (1961, p. 34-35), and Hardt and Hilton (1969, p. 11).

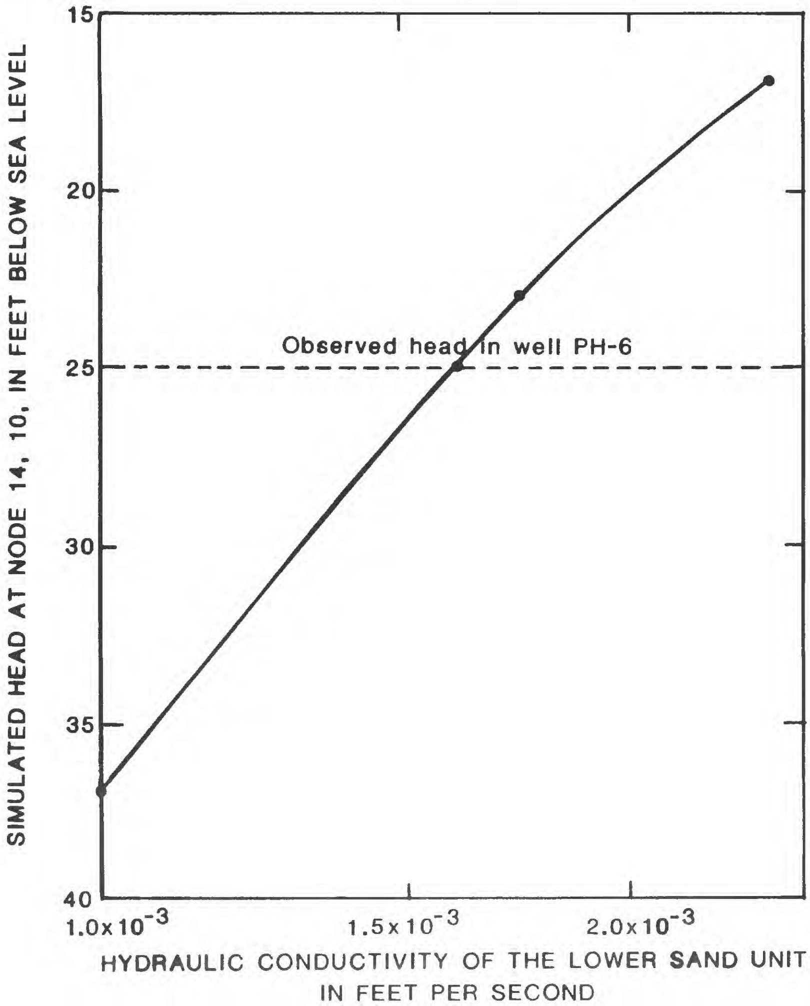


Figure 15.--Effect of varying the hydraulic conductivity of the lower sand unit on simulated head (1945) at node 14, 10. Hydraulic conductivity of the upper confining unit is 1.0×10^{-8} feet per second.

Storage coefficient

The storage coefficient of the lower sand unit was determined based on 15 aquifer tests. Values ranged from 1.5×10^{-3} to 9.0×10^{-5}, with an average value of 2.7×10^{-4}. A transient-flow sensitivity analysis for 1904-45 showed that heads in the lower sand unit were not sensitive to changes in the value of the storage coefficient. The simulated head at node 14,10 changed less than 0.1 foot when the storage coefficient was varied from 1.5×10^{-3} to 7.0×10^{-5}. The water budgets showed that the change in the rate of release of water from storage was less than 0.1 ft^3/s (cubic feet per second). Less than 1 percent of pumpage was water released from storage. A storage coefficient of 3.0×10^{-4} was used as the final value for model simulations. This value is consistent with that of Barksdale and others (1958, p. 98).

Specific yield

The unconfined part of the modeled aquifer is thin, of small areal extent, and generally not tapped by wells. A specific yield of 0.35 was selected for model simulations based on an estimate of 35 percent for the average specific yield for aquifers in the Raritan Formation (Barksdale and others, 1958, p. 98).

Recharge

Direct recharge from precipitation occurs only on the unconfined part of the lower sand unit, which is of small areal extent and mostly covered by impermeable surfaces. A transient-flow sensitivity analysis for 1904-45 was made using recharge rates ranging from 4 to 12 inches per year. Changing the recharge rate did not change the head at node 14,10 in the confined part of the aquifer, but produced a change of 3.0 feet in head at node 5,25 in the unconfined part. A recharge rate of 5 inches per year (Farlekas, 1979, p. 32) was selected for model simulations.

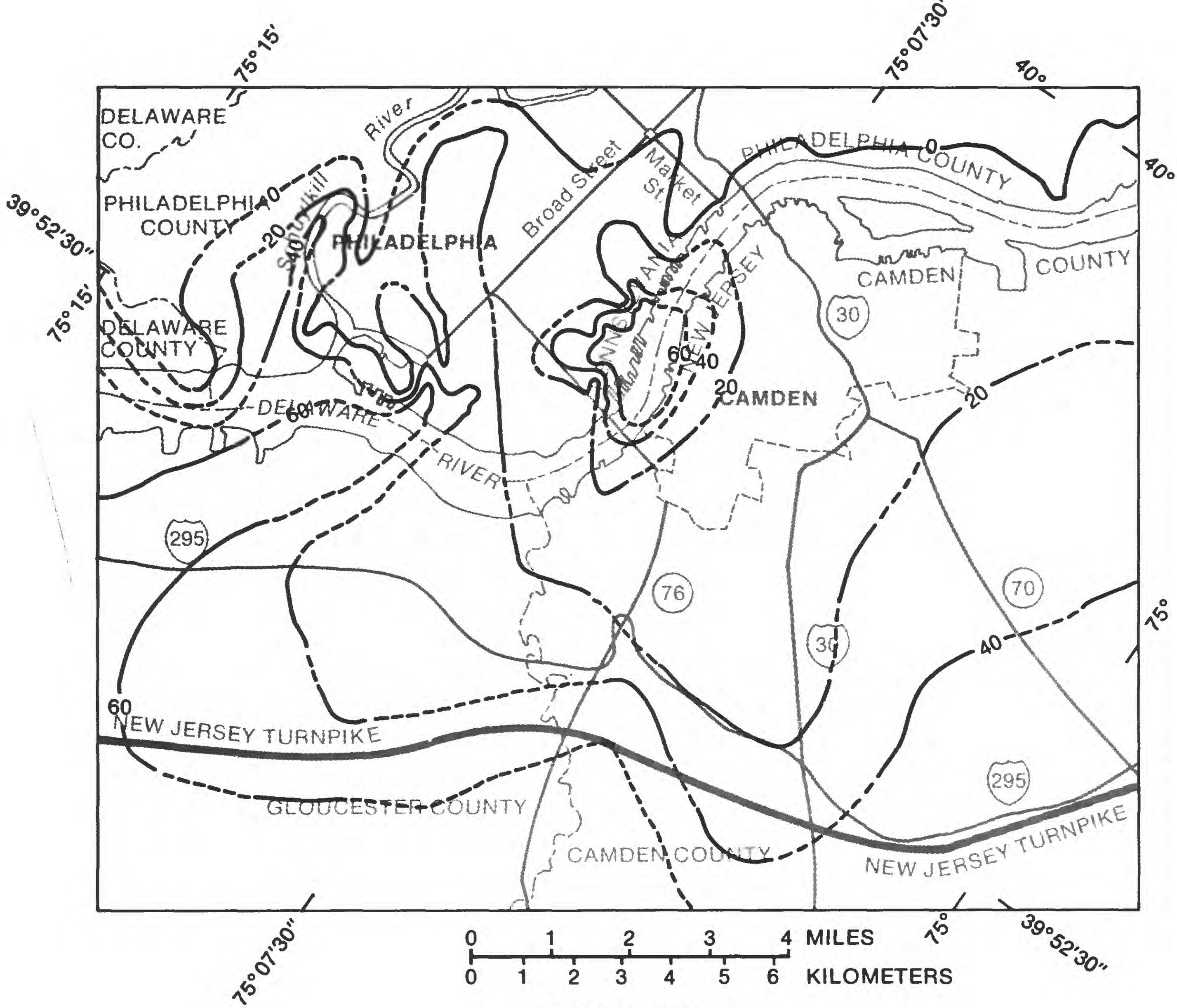
Upper Confining Unit

Confining-bed characteristics required by the model program include thickness, hydraulic conductivity, and specific storage.

Thickness

The thickness and extent of the upper confining unit is shown on figure 16. Thickness ranged from zero to more than 60 feet. Water in the lower sand unit is under artesian conditions where it is overlain by the upper confining unit. Figure 16 combines data from Greenman and others (1961, plates 18 and 19), geologic and geophysical log data from recently completed wells and borings in Pennsylvania, and hydrogeologic data from New Jersey (Zapecza, O. S., U.S. Geological Survey, written commun., 1981).

To test the sensitivity of simulated heads to changes in the thickness of the upper confining unit, thickness was increased by 20 and 100 percent and reduced by 20 and 50 percent for transient-flow simulations for 1904-45. The upper confining unit is 30 feet thick at node 14,10. Increasing the thickness by 20 percent decreased the simulated head 0.9 foot at node 14,10 and doubling



EXPLANATION

—— 20 —— LINE OF EQUAL THICKNESS--dashed where approximately located. Interval 20 feet. Datum is sea level.

Figure 16.-- Thickness of the upper confining unit.

the thickness decreased the simulated head 3.0 feet. Decreasing the thickness by 20 percent increased the simulated head 1.2 feet at node 14,10 and halving the thickness increased the simulated head 4.0 feet. The sensitivity analysis showed that simulated head is sensitive to changes in the thickness of the upper confining unit, but that errors in simulated head caused by interpolation of the thickness between data points are probably less than 5 feet.

Hydraulic conductivity

No hydraulic conductivity data are available for the upper confining unit. Barksdale and others (1958, p. 105) estimated that the hydraulic conductivity of clays of the Raritan Formation are probably less than 1.6×10^{-7} ft/s.

A transient-flow sensitivity analysis for 1904-45 was made using values of hydraulic conductivity ranging from 1.0×10^{-5} to 1.0×10^{-11} ft/s. The upper confining unit was also simulated as an impermeable layer by assigning it a hydraulic conductivity of zero. Results of the simulations showed that the hydraulic conductivity is approximately 4.0×10^{-8} ft/s and that, if the hydraulic conductivity were less than 1.0×10^{-8} ft/s, the unit would be essentially impermeable. Figure 17 shows the range in simulated head at node 14,10 was 30 feet when the hydraulic conductivity of the upper confining unit was varied from 1.0×10^{-5} to 1.0×10^{-11} ft/s.

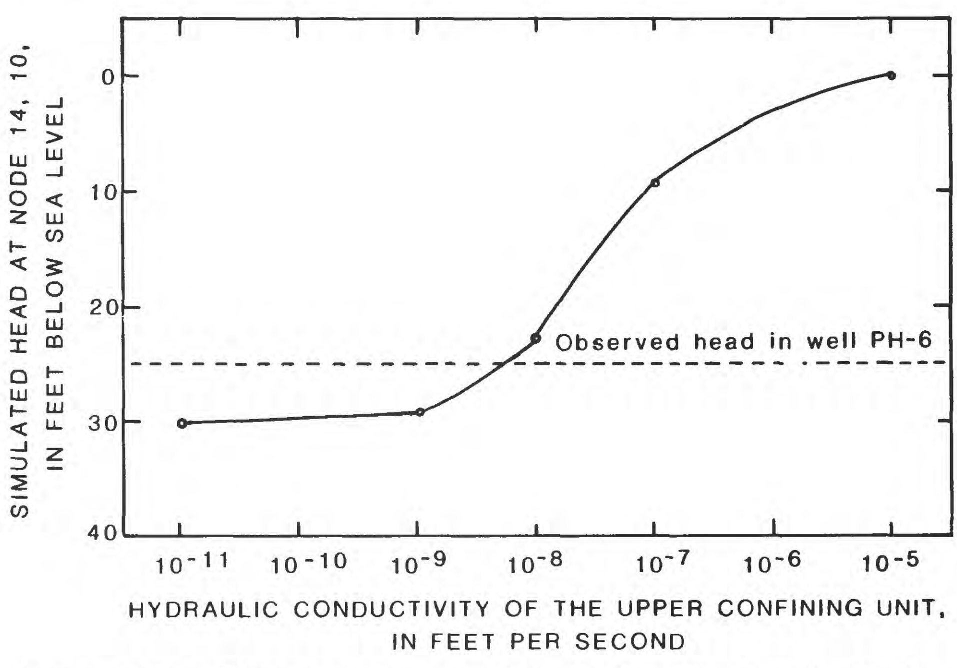


Figure 17 --Effect of varying the hydraulic conductivity of the upper confining unit on simulated head (1945) at node 14, 10. Hydraulic conductivity of the lower sand unit is 1.74 x 10-3 feet per second.

Many combinations of aquifer and upper confining unit hydraulic conductivity values can produce the same simulated head at a particular node (fig. 18). Different combinations of hydraulic conductivity of the lower sand and upper confining units, however, produced different simulated regional potentiometric surfaces. Several combinations were used for transient simulations for 1904-45, and the simulated potentiometric surface for 1945 was compared to Greenman and others (1961, fig. 16). Two of the simulations-- one using hydraulic conductivity values of 1.6×10^{-3} ft/s and 4.0×10^{-8} ft/s for the lower sand and upper confining units, respectively, and one using hydraulic conductivity values of 1.7×10^{-3} ft/s and 3.0×10^{-8} ft/s for the lower sand and upper confining units, respectively--best simulated the observed potentiometric surface for 1945. Transient simulations using these two sets of hydraulic conductivities were continued for 1946-56, and the simulated potentiometric surface for 1956 was compared to that of Farlekas and others (1976, p. 31). The simulation using hydraulic conductivities of 1.6×10^{-3} ft/s and 4.0×10^{-8} ft/s for the lower sand and upper confining units, respectively, best simulated the observed potentiometric surface for 1956. Therefore, a hydraulic conductivity of 4.0×10^{-8} ft/s for the upper confining unit was selected as the final value for model simulations.

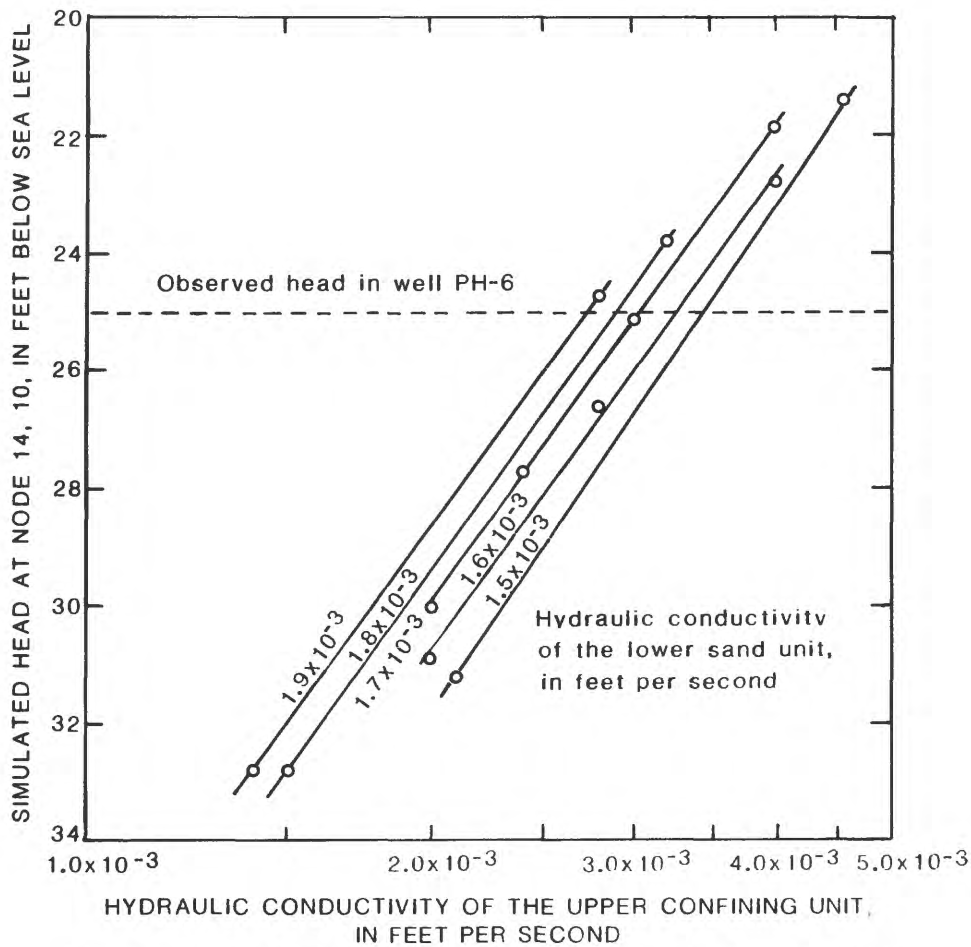


Figure 18.--Effect of varying the hydraulic conductivity of the lower sand and upper confining units on simulated head (1945) at node 14, 10.

Specific storage

No data are available for specific storage of the upper confining unit. To estimate specific storage, transient-flow simulations for 1904-45 were made using specific storage values of zero, 1.0×10^{-7}/ft, and 1.0×10^{-5}/ft. A specific storage of zero causes vertical leakage to occur only as steady leakage through the upper confining unit, whereas values greater than zero cause vertical leakage to occur as steady leakage plus transient leakage from storage within the upper confining unit. All three simulations produced the same head at node 14,10. A simulation using an unrealistically large specific storage of 1.0×10^{-2}/ft caused an increase in the simulated head at node 14,10 of 0.1 foot and an increase in the areal leakage rate of 0.3 ft^3/s. These simulations indicate that steady leakage is the major component of vertical leakage and that transient leakage is probably negligible. A specific storage of 1.0×10^{-5}/ft for the upper confining unit was selected for model simulations.

Head Above the Upper Confining Unit

Where the upper confining unit is present, the computer program used to simulate ground-water flow requires the head in the aquifer above it. In Philadelphia, this aquifer is the water-table-aquifer system. In New Jersey, this aquifer is the upper aquifer of the Potomac-Raritan-Magothy aquifer system.

Heads in the aquifer above the upper confining unit change in response to pumping from that aquifer and pumping from the lower sand unit. Heads in this aquifer have declined with time. Walker (1983, p. 24) described measured water-level declines in the upper aquifer of the Potomac-Raritan-Magothy aquifer system in Burlington, Camden, and Gloucester Counties, New Jersey, of 5 to 18 feet from 1973-78. The computer program, however, requires a constant head in the aquifer above the upper confining unit for the entire simulation. In order to simulate the hydrologic system more realistically, the computer program was modified to simulate declining heads in the aquifer above the upper confining unit. The computer program was modified to accept two sets of heads for the aquifer above the upper confining unit and to linearly interpolate between them to calculate a new set of heads for each stress period. The calculated head is held constant for that stress period. For example, simulations for 1957-78 used head data for 1956 and 1978. For the first stress period, 1957-58, a set of heads for 1958 are computed by interpolating between the 1956 and 1978 heads. The calculated heads for 1958 are then used for the 1957-58 stress period. The procedure is repeated for each stress period. This allows the head in the aquifer above the upper confining unit to vary with time. Heads for the Delaware and Schuylkill Rivers, where the riverbeds are separated from the lower sand unit by the upper confining unit, were simulated as constant heads of zero feet (mean sea level).

Few data on head in the aquifer above the upper confining unit are available before 1956. Heads above the upper confining unit for prepumping conditions were taken from prepumping (1900) potentiometric-surface maps of the Potomac-Raritan-Magothy aquifer system of Gill and Farlekas (1976) for Philadelphia, and Farlekas and others (1976, p. 27) for New Jersey. Heads above the upper confining unit for 1956 for Philadelphia were taken from Gill and Farlekas (1956), Paulachok and Wood (1984), and water-level records. Heads above the upper confining unit in New Jersey for 1956 were taken from the potentiometric-surface map of the Potomac-Raritan-Magothy aquifer system for 1956 of Farlekas and others (1976, p. 31) for Camden County, and Gill and Farlekas (1976) for Gloucester County. Heads above the upper confining unit for 1978 for Philadelphia were taken from the water-table map of Paulachok and Wood (1984). Heads above the upper confining unit for New Jersey for 1978 were taken from the potentiometric-surface map of the upper aquifer of the Potomac-Raritan-Magothy aquifer system of Walker (1983, plate 2).

Transient-flow sensitivity analyses were made for 1904-45 to evaluate the effects of using specified heads in the aquifer above the upper confining unit and to determine the effects of error in estimating head above the upper confining unit on head in the lower sand unit. The simulation using specified heads in the aquifer above the upper confining unit produced a simulated head of -23.2 feet at node 14,10 at the U.S. Naval Base for 1945. Downward leakage through the upper confining unit was 55 percent of inflow to the lower sand unit. Upward leakage through the upper confining unit was 27 percent of discharge from the lower sand unit. Prepumping heads held constant in the aquifer above the upper confining unit produced a simulated head of -22.7 feet at node 14,10 for 1945, an increase of 0.5 foot. Downward leakage through the upper confining unit was 56 percent of inflow to the lower sand unit. Upward leakage through the upper confining unit was 27 percent of discharge from the lower sand unit. Heads for 1946 that were held constant in the aquifer above the upper confining unit produced a simulated head of -23.1 feet at node 14,10 for 1945. Downward leakage through the upper confining unit was 55 percent of inflow to the lower sand unit. Upward leakage through the upper confining unit was 29 percent of discharge from the lower sand unit.

To determine the effect of error in estimating head in the aquifer above the upper confining unit, heads in that aquifer were increased 10 feet and decreased 10 feet over the modeled area except for cells occupied by the Delaware and Schuylkill Rivers, where head was held constant at zero feet. Raising the head in the aquifer above the upper confining unit by 10 feet increased the simulated head 1.9 feet at node 14,10 for 1945. The upper confining unit is 30 feet thick at node 14,10. Downward leakage through the upper confining unit was 57 percent of the inflow to the lower sand unit. Upward leakage through the upper confining unit was 29 percent of discharge from the lower confining unit. Lowering the head in the aquifer above the upper confining unit decreased the simulated head 1.9 feet at node 14,10 for 1945. Downward leakage through the upper confining unit was 56 percent of inflow to the lower sand unit. Upward leakage through the upper confining unit was 34 percent of the discharge from the lower sand unit.

Model Simulations

Transient Simulations

Except for wells at the U.S. Naval Base, pumpage data are incomplete and mostly estimated for 1904-45; however, the model adequately simulated the potentiometric surface of the lower sand unit in south Philadelphia for 1945 (fig. 19). A comparison of the observed potentiometric surface of Greenman and others (1961, fig. 16) shown on figure 20 and the simulated potentiometric surface shows that the simulated cones of depression in Philadelphia are at the proper location and of approximately the right magnitude. At the U.S. Naval Base, differences between simulated and observed heads ranged from less than 2 feet in the center of the cone of depression to less than 5 feet at the edge of the cone. Differences between simulated and observed heads in the cones of depression in the industrial area of south Philadelphia bordering the Delaware River across from Camden ranged from 0 to 20 feet. Differences between simulated and observed heads in the rest of the modeled area in Philadelphia generally were less than 10 feet. Comparison of simulated head and observed heads outside of Philadelphia is difficult because Greenman and others (1961, fig. 16) did not consider pumping in New Jersey.

Pumpage for 1904-45 totaled 133 billion gallons and accounted for 66 percent of the discharge from the lower sand unit. The major source of water for this pumpage was downward leakage through the upper confining unit. Other discharges from the lower sand unit were upward leakage through the upper confining unit (54 billion gallons or 27 percent of the total discharge), direct discharge to the Delaware and Schuylkill Rivers (8 billion gallons or 4 percent of discharge), and flow across boundaries out of the modeled area (6 billion gallons or 3 percent of discharge).

Downward leakage was the largest source of inflow to the lower sand unit for 1904-45. Downward leakage totaled 110 billion gallons or 55 percent of the total inflow. Other sources of inflow were induced recharge from the Delaware and Schuylkill Rivers (34 billion gallons or 17 percent of the total inflow), flow across boundaries from outside the modeled area (31 billion gallons or 15 percent of inflow), and recharge on the unconfined part of the lower sand unit (25 billion gallons or 13 percent of inflow). Less than 1 percent was water released from storage (0.2 billion gallons).

Except for wells at the U.S. Naval Base where pumpage data are available for 1946-53, pumpage data are mostly estimated for 1946-56. The simulated potentiometric surface for 1954 (fig. 21) for Philadelphia was compared with that of Greenman and others (1961, fig. 17) for March 24, 1954 (fig. 22). The simulated head at the center of the cone of depression at the U.S. Naval Base was within 20 feet of the observed head. This difference is mainly the result of using estimated pumpage for wells at the U.S. Naval Base and comparing simulated heads with observed heads measured on a specific date. Simulated heads in the cones of depression in the industrial area of south Philadelphia were within 10 feet of observed heads. Greenman and others (1961, fig. 17) did not consider pumping in New Jersey; therefore, their potentiometric surface map cannot be used for comparison of heads outside of Philadelphia.

The model adequately simulated the regional potentiometric surface of the lower sand unit for 1956 (fig. 23). The simulated potentiometric surface for 1956 was compared with that of Gill and Farlekas (1976). The difference between simulated and observed head for the cone of depression at the U.S. Naval Base and at the oil refinery in New Jersey south of the Naval Base was less than 10 feet. For most of the modeled area, differences between simulated and observed heads were less than 10 feet. For the cone of depression in the industrialized area of south Philadelphia, the difference between simulated and observed head was 30 feet.

Pumpage from the lower sand unit for 1946-56 totaled 117 billion gallons. The major source of water for this pumpage was downward leakage through the upper confining unit. Average pumpage for 1946-56 was 11 billion gallons per year; average pumpage for 1904-45 was 3 billion gallons per year. This increase in pumpage caused a large change in the water budget. For 1946-56, pumpage accounted for 90 percent of the discharge from the lower sand unit; for 1904-45, it accounted for 64 percent of the discharge. For 1946-56, downward leakage totaled 91 billion gallons (8 billion gallons per year) and accounted for 70 percent of the inflow to the lower sand unit. For 1904-45, downward leakage totaled 110 billion gallons (3 billion gallons per year) and accounted for 55 percent of the inflow to the lower sand unit.

In addition to pumpage, other discharges from the lower sand unit for 1946-56 include upward leakage through the upper confining unit (8 billion gallon or 6 percent of the total discharge), direct discharge to the Delaware and Schuylkill Rivers (3 billion gallons or 2 percent of the discharge), and flow across boundaries out of the modeled area (2 billion gallon or 2 percent of the discharge).

Downward leakage was the greatest source of inflow to the lower sand unit, accounting for 70 percent of the inflow. Other sources of inflow include flow across boundaries into the modeled area (21 billion gallons or 16 percent of total inflow), induced recharge from the Delaware and Schuylkill Rivers (11 billion gallons or 9 percent of inflow), and recharge on the unconfined part of lower sand unit (7 billion gallons or 5 percent of inflow. During 1946-56, induced recharge from the Delaware and Schuylkill Rivers averaged 1.0 billion gallons per year. This is higher than for 1904-45 (0.8 billion gallons per year) because cones of depression were larger as a result of increased pumping. Less than 1 percent was water released from storage (0.03 billion gallons).

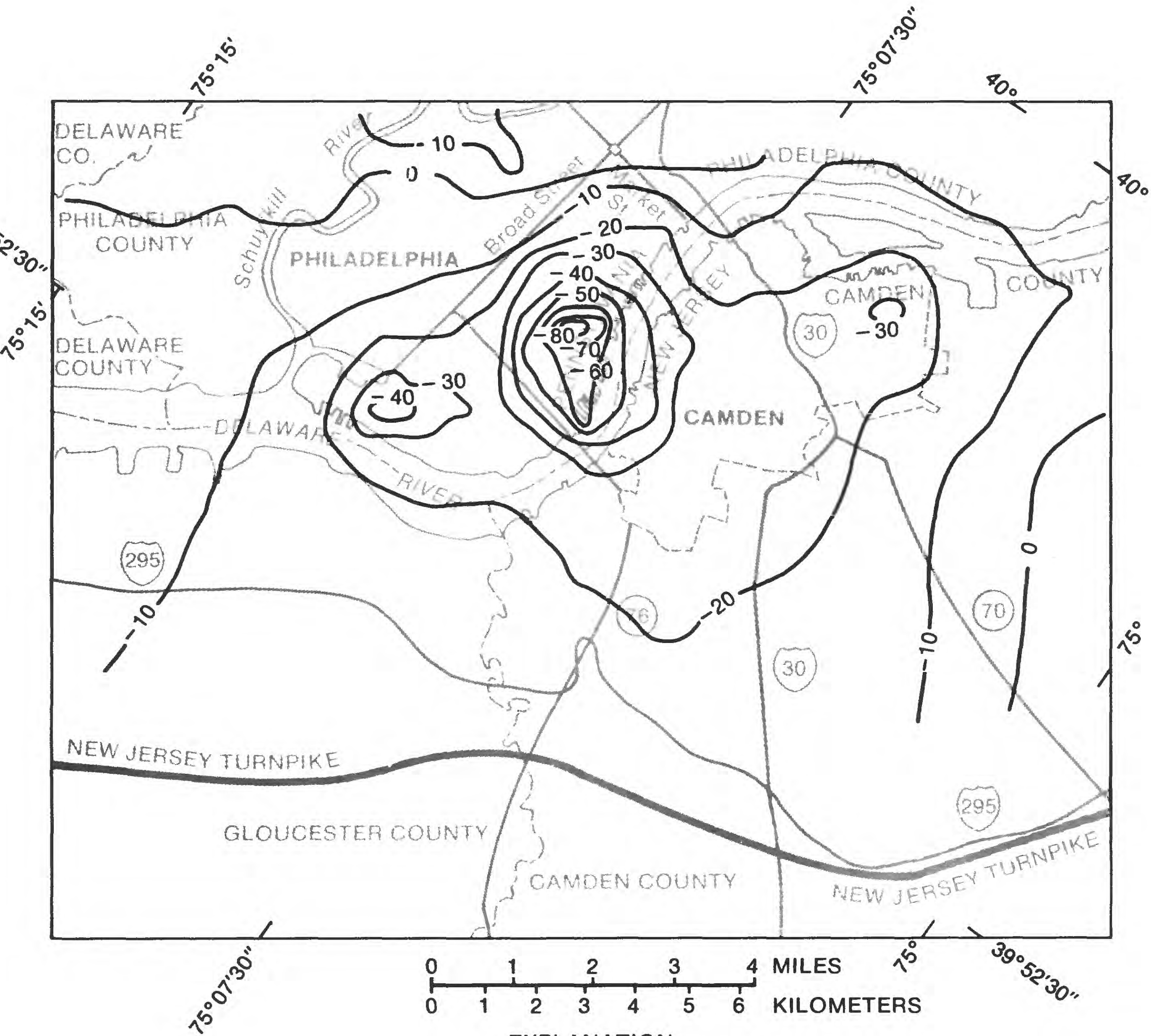
Pumpage for wells in Philadelphia for 1957-78 was mostly estimated. Monthly pumpage data for major production wells in Camden and Gloucester Counties, New Jersey are available for 1957-78. The model adequately simulated the regional potentiometric surface for 1978 (fig. 24). The simulated potentiometric surface for 1978 was compared with the potentiometric surface mapped by Paulachok (U.S. Geological Survey, written commun., 1982) for Philadelphia and with the potentiometric surface mapped by Walker (1983, plate 1) for New Jersey. A composite potentiometric surface map constructed from these two sources for the modeled area is shown in figure 25. The difference between simulated and observed heads in Philadelphia ranged from 0 to 15 feet, and generally were less than 5 feet. Difference between simulated and observed heads in New Jersey ranged from 0 to 15 feet and generally were less than 10 feet.

Pumpage for 1957-78 totaled 266 billion gallons and accounted for 93 percent of the discharge from the lower sand unit. This is slightly more than for 1946-56 (90 percent) because of increased pumpage. Average pumpage for 1957-78 was 12 billion gallons per year; average pumpage for 1946-56 was 11 billion gallons per year. The major source of water for this pumpage was downward leakage, which also increased. For 1957-78, downward leakage totaled 221 billion gallons (10 billion gallons per year) and accounted for 77 percent of the inflow to the lower sand unit; for 1946-56, downward leakage totaled 91 billion gallons (8 billion gallons per year) and accounted for 70 percent of the inflow to the lower sand unit.

In addition to pumpage, other discharges from the lower sand unit include flow across boundaries out of the modeled area (11 billion gallons or 4 percent of the total discharge), direct discharge to the Delaware and Schuylkill Rivers (8 billion gallons or 3 percent of discharge), and upward leakage through the upper confining unit (3 billion gallons or 1 percent of discharge).

Downward leakage was the greatest source of inflow to the lower sand unit, accounting for 77 percent of the inflow. Other sources of inflow include flow across boundaries into the modeled area (41 billion gallons or 14 percent of total inflow), recharge on the unconfined part of the lower sand unit (13 billion gallons or 5 percent of inflow), and induced recharge from the Delaware and Schuylkill Rivers (12 billion gallons or 4 percent of inflow). Induced recharge from the Delaware and Schuylkill rivers declined to 0.5 billion gallons per year for 1957-78 because of the sharp decrease in pumping in Philadelphia and the disappearance of large, local cones of depression. Less than 1 percent was water released from storage (0.06 billion gallons).

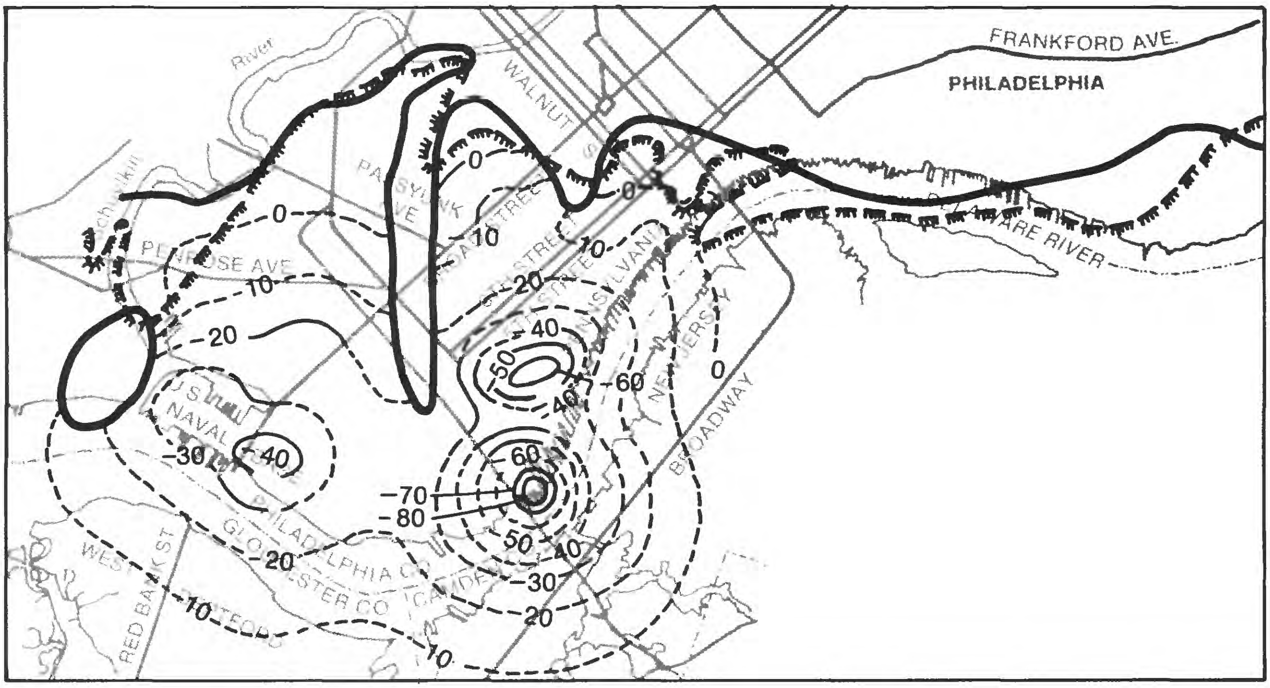
Figure 26 compares the simulated head at node 17,10 at the U.S. Naval Base and the average annual water level in well PH-20. The simulated hydrograph shows the decline in water level that occurred as a result of pumping at the U.S. Naval Base, the rise in water level when pumping stopped (about 1966), and the return to nonpumping conditions by the early 1970's. The dashed line in figure 26 also shows a greater deviation between the observed and simulated hydrographs where pumpage for 1953-66 was estimated.



EXPLANATION

——10—— POTENTIOMETRIC CONTOUR--shows altitude of the potentiometric surface. Contour interval 10 feet. Datum is sea level.

Figure 19.-- Simulated potentiometric surface of the lower sand unit, 1945.



0 1 MILE
0 1 KILOMETER

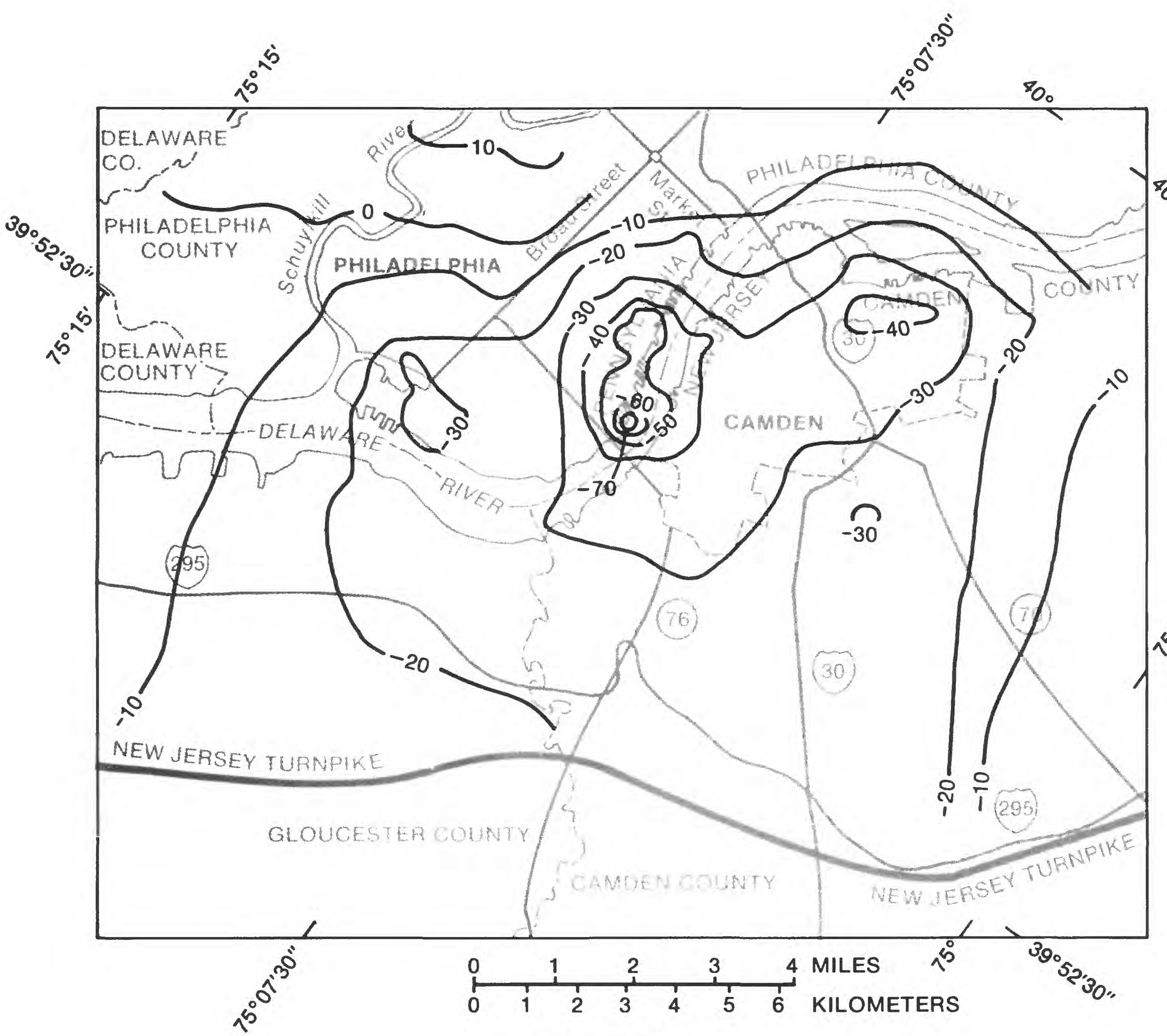
EXPLANATION

—— -20 —— POTENTIOMETRIC CONTOUR-- shows equal altitude of the potentiometric surface. Dashed where inferred. Contour interval 10 feet.

Line showing the limit of the lower sand unit.

Edge of the upper confining unit.

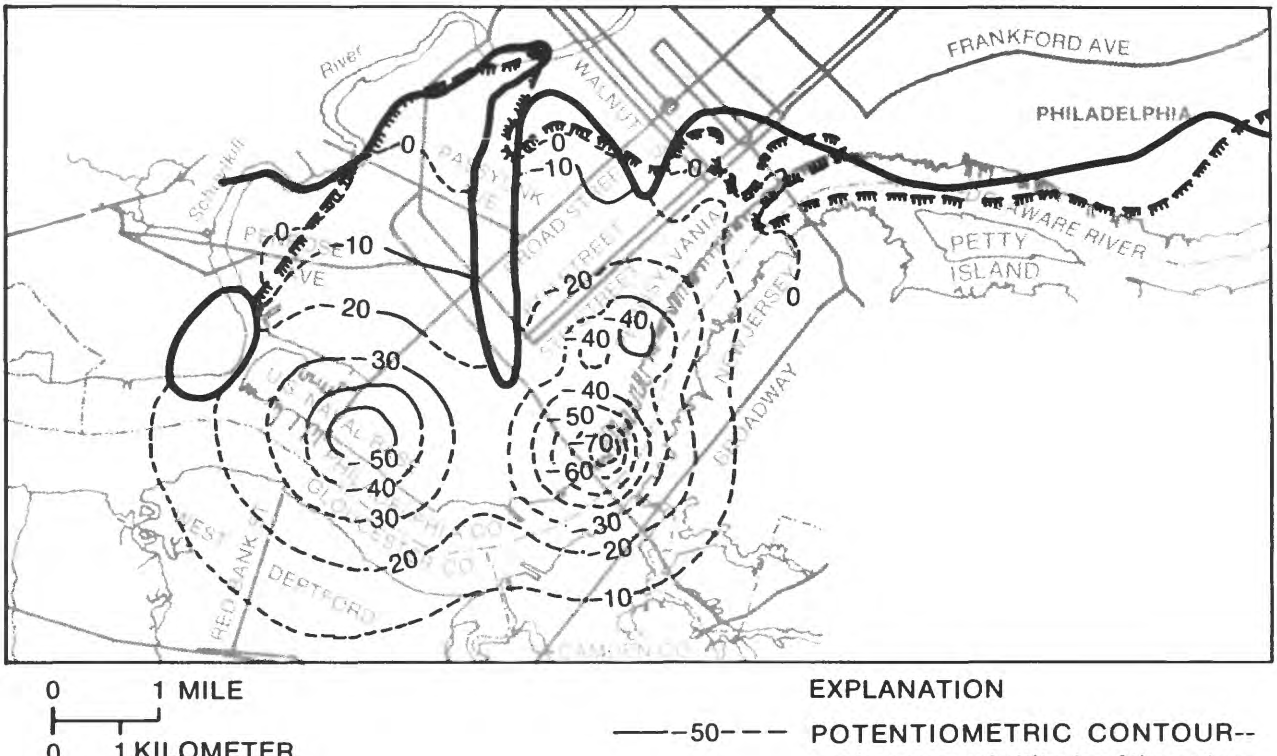
Figure 20.-- Potentiometric surface of the lower sand unit in August 1945. (From Greenman and others, 1961, figure 16).



EXPLANATION

——— -10 ——— POTENTIOMETRIC CONTOUR-- shows altitude of the potentiometric surface. Contour interval 10 feet. Datum is sea level.

Figure 21.-- Simulated potentiometric surface of the lower sand unit, 1954.



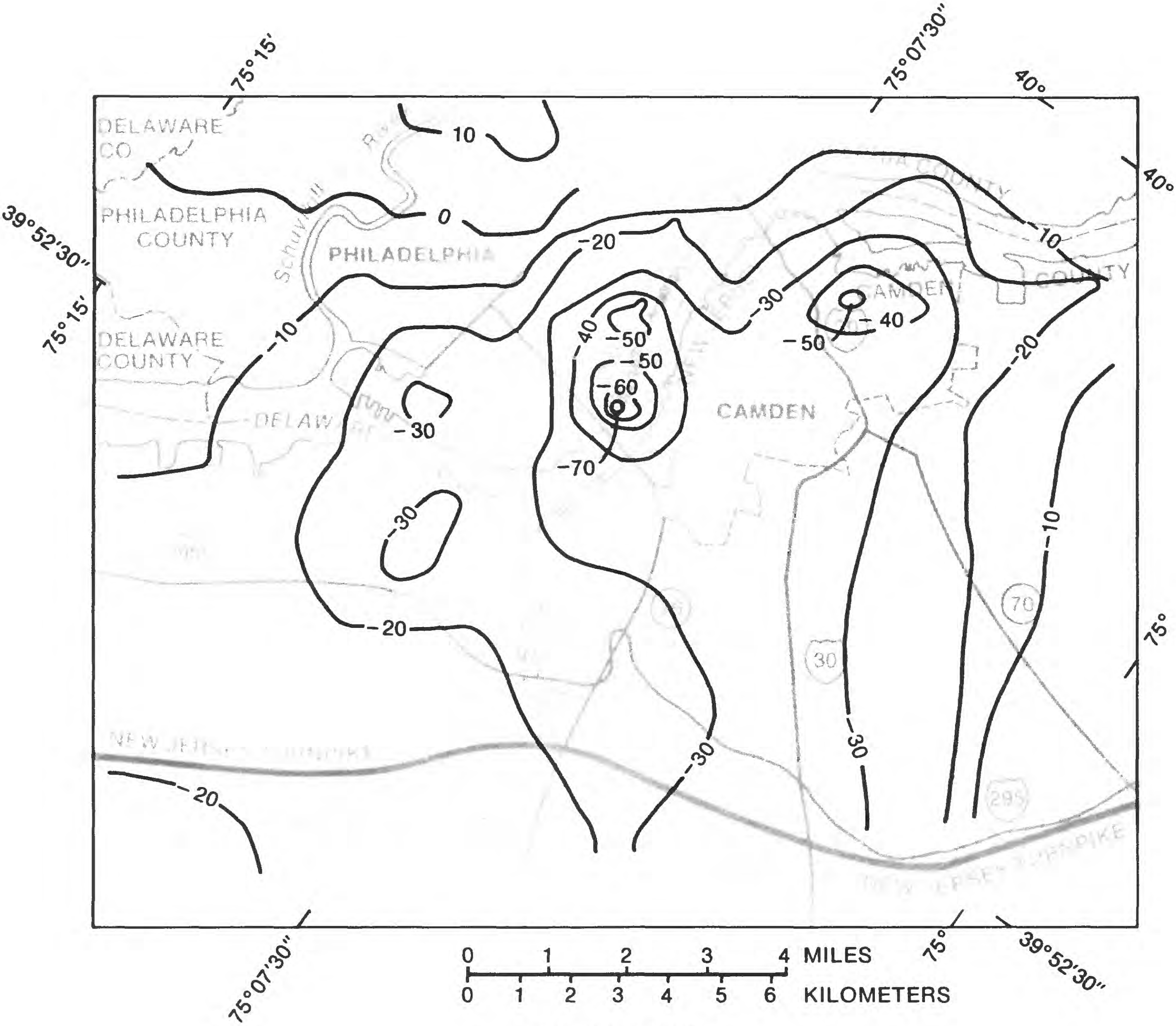
EXPLANATION

——-50- - - POTENTIOMETRIC CONTOUR--shows equal altitude of the potentiometric surface. Dashed where approximate. Contour interval 10 feet.

Line showing the limit of the lower sand unit.

Edge of the upper confining unit.

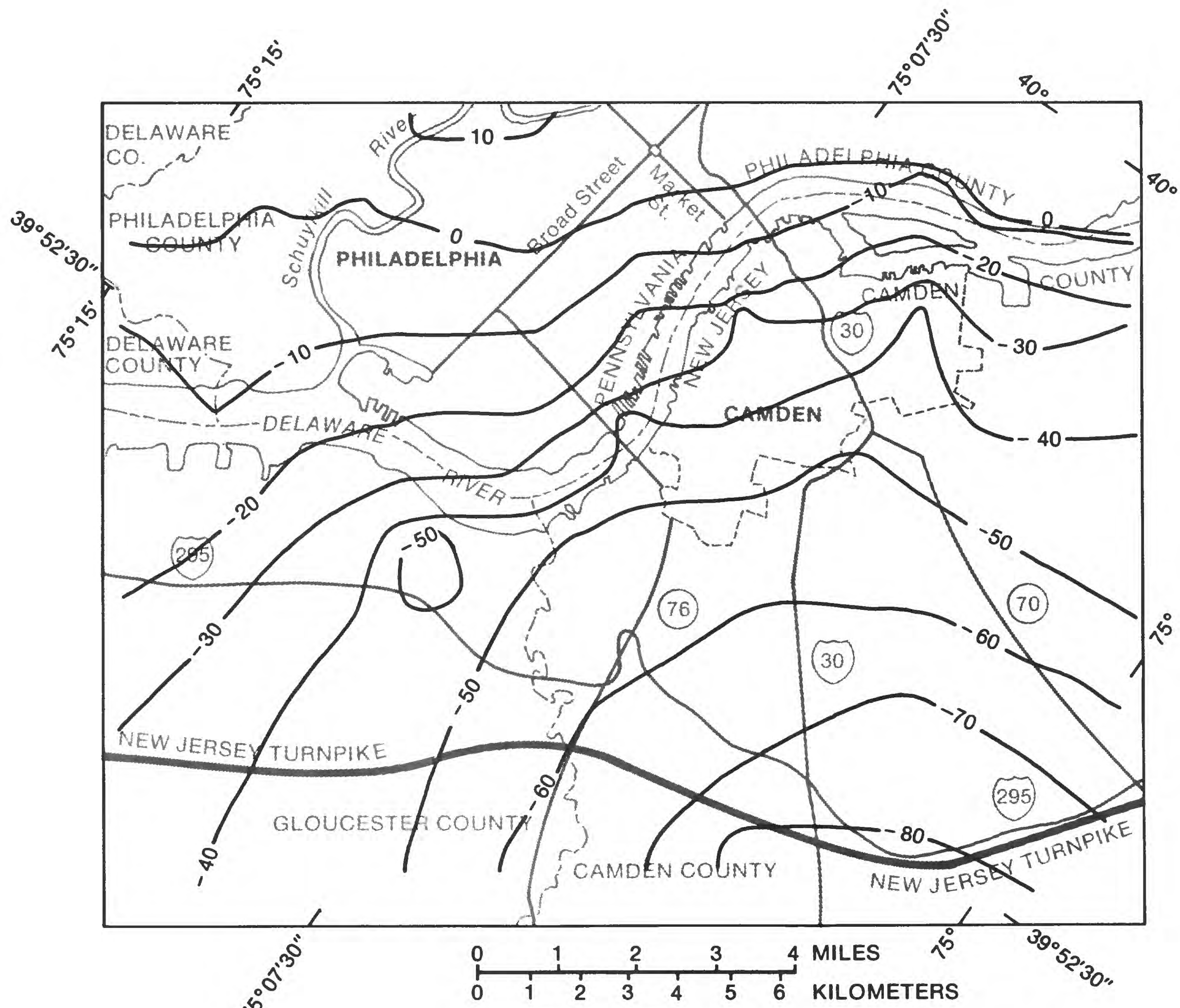
Figure 22.-- Potentiometric surface of the lower sand unit on March 24, 1954. (From Greenman and others, 1961, figure 17).



EXPLANATION

——— -20 ——— POTENTIOMETRIC CONTOUR-- shows altitude of the potentiometric surface. Contour interval 10 feet. Datum is sea level.

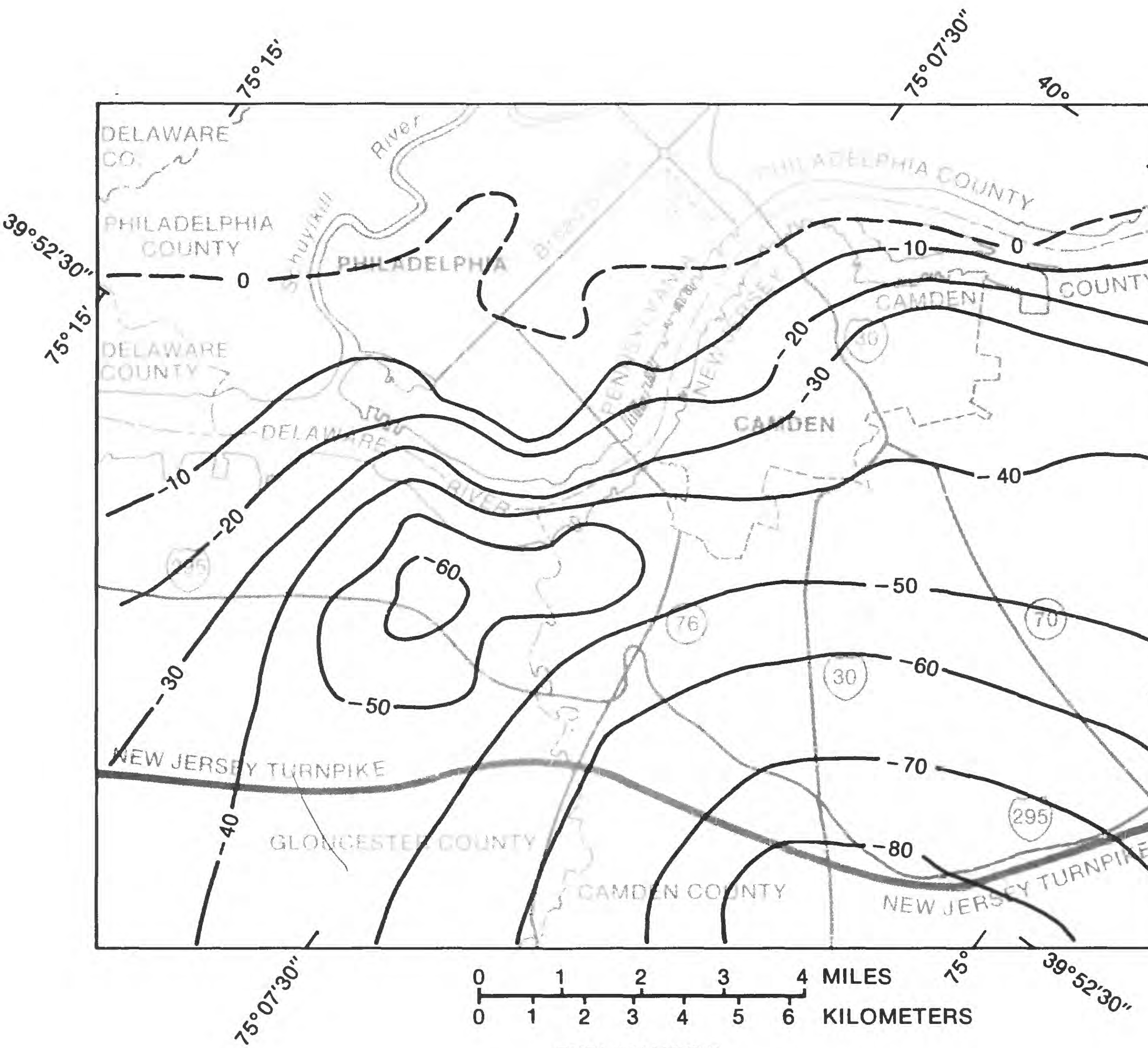
Figure 23.-- Simulated potentiometric surface of the lower sand unit, 1956.



EXPLANATION

—— -10 —— POTENTIOMETRIC CONTOUR-- shows altitude of the potentiometric surface. Contour interval 10 feet. Datum is sea level.

Figure 24.-- Simulated potentiometric surface of the lower sand unit, 1978.



EXPLANATION

——-10—— POTENTIOMETRIC CONTOUR-- shows altitude of the potentiometric surface. Contour interval 10 feet. Datum is sea level.

Figure 25.-- Potentiometric surface of the lower sand unit, 1978. From Walker (1983, plate 1) and Paulachok (U.S. Geological Survey, written commun., 1982).

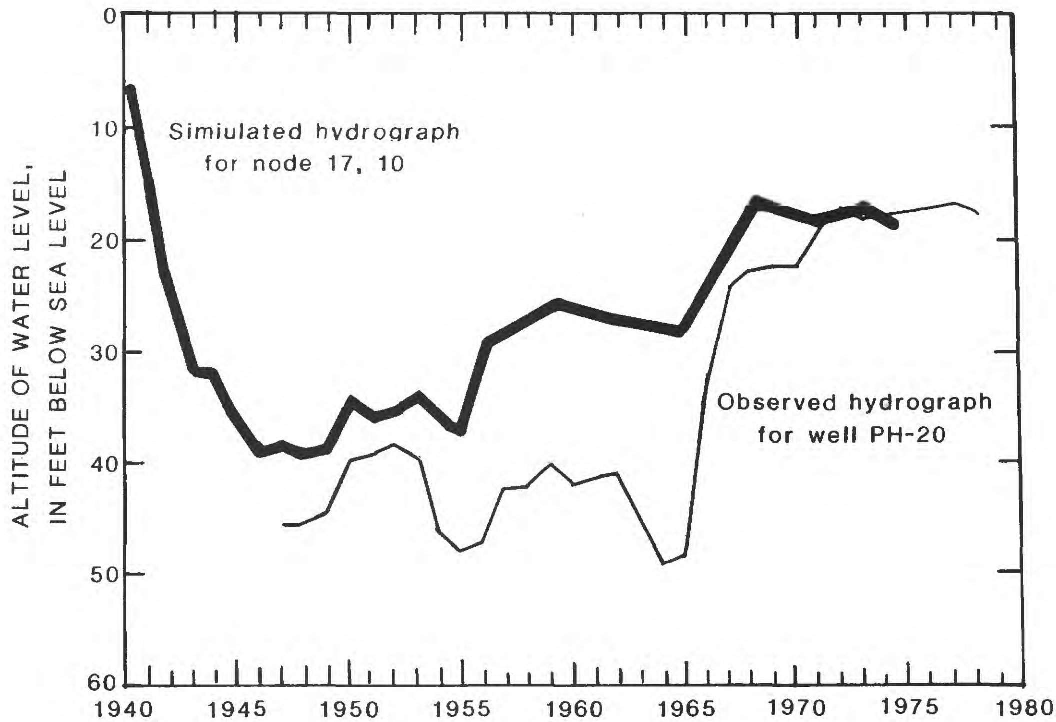


Figure 26.--Comparison of simulated hydrograph at node 17, 10 with observed hydrograph (average annual water level) in well PH-20, 1947-74.

Simulation of Potential Increases in Ground-Water Pumping

The calibrated model is considered acceptable for the simulation of ground-water flow in the lower sand unit in south Philadelphia. It can be used to estimate the effect of various pumping scenarios on water levels in south Philadelphia. Model results are not considered to be accurate at or near the southeastern, southwestern, or most of the northeastern boundaries, because heads in these areas are controlled by the constant heads specified at the boundaries.

Simulations were made to determine the potential effects on water levels of new industrial pumping in Philadelphia and development of an emergency municipal ground-water supply in Philadelphia. The effects of these stresses were simulated by superposition (Reilly and others, 1984). By using superposition, the effect of only the simulated stress on the system can be evaluated. Heads in the lower sand unit and in the aquifer above the upper confining unit were set to zero at the start of the simulation. Simulation results are in terms of drawdown caused by the stress. These drawdowns can be superimposed on the current or some future potentiometric surface of the lower sand unit to determine the effects of the addition of that stress to the system.

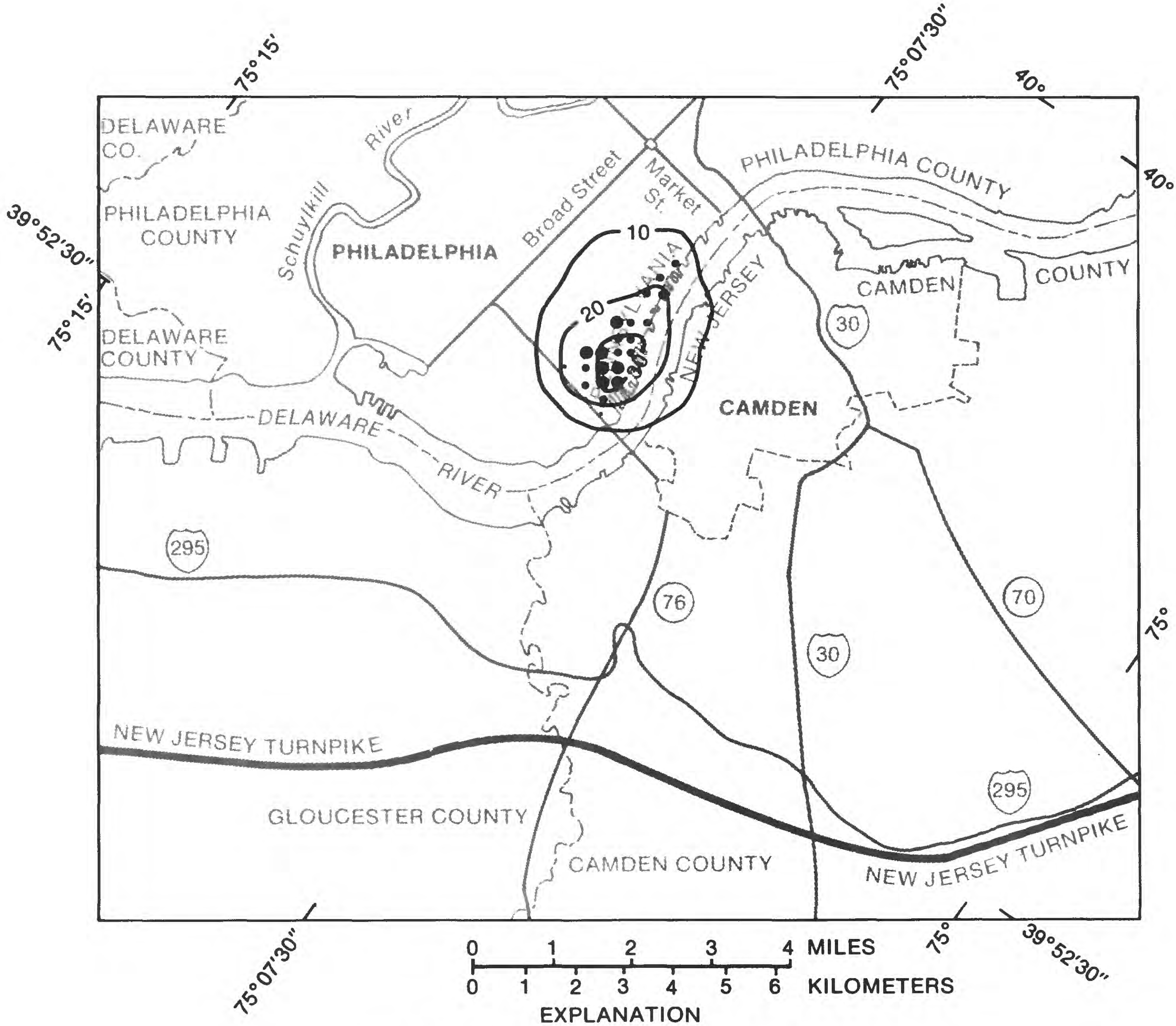
Simulations were made to determine the effects of increases in industrial ground-water pumpage of 5 and 10 Mgal/d in south Philadelphia. Pumping was concentrated along the Delaware River between the U.S. Naval Base and the Benjamin Franklin Bridge-- an industrial area with potential for growth. The pumping was represented as pumpage from 25 nodes; the pumping rate for each node was based on aquifer thickness. At a rate of 5 Mgal/d, pumpage was 0.094 Mgal/d at four nodes, 0.189 Mgal/d at 14 nodes, and 0.283 Mgal/d at seven nodes. At a rate of 10 Mgal/d, rates at nodes doubled.

The simulated drawdown in the potentiometric surface of the lower sand unit caused by 5 Mgal/d of industrial pumpage in Philadelphia is shown on figure 27. Locations and pumping rates of wells are also shown on figure 27. Heads in the lower sand unit in Philadelphia would decline by as much as 33 feet.

The simulated drawdown in the potentiometric surface of the lower sand unit caused by 10 Mgal/d of industrial pumpage in Philadelphia is shown on figure 28. Locations and pumping rates of wells are also shown on figure 28. Heads in the lower sand unit in Philadelphia would decline by as much as 66 feet.

The effects on water levels of developing a 60 Mgal/d emergency municipal ground-water supply in Philadelphia were simulated. Pumping was concentrated in areas owned by the City of Philadelphia near the Delaware and Schuylkill Rivers. Pumping 60 Mgal/d was represented as pumpage from 48 nodes at rates of 0.480 Mgal/d at four nodes, 0.960 Mgal/d at 18 nodes, 1.441 Mgal/d at 19 nodes, and 1.921 Mgal/d at 7 nodes. Pumping rates for each node were based on aquifer thickness.

The simulated drawdown in the potentiometric surface of the lower sand unit caused by pumping 60 Mgal/d for 30 days is shown on figure 29. Locations and pumping rates of wells are also shown on figure 29. Heads in the lower sand unit in Philadelphia would decline by as much as 121 feet.



EXPLANATION

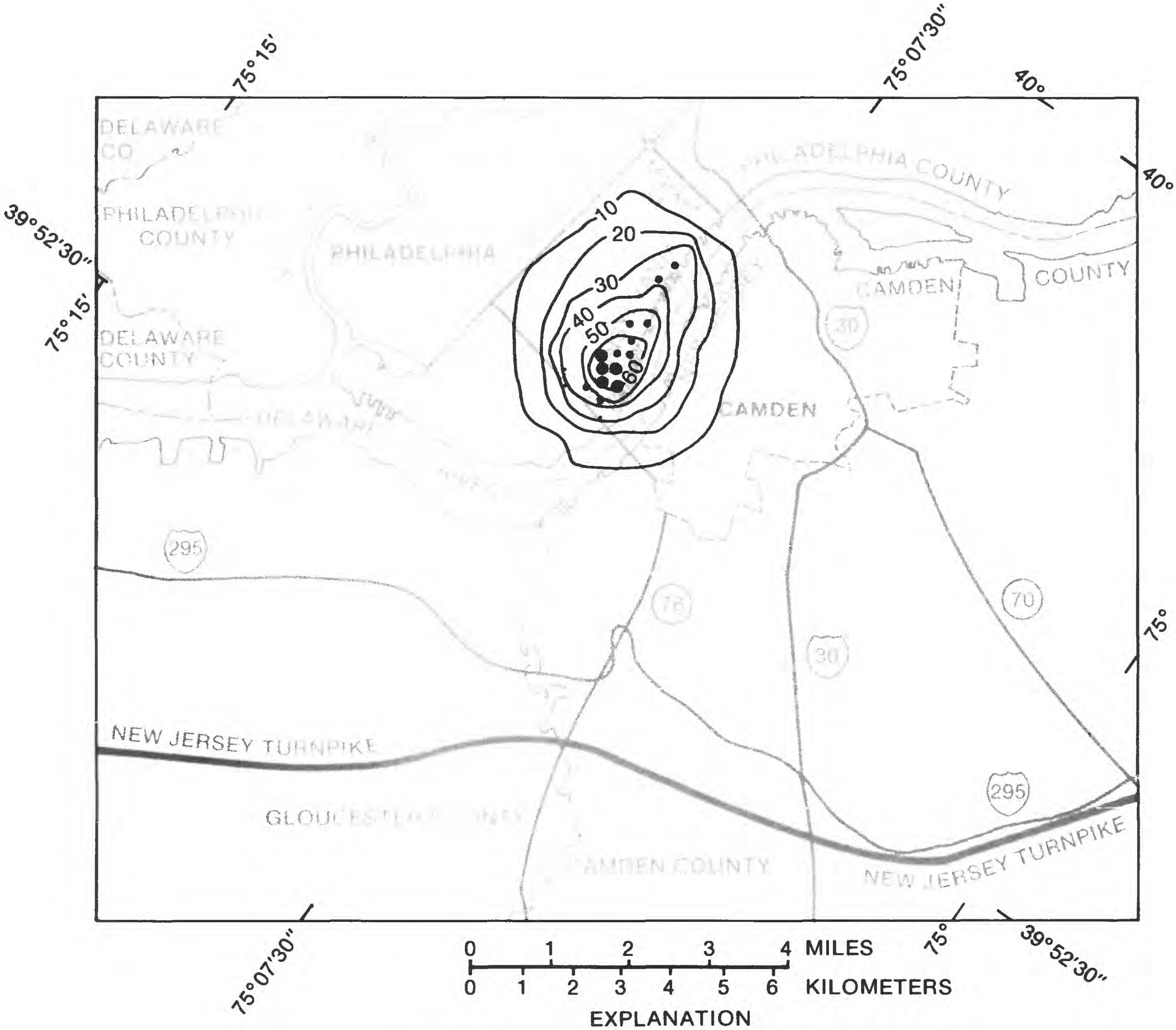
—— 10 —— LINE OF EQUAL DRAWDOWN-- Simulated drawdown in the potentiometric surface. Contour interval 10 feet.

● Well Pumping 0.094 million gallons per day.

• Well Pumping 0.189 million gallons per day.

· Well Pumping 0.283 million gallons per day.

Figure 27.-- Simulated drawdown in the potentiometric surface of the lower sand unit resulting from a 5-million gallon per day increase in industrial pumpage.



EXPLANATION

—— 10 —— LINE OF EQUAL DRAWDOWN-- Simulated drawdown in the potentiometric surface. Contour interval 10 feet.

● Well Pumping 0.189 million gallons per day.

• Well Pumping 0.377 million gallons per day.

· Well Pumping 0.566 million gallons per day.

Figure 28.-- Simulated drawdown in the potentiometric surface of the lower sand unit resulting from a 10-million gallon per day increase in industrial pumpage.

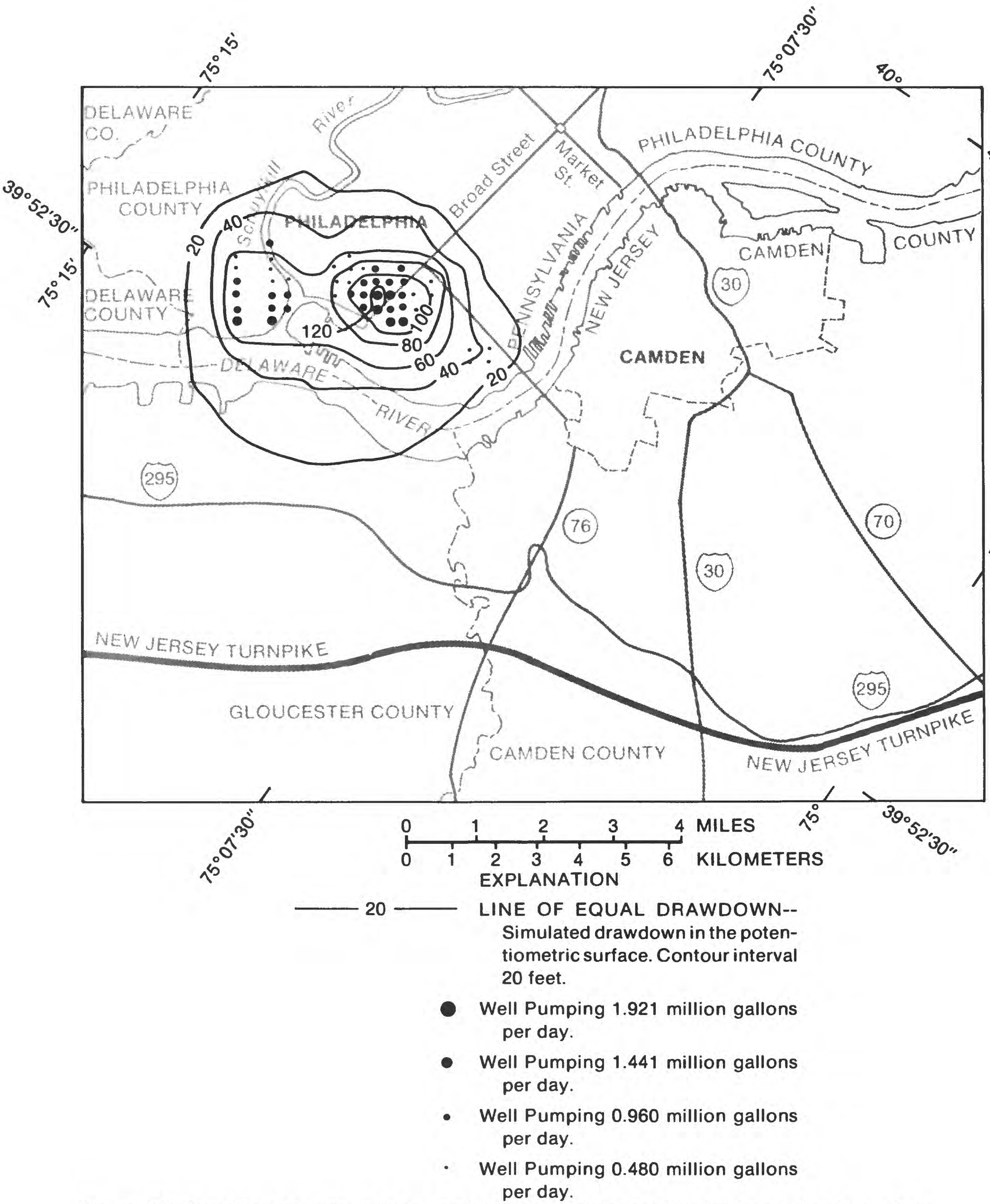


Figure 29.--Simulated drawdown in the potentiometric surface of the lower sand unit resulting from pumping 60 million gallons per day for 30 days in south Philadelphia.

SUMMARY

Ground-water flow in the lower sand unit of the Potomac-Raritan-Magothy aquifer system in Philadelphia was simulated. The 133 mi^2 modeled area includes the City of Philadelphia and parts of Delaware County, Pennsylvania and Camden and Gloucester Counties, New Jersey. The lower sand unit is Cretaceous in age and consists of well-sorted coarse sand and fine gravel that grades upward into fine to medium sand containing a few thin beds of clay. The modeled aquifer consists of the lower sand unit in Philadelphia and the lowermost sand unit of the Potomac-Raritan-Magothy aquifer system in New Jersey. Throughout most of the area, the lower sand unit is overlain by a confining unit consisting of either the lower clay unit, the middle clay unit, or both. Near the Fall Line, the clays are absent and the lower sand unit is unconfined.

A hydraulic conductivity of 1.6×10^{-3} ft/s--the average value from 15 aquifer tests--was assigned to the lower sand unit. The hydraulic conductivity of the upper confining unit--4.0×10^{-8} ft/s--was based on transient-flow sensitivity analysis. Water levels were not sensitive to changes in the value for specific storage of the upper confining unit, indicating that most vertical leakage occurs as steady leakage.

Changes in the potentiometric surface of the lower sand unit were simulated for 1904-78. Most pumpage from Philadelphia was estimated from records of wells and water-use surveys. Early pumpage for New Jersey (1922-55) was mostly estimated. Simulated potentiometric surfaces of the lower sand unit in Philadelphia for 1900, 1945, 1956, and 1978 were compared with historical potentiometric surfaces. Differences between simulated and observed heads for a steady-state simulation of prepumping conditions around 1900 generally were less than 10 feet. Differences between simulated and observed heads for 1945 were from 1 to 5 feet for the U.S. Naval Base, 0 to 20 feet for the south Philadelphia industrial area, and generally less than 10 feet for the rest of the modeled area. Differences between simulated and observed heads for 1956 generally were less than 10 feet. Difference between simulated and observed heads for 1978 generally were less than 5 feet for Philadelphia and generally less than 10 feet for New Jersey.

Simulations were made to determine the effects on water levels of increases in industrial pumpage of 5 and 10 Mgal/d and of an emergency 60 Mgal/d municipal supply in Philadelphia. A 5-Mgal/d increase in industrial pumpage would lower heads in the lower sand unit by as much as 33 feet. A 10-Mgal/d increase in industrial pumpage would lower heads in the lower sand unit by as much as 66 feet. Pumping of an emergency supply of 60 Mgal/d for 30 days would lower heads as much as 121 feet in the lower sand unit.

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