U.S. Department of the Interior
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Simulation of Ground-Water Flow in the Potomac-Raritan-Magothy Aquifer System Near the Defense Supply Center Philadelphia, and the Point Breeze Refinery, Southern Philadelphia County, Pennsylvania

Water-Resources Investigations Report 01-4218

Prepared for the
U.S. ENVIRONMENTAL PROTECTION AGENCY

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by Curtis L. Schreffler

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New Cumberland, Pennsylvania
2001

U.S. DEPARTMENT OF THE INTERIOR
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CONTENTS

Page

ILLUSTRATIONS

ILLUSTRATIONS—Continued

ILLUSTRATIONS—Continued

Page

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	by	To obtain
	Length	
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Volume	
gallon (gal)	3.785	liter
gallon (gal)	0.003785	cubic meters
million gallons (Mgal)	3,785	cubic meters
	Flow	
million gallons per day (Mgal/d)	3,785	cubic meter per day
billion gallons per year (Bgal/yr)	10,370	cubic meters per day
inch per year (in/yr)	0.0000696	meters per day
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meters per day

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

SIMULATION OF GROUND-WATER FLOW IN THE POTOMAC-RARITAN-MAGOTHY AQUIFER SYSTEM NEAR THE DEFENSE SUPPLY CENTER PHILADELPHIA, AND THE POINT BREEZE REFINERY, SOUTHERN PHILADELPHIA COUNTY, PENNSYLVANIA

by Curtis L. Schreffler

ABSTRACT

Ground-water flow in the Potomac-Raritan-Magothy aquifer system (PRM) in south Philadelphia and adjacent southwestern New Jersey was simulated by use of a three-dimensional, seven-layer finite-difference numerical flow model. The simulation was run from 1900, which was prior to ground-water development, through 1995 with 21 stress periods. The focus of the modeling was on a smaller area of concern in south Philadelphia in the vicinity of the Defense Supply Center Philadelphia (DSCP) and the Point Breeze Refinery (PBR). In order to adequately simulate the ground-water flow system in the area of concern, a much larger area was modeled that included parts of New Jersey where significant ground-water withdrawals, which affect water levels in southern Philadelphia, had occurred in the past. At issue in the area of concern is a hydrocarbon plume of unknown origin and time of release.

The ground-water-flow system was simulated to estimate past water-level altitudes in and near the area of concern and to determine the effect of the Packer Avenue sewer, which lies south of the DSCP, on the ground-water-flow system. Simulated water-level altitudes for the lower sand unit of the PRM on the DSCP prior to 1945 ranged from pre-development, unstressed altitudes to 3 feet below sea level. Simulated water-level altitudes for the lower sand unit ranged from 3 to 7 feet below sea level from 1946 to 1954, from 6 to 10 feet below sea level from 1955 to 1968, and from 9 to 11 feet below sea level from 1969 to 1978. The lowest simulated water-level altitude on the DSCP was 10.69 feet below sea level near the end of 1974. Model simulations indicate ground water was infiltrating the Packer Avenue sewer prior to approximately 1947 or 1948. Subsequent to that time, simulated ground-water-level altitudes were lower than the bottom of the sewer.

INTRODUCTION

The Potomac-Raritan-Magothy (PRM) aquifer system in south Philadelphia historically has been a major water-supply source in the south Philadelphia region. Because of the abundant ground-water resource and subsequent ground-water withdrawals, the flow system in the PRM has changed through history. The south Philadelphia area historically has been a highly industrialized area, especially operations at the Philadelphia Naval Shipyard (PNSY). Industries and the PNSY withdrew large amounts of water from the PRM for day-to-day operations. Increasing development across the Delaware River in New Jersey has influenced ground-water levels in Pennsylvania in the past and currently (2001).

Because of the development in the area, the quality of water in the PRM has been degraded. Some degradation in the upper part of the aquifer is the result of numerous hydrocarbon plumes. Some of the accidental organic releases have been non-aqueous phase hydrocarbons (NAPL). Since the early 1990's, the Pennsylvania Department of Environmental Protection (PaDEP) has been overseeing investigations of multiple localized NAPL hydrocarbon plumes floating on the water-table surface in the south Philadelphia area (fig. 1). The PaDEP's oversight is for NAPL investigations focused on specific plumes. Although localized NAPL is a major concern, a more regional look at the entire area was needed to assess areal problems.

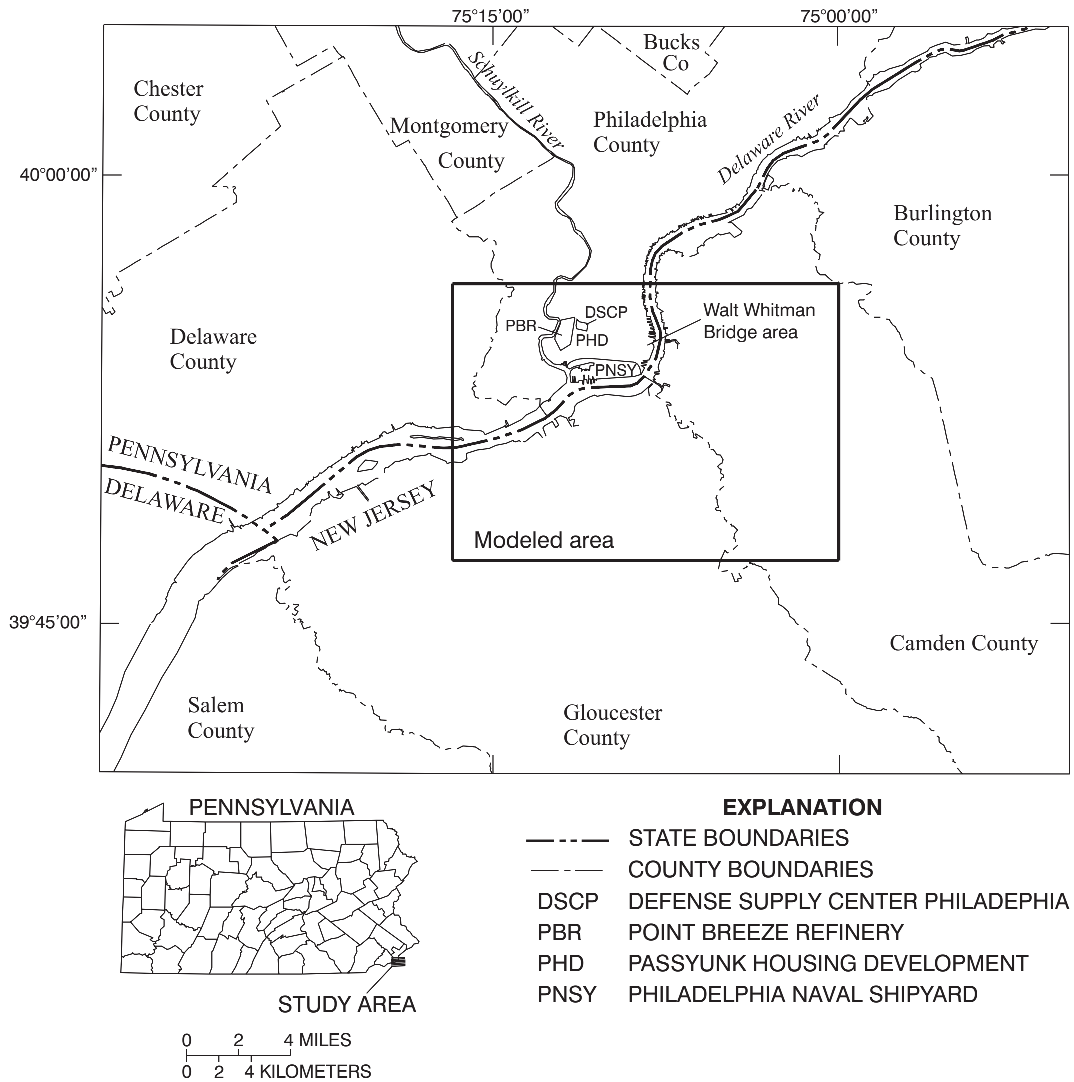


Figure 1. Location of study area.

An area of concern for the PaDEP is east of the Point Breeze Refinery (PBR) on the Defense Logistics Agency's Defense Supply Center, Philadelphia (DSCP), and the Philadelphia Housing Authority Passyunk Housing Development (PHD). During construction activities in 1989, a NAPL plume was discovered under the DSCP property. The PaDEP was notified by the DSCP of the plume, and PaDEP oversight began.

The source or sources of the NAPL in the area of concern and the migration pathways are unknown. The timing of the release(s) are unknown, and the migration of the NAPL depends on when the release or releases occurred. It is possible that the release(s) date from the late 1940's to 1980 (Pennsylvania Department of Environmental Protection, written commun., Dec. 9, 1998). Historically, the large ground-water pumping centers in the area, specifically at the PNSY to the south and at Publicker Industries, which was near the Walt Whitman Bridge to the east, and the associated affects on ground-water levels controlled the direction and gradient or rate of ground-water flow in the area. Another factor controlling hydrocarbon plume migration is the Packer Avenue sewer, which lies south of the DSCP.

Through the course of environmental investigations of the NAPL plume, a residual staining of aquifer material was identified beneath the water table in 1997. This indicates hydrocarbons existed below the present-day water table in this area. A NAPL floating on top of the water table would leave residual hydrocarbons in the soil matrix. Residual hydrocarbons in the soil were detected at an altitude of 4.08 to 14.88 ft below sea level on property between the DSCP and PBR, and on the DSCP. Therefore, evaluating historical water-level altitudes and determining at what time in the past water-level altitudes reached 4 to 14 ft below sea level would be beneficial in evaluating the timing of NAPL release(s).

The modeling effort described in this report is a continuation of investigations being done by U.S. Geological Survey (USGS), which started in 1997 at the request of the U.S. Environmental Protection Agency (USEPA). Most historical ground-water-level data in the vicinity was from the 1940's through the mid 1950's. Very little data are available for other time periods. The author of this report compiled all available historical ground-water-level data and summarized water-level altitudes for the following time intervals: prior to 1945, 1946 through 1954, 1955 through 1968, and 1969 through 1978. Those data and the results of the author's analyses of the data are freely used in this report. These time periods were chosen because potentiometric-surface maps of the lower sand unit in south Philadelphia have been published for 1945, 1954, 1968, and 1978. Potentiometric-surface maps for 1945 and 1954 were published by Greenman and others (1961). Gill and Farlekas (1976) published a potentiometric-surface map of the lower sand unit for 1968. Sloto (1988) published a potentiometric-surface map of the lower sand unit for 1978 from Walker (1983) and Paulachok (U.S. Geological Survey, written commun., 1982).

The results of simulations made with a calibrated ground-water-flow model would assist in evaluating past ground-water-level altitudes. The evaluation of ground-water-level altitudes would yield ground-water flow directions and the direction of ground-water flow is a controlling factor in migration of the hydrocarbon plume.

PURPOSE AND SCOPE

This report presents an abbreviated description of the hydrogeology and ground-water-flow system of the Potomac-Raritan-Magothy aquifer system in south Philadelphia. The report describes the construction of a model used to simulate ground-water flow in the PRM. The report presents an analysis of water-level altitudes in the area of concern at the DSCP and PBR sites from 1900 to 1995 and an evaluation of the effects of the Packer Avenue sewer, which lies just south of the DSCP, on the ground-water-flow system and subsequent plume migration.

LOCATION AND EXTENT OF STUDY AREA

The extent of the regional assessment of the PRM in southern Philadelphia County also includes areas in eastern Delaware County, Pa., and parts of northern Gloucester and western Camden Counties in New Jersey. The areas in New Jersey are included because of large ground-water withdrawals from the PRM historically and currently (2001).

PREVIOUS INVESTIGATIONS

Many water-resource investigations have been done in the south Philadelphia area. Bascom (1904) was the first to describe the water resources of the Philadelphia area. Hall (1934) described ground-water resources of southeastern Pennsylvania. Graham and Kammerer (1952) investigated the ground-water resources of the U.S. Naval Base in south Philadelphia. Barksdale and others (1958) summarized the ground-water resources in the tri-state region of the lower Delaware River that consisted of Pennsylvania, New Jersey, and Delaware. Greenman and others (1961) published a comprehensive assessment of geology and ground-water resources of the Coastal Plain area of southeastern Pennsylvania. Paulachok and Wood (1984) published a water-table map of Philadelphia County, and Paulachok and others (1984) published hydrologic data for Philadelphia County. Sloto (1988) simulated ground-water flow in the lower sand unit of the PRM in south Philadelphia. Paulachok (1991) published a comprehensive assessment of the ground-water resources of Philadelphia County. Many water-resource investigations have been done in the Gloucester and Camden County areas of New Jersey. A summary of water-resource investigation reports by the USGS New Jersey District are listed in table 1.

Table 1. *Summary of reports by the U.S. Geological Survey, New Jersey District, that includes area of Gloucester and Camden Counties, New Jersey*

Report title	Authors and year of publication	Period of investigation	Areas of investigation	Principle topic of investigation
Water levels in major artesian aquifers of the New Jersey Coastal Plain, 1983	Eckel and Walker, 1986	1983	Camden and Gloucester Counties, N.J., and some parts of southern Philadelphia County, Pa.	Ground-water levels
Water quality of the Potomac-Raritan-Magothy aquifer system in the Coastal Plain, west-central New Jersey, 1923-83	Ervin, Voronin, and Fusillo, 1994	1923-83	Camden and Gloucester Counties, N.J.	Ground-water quality
Geology and ground-water resources of Camden County, New Jersey	Farlekas, Nemickas, and Gill, 1976	1900-68	Camden County, N.J. and some parts of southern Philadelphia County, Pa.	Hydrology, geology and water-quality; includes ground-water levels.
Water-quality data for the Potomac-Raritan-Magothy aquifer system in southwestern New Jersey, 1980	Fusillo, Hochreiter, and Lord, 1984	1980	Camden and Gloucester Counties, N.J., and some parts of southern Philadelphia County, Pa.	Ground-water quality
Geohydrologic maps of the Potomac-Raritan-Magothy aquifer system in the New Jersey Coastal Plain	Gill and Farlekas, 1976	1900-68	Camden and Gloucester Counties, N.J., and some parts of southern Philadelphia County, Pa.	Ground-water levels and geohydrology
Digital-simulation and projection of head changes in the Potomac-Raritan-Magothy aquifer system, Coastal Plain, New Jersey	Luzier, 1980	1956-73	New Jersey Coastal Plain	Ground-water flow
Ground-water flow in the New Jersey Coastal Plain	Martin, 1998	1895-1981	New Jersey Coastal Plain	Ground-water flow
Ground-water flow and future conditions in the Potomac-Raritan-Magothy aquifer system, Camden area, New Jersey	Navoy and Carleton, 1995	1987	Camden and Gloucester Counties, N.J., and some parts of southern Philadelphia County, Pa.	Computer simulations of ground-water flow and water levels
Simulation of ground-water flow and movement of the freshwater -saltwater interface in the New Jersey Coastal Plain	Pope and Gordon, 1999	1896-1998	New Jersey Coastal Plain	Ground-water flow
Potentiometric surfaces of the Potomac-Raritan-Magothy aquifer system near National Park, New Jersey	Rosman, 1997	1996	New Jersey Coastal Plain	Ground-water levels
Water levels in major artesian aquifers of the New Jersey Coastal Plain, 1988	Rosman, Lacombe, and Storck, 1995	1988	New Jersey Coastal Plain and some parts of southern Philadelphia County, Pa.	Ground-water levels
Evaluation of water levels in major aquifers of the New Jersey Coastal Plain, 1978	Walker, 1983	1978	New Jersey Coastal Plain and some parts of southern Philadelphia County, Pa.	Ground-water levels

HYDROGEOLOGIC SETTING

Geology

The study area in Pennsylvania from the Fall Line to the Delaware River is underlain by Coastal Plain sediments that range in age from Late Cretaceous to Holocene. The unconsolidated Cretaceous sediments are referred to on a regional basis as the Potomac-Raritan-Magothy (PRM) aquifer system. These sediments consist of highly permeable sands and gravels separated by less-permeable layers of silts and clays. The PRM aquifer system in Pennsylvania can be subdivided into units: upper clay, upper sand, middle clay, middle sand, lower clay, and lower sand (Sloto, 1988, p. 8) (fig. 2). The PRM is overlain by Quaternary deposits referred to informally as the Trenton gravel by Owens and Minard (1979). These deposits are overlain by Holocene alluvium and fill. Large areas of south Philadelphia historically have undergone extensive filling activities. The thickness of the fill varies across the region and is not well defined. For purposes of this report, the Trenton gravel, alluvium, and fill material have been combined and referred to as alluvium. The unconsolidated deposits of the PRM aquifer system lie on pre-Cretaceous mica and hornblende schists and gneisses comprised primarily of the Wissahickon Formation. All beds dip to the southeast from the Fall Line. In areas near the Fall Line, many upper units pinch out, and the lower sand unit may be directly overlain by alluvium; confining units may not be present or are very thin. The unconsolidated deposits thicken toward the southeast. Greenman and others (1961) extensively characterize the Coastal Plain deposits in Pennsylvania.

From the Delaware River southeastward in New Jersey, the Coastal Plain consists of the PRM and other unconsolidated deposits that do not exist in Pennsylvania. For purposes of this report and the model, the unconsolidated deposits that do not exist in Pennsylvania have been grouped with the alluvial deposit layer in the model. Navoy and Carleton (1995, p. 7) characterize the Coastal Plain sediments in the Camden area.

SYSTEM	SERIES	HYDROGEOLOGIC UNIT		MODEL LAYER
Quaternary	Holocene	Alluvium		Layer 1
	Pleistocene	Trenton gravel (informal usage)		
Cretaceous	Upper Cretaceous	Potomac-Raritan-Magothy aquifer system	Upper clay unit	Layer 2
			Upper sand unit	Layer 3
			Middle clay unit	Layer 4
			Middle sand unit	Layer 5
			Lower clay unit	Layer 6
	Lower Cretaceous		Lower sand unit	Layer 7
Pre-Cretaceous		Wissahickon Formation		

Figure 2. Generalized stratigraphic section of the Coastal Plain in the Philadelphia, Pa., region and correspondence of hydrogeologic units to layers in model developed for this study.

Aquifer and Confining Unit Thicknesses and Altitudes

A spatially related stratigraphic contouring software package was used to determine aquifer and confining-unit thicknesses. Geologic logs from borings were compiled from USGS references, drillers' well logs, and environmental consultant reports and entered into the stratigraphic software package. Unit thickness or isopach maps were generated and used as input for the model. A total of 93 geologic well logs in Pennsylvania and 39 geologic well logs in New Jersey were used to construct the unit isopach maps.

Altitudes of the top and bottom of units for the model were generated from isopach maps using MODFLOW-2000 pre-processing software Argus ONE (Argus Interware, Inc., 1997). The top of the model or land surface was derived from USGS Digital Elevation Models (DEM) of the study area.

Subsequently subtracting unit thicknesses from the unit isopach maps starting at the land surface yielded estimated structure contours of the top and bottom of the modeled units.

The alluvial unit (model layer 1) extends from the land surface to the top of the upper confining clay. The alluvial unit consists of many sand and clay lenses and, for purposes of this report, is combined with the fill material and the Trenton gravel to form one unit. The thickness of this combined alluvial unit in Pennsylvania ranges from 0 to 60 ft with local lenses up to 80 ft thick (fig. 3). The unit thickens toward the southeast in New Jersey, which does not depict a true representation of the system because the unit is further combined with unconsolidated deposits of the New Jersey Coastal Plain that do not exist in Pennsylvania. The altitude of the bottom of the alluvial unit is shown on figure 4.

The thickness of the upper confining clay (model layer 2) in Pennsylvania ranges from 0 to 10 ft with local lenses up to 20 ft thick (fig. 5). This unit is discontinuous in Pennsylvania. The unit thickens to the southeast in New Jersey.

The thickness of the upper sand unit (model layer 3) in Pennsylvania ranges from 0 to 30 ft with localized lenses up to 40 ft thick in Pennsylvania (fig. 6). This unit also is discontinuous in Pennsylvania and pinches out to the northwest near the Fall Line. In New Jersey, the unit ranges from 20 to 100 ft thick with a local lens up to 120 ft thick. The altitude of the top of the upper sand unit (model layer 3) is shown in figure 7.

The thickness of the middle confining clay unit (model layer 4) in Pennsylvania ranges from 0 to 20 ft with local lenses up to 40 ft thick (fig. 8). This unit is the least extensive of the Coastal Plain units in Pennsylvania and pinches out to the northwest near the Fall Line. In New Jersey, the unit ranges from 20 to 40 ft thick.

The thickness of the middle sand unit (model layer 5) in Pennsylvania ranges from 0 to 10 ft with a local lens up to 20 ft thick (fig. 9). Of the PRM aquifers in Pennsylvania, this unit is the least extensive and pinches out or is nonexistent as it grades to the northwest near the Fall Line. In New Jersey, the unit ranges from 20 to 160 ft thick. The altitude of the top of the middle sand unit is shown in figure 10.

The thickness of the lower confining clay (model layer 6) ranges from 0 to 20 ft with local lenses up to 60 ft thick (fig. 11). This unit pinches out towards the Fall Line. In New Jersey, the unit ranges from 20 to 180 ft thick.

The thickness of the lower sand unit (model layer 7) ranges from 0 ft at the Fall Line to 40 ft with local lenses up to 60 ft thick in Pennsylvania (fig. 12). This unit is the most continuous of the Coastal Plain units in Pennsylvania, and in areas near the Fall Line it may be unconfined. In New Jersey, the unit ranges from 40 to 260 ft thick. The altitude of the top of the lower sand unit is shown in figure 13. The altitude of the bottom of the lower sand unit, which is equivalent to the altitude of the top of the bedrock surface, is shown in figure 14. The north to south and west to east trending cross sections that depict the lithologic structure used in the model are shown in figure 15.

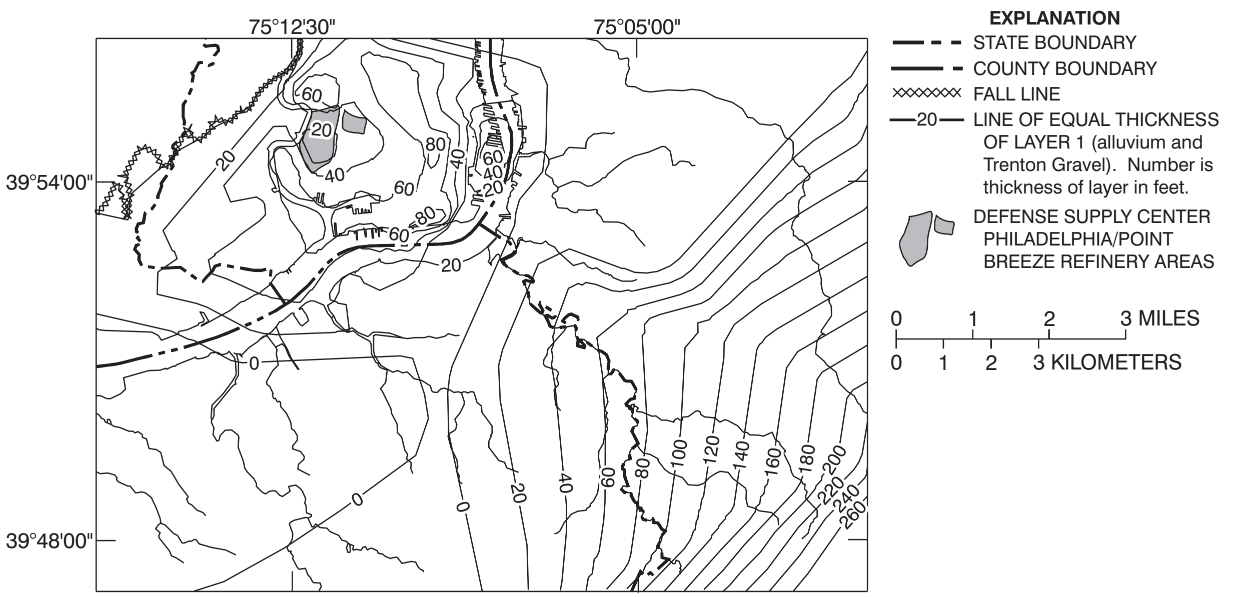


Figure 3. Thickness of the alluvium and Trenton gravel (model layer 1) in the south Philadelphia area and adjacent New Jersey.

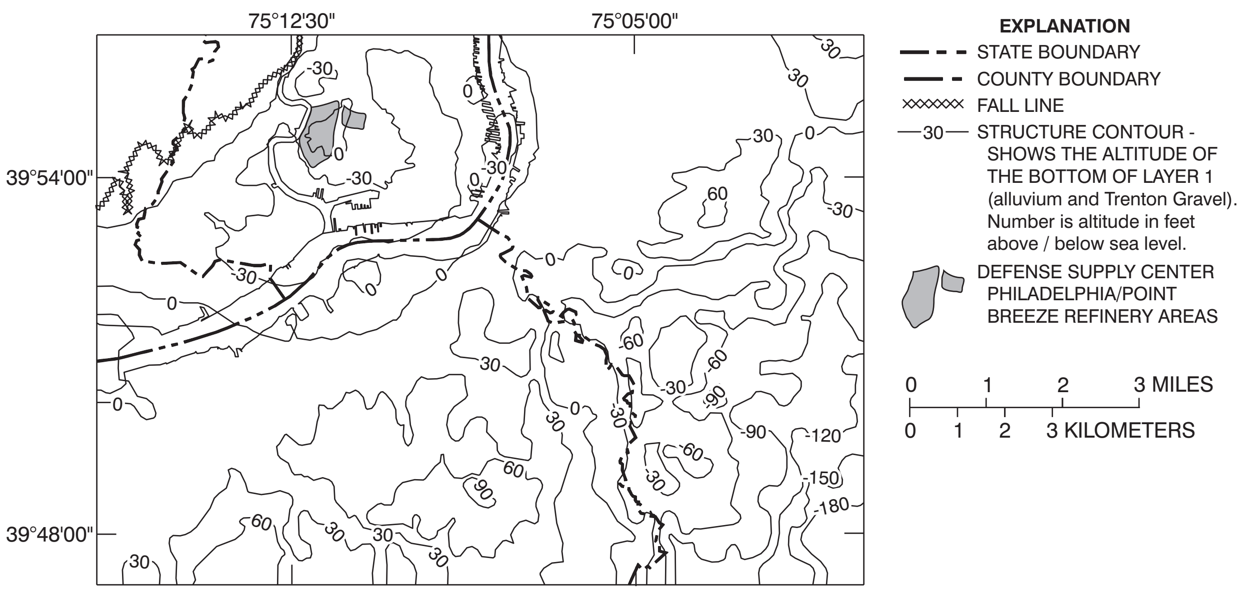


Figure 4. Altitude of the bottom of the alluvium and Trenton gravel (model layer 1) in the south Philadelphia, Pa., area and parts of Gloucester and Camden Counties, N.J.

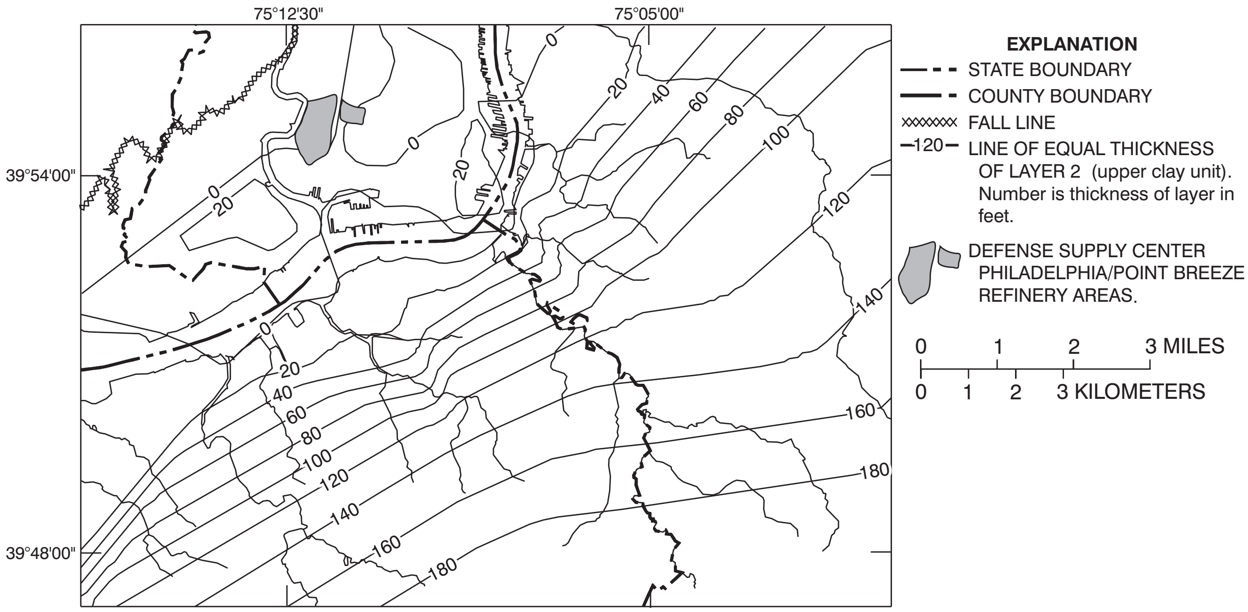


Figure 5. Thickness of the upper clay unit (model layer 2) of the Potomac-Raritan-Magothy aquifer system in the south Philadelphia area.

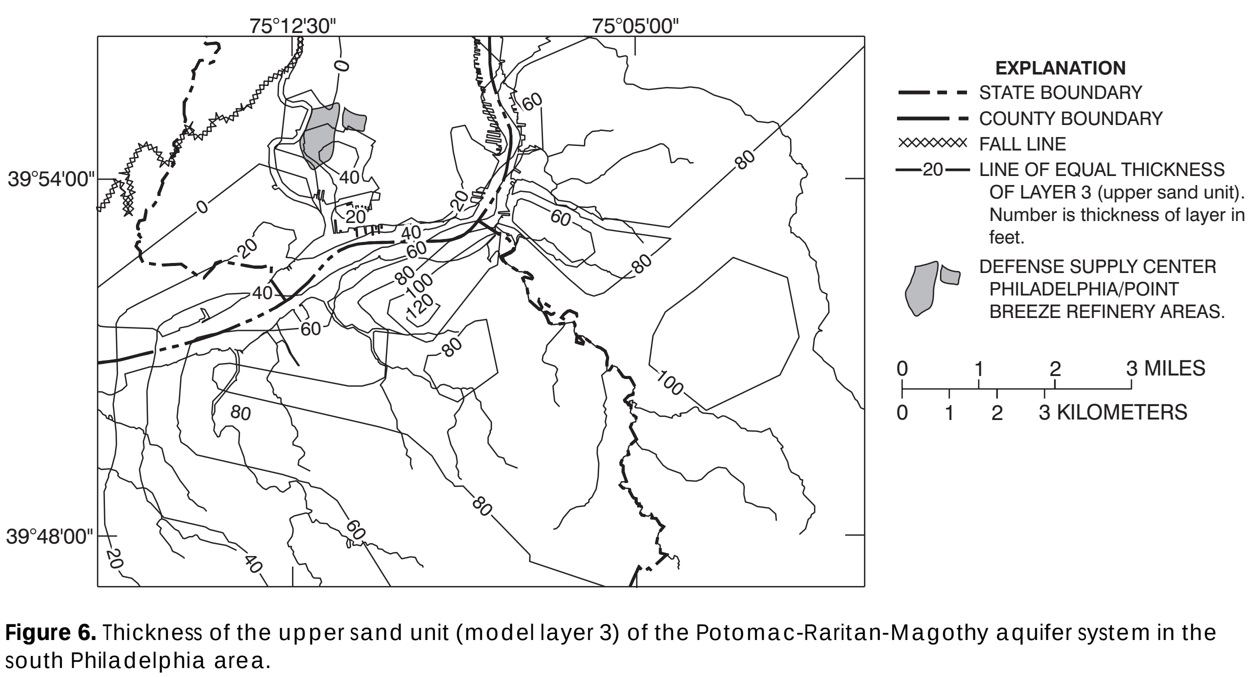


Figure 6. Thickness of the upper sand unit (model layer 3) of the Potomac-Raritan-Magothy aquifer system in the south Philadelphia area.

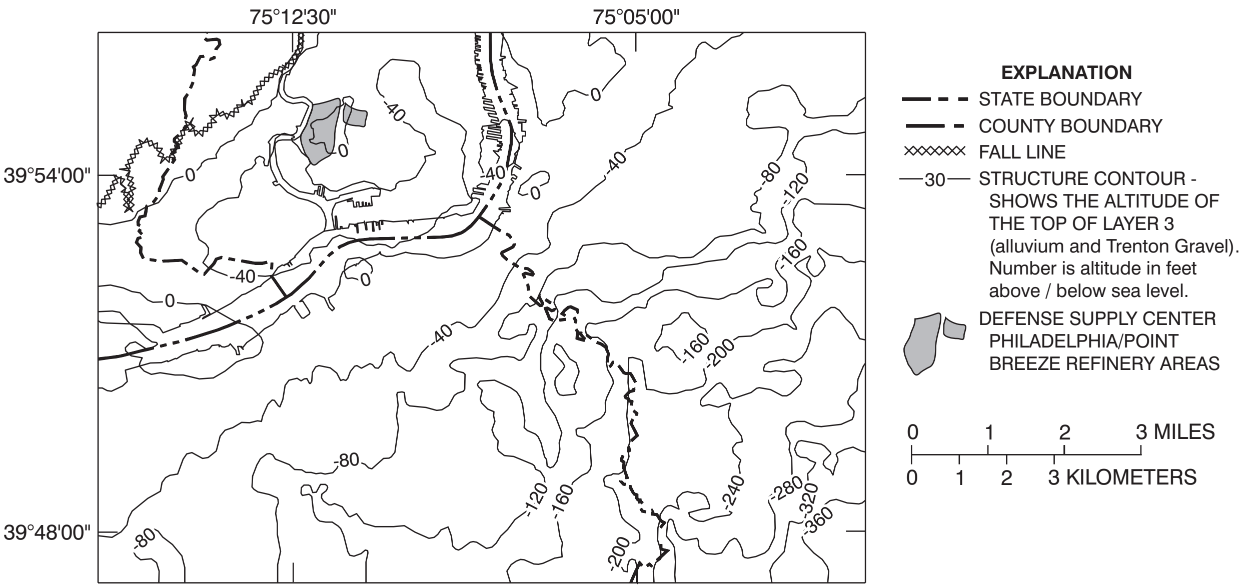


Figure 7. Altitude of the top of the upper sand unit (model layer 3) of the Potomac-Raritan-Magothy aquifer system in the south Philadelphia area.

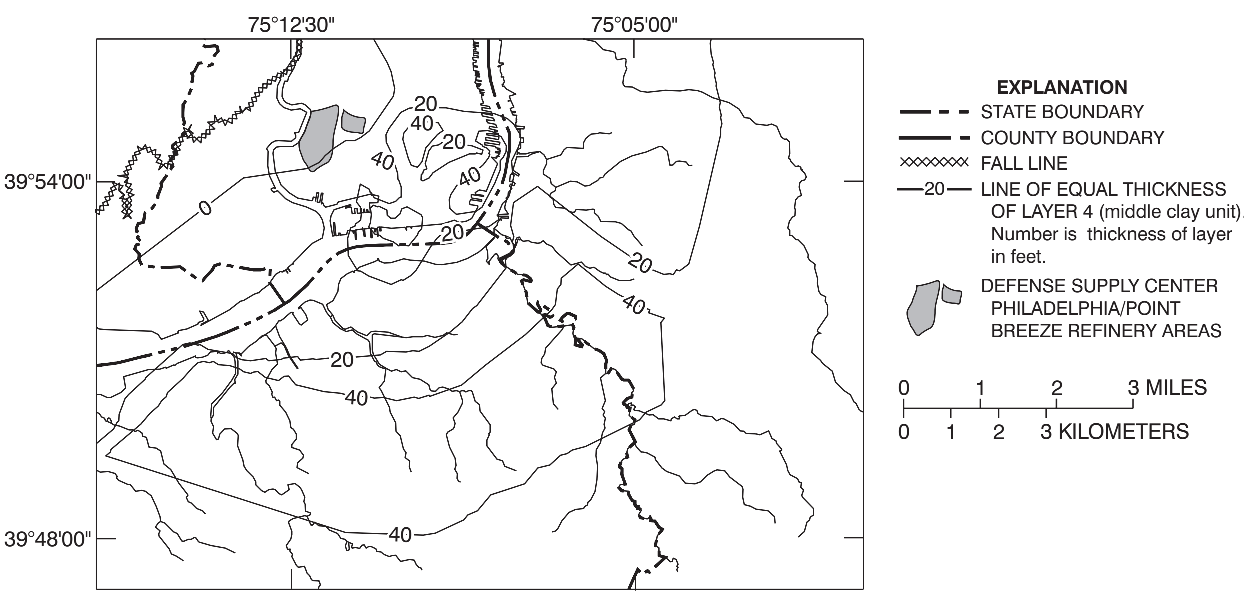


Figure 8. Thickness of the middle clay unit (model layer 4) of the Potomac-Raritan-Magothy aquifer system in the south Philadelphia area.

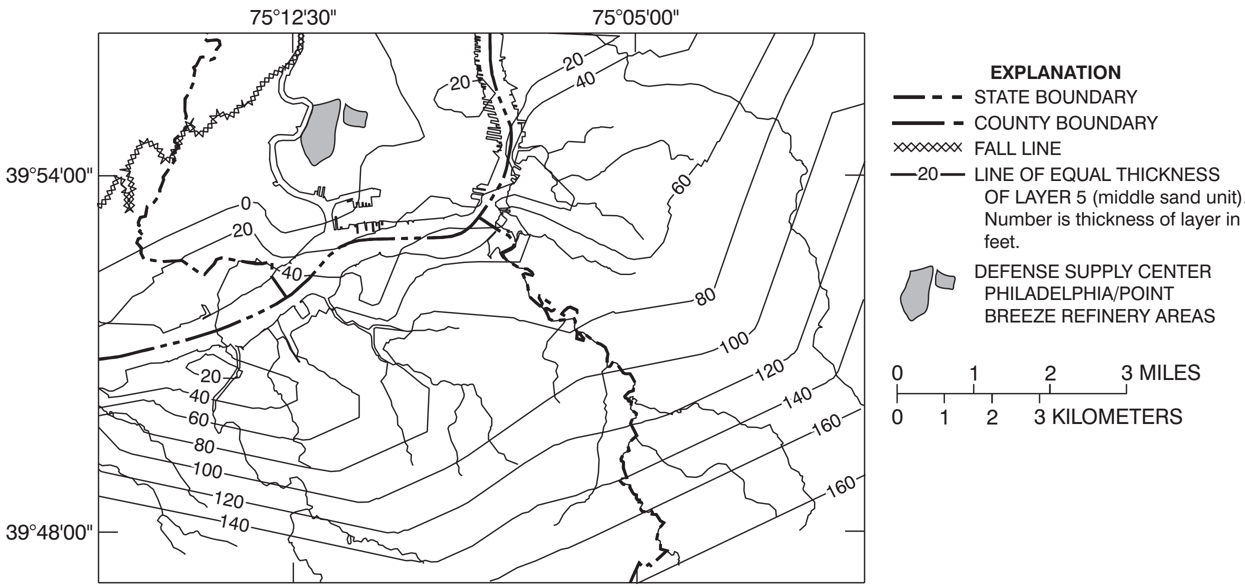


Figure 9. Thickness of the middle sand unit (model layer 5) of the Potomac-Raritan-Magothy aquifer system in the south Philadelphia area.

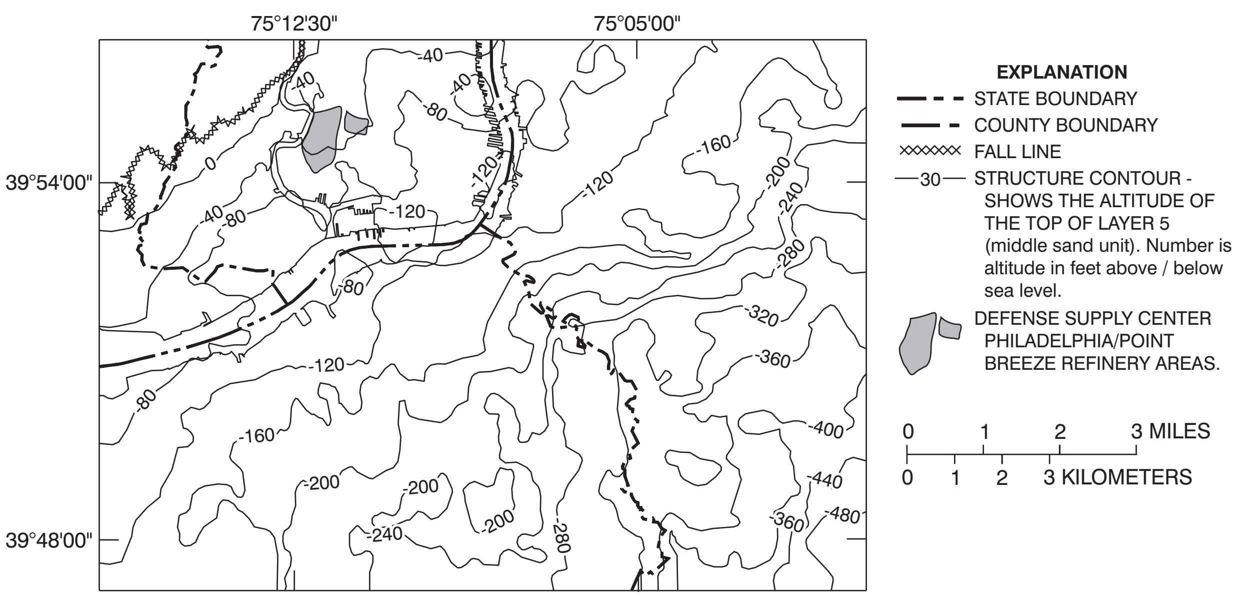


Figure 10. Altitude of the top of the middle sand unit (model layer 5) of the Potomac-Raritan-Magothy aquifer system in the south Philadelphia area.

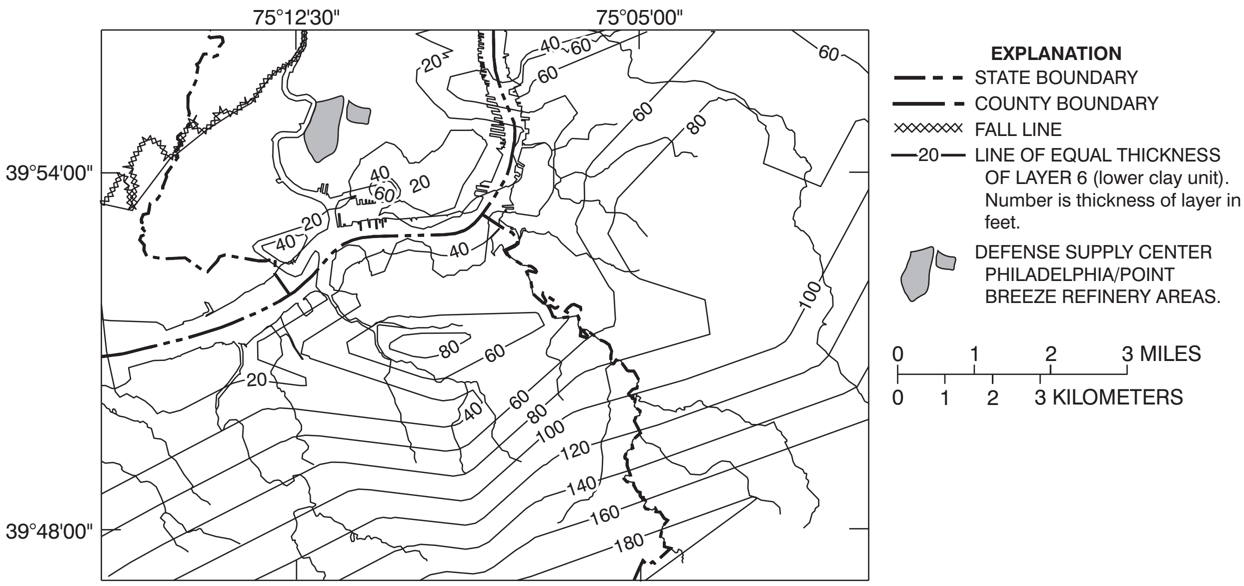


Figure 11. Thickness of the lower clay unit (model layer 6) of the Potomac-Raritan-Magothy aquifer system in the south Philadelphia area.

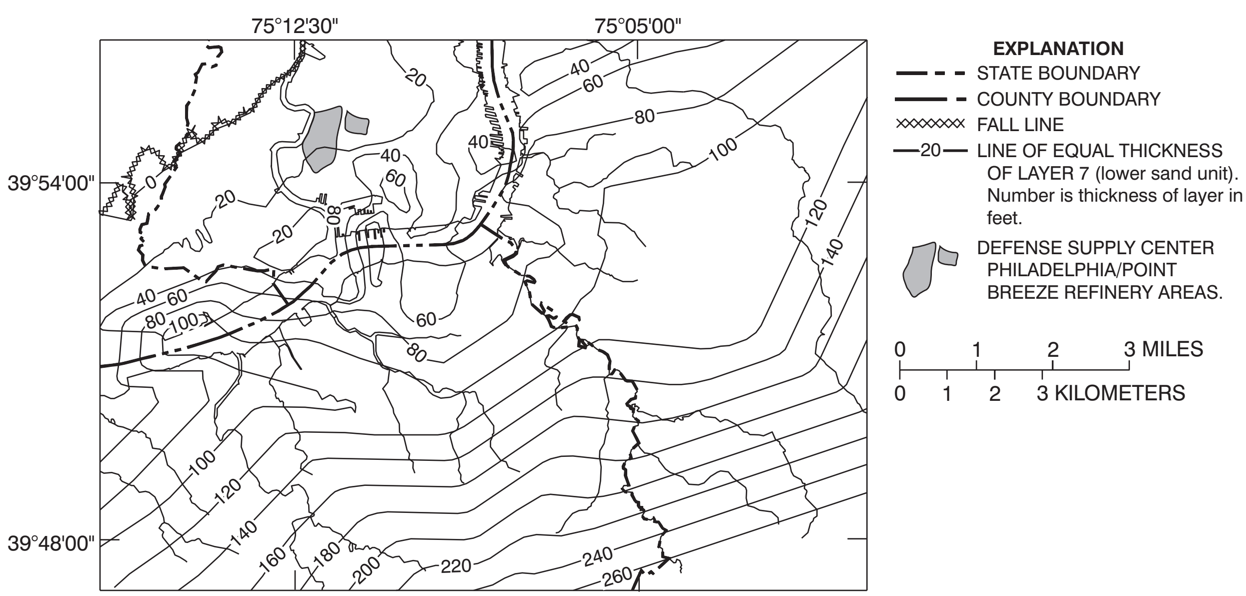


Figure 12. Thickness of the lower sand unit (model layer 7) of the Potomac-Raritan-Magothy aquifer system in the south Philadelphia area.

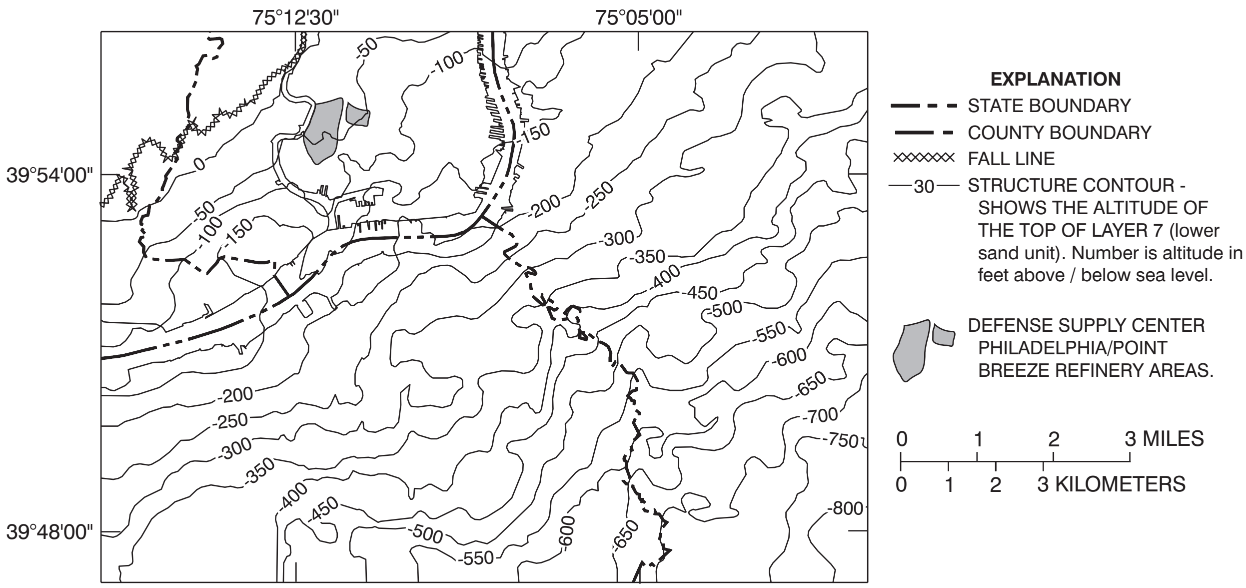


Figure 13. Altitude of the top of the lower sand unit (model layer 7) of the Potomac-Raritan-Magothy aquifer system in the south Philadelphia area.

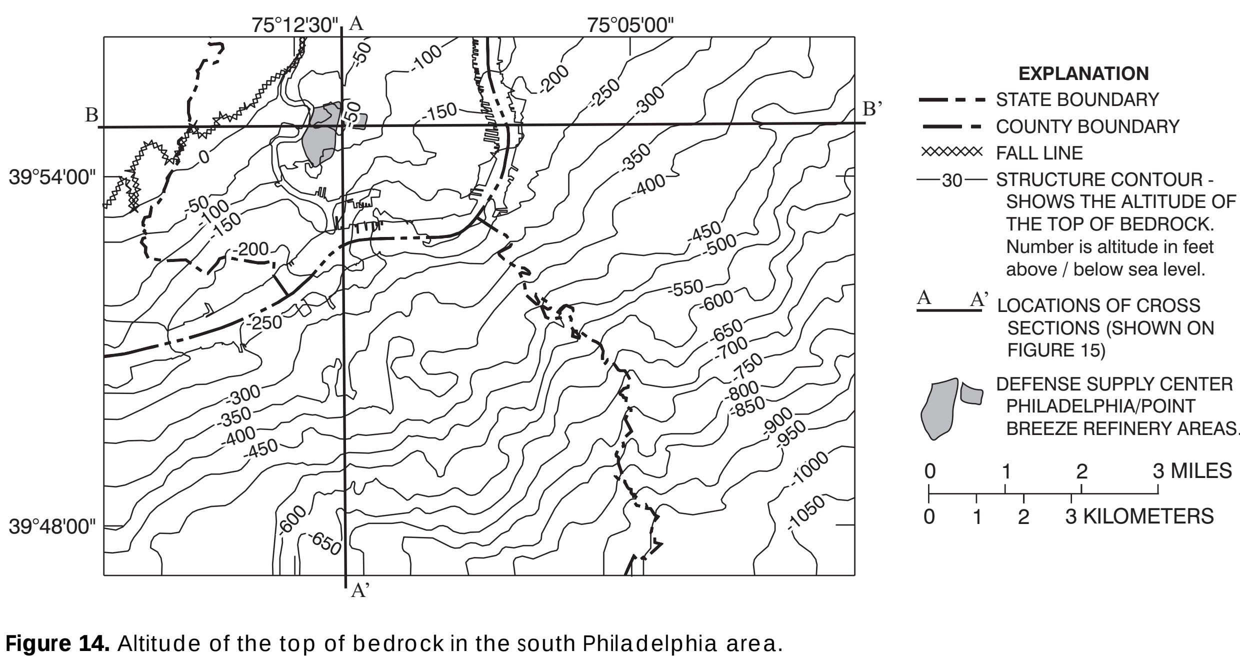


Figure 14. Altitude of the top of bedrock in the south Philadelphia area.

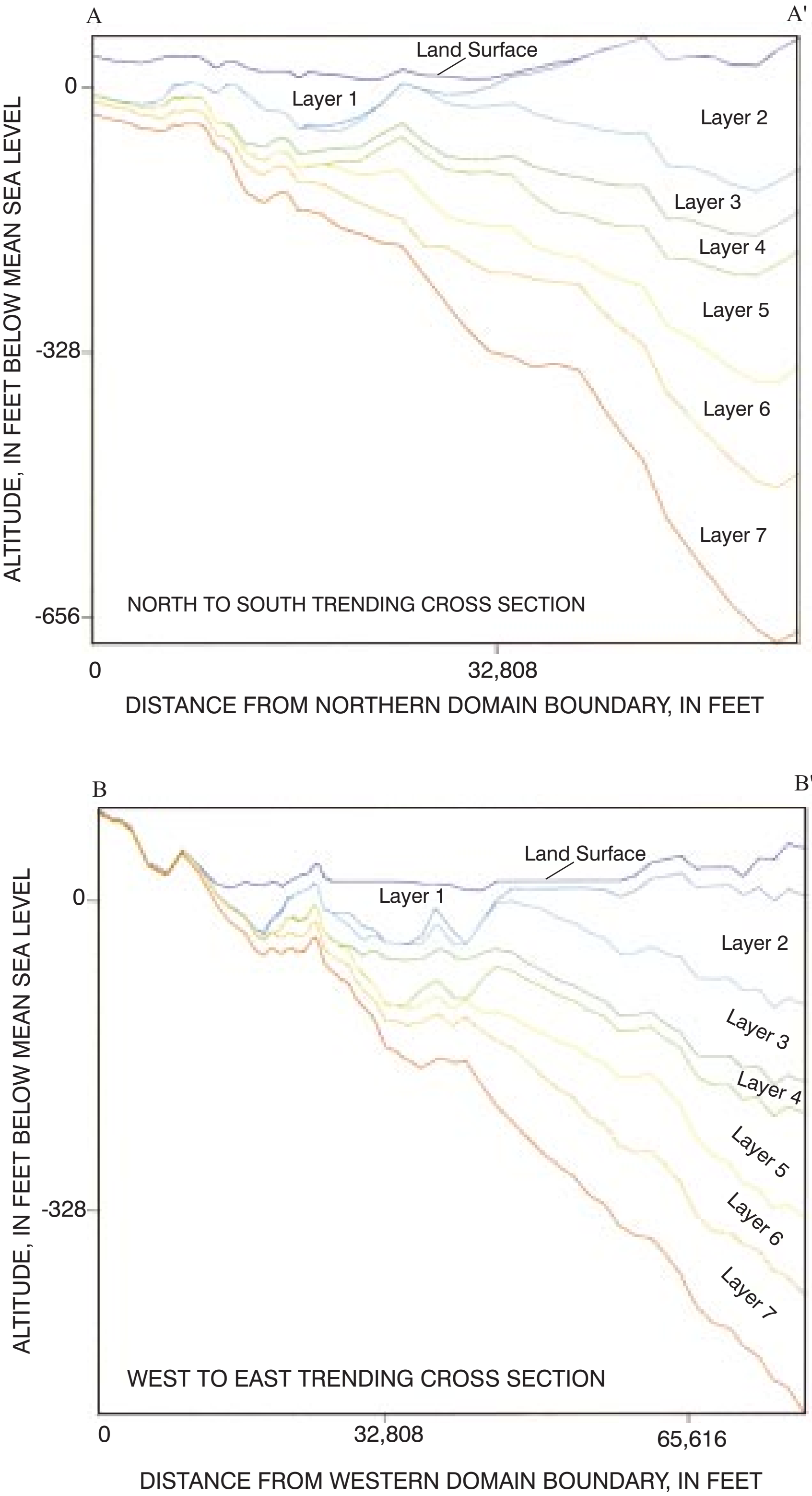


Figure 15. North to south and west to east trending cross sections of lithology used in the model of south Philadelphia and adjacent parts of New Jersey.

Potomac-Raritan-Magothy Aquifer System

Because the PRM aquifer system yields large amounts of water, withdrawals have been extensive in the south Philadelphia area. Starting in the early 1900's, pumping started to show an effect on the ground-water-flow system. Because of these withdrawals and the changes in the location of major pumping centers through the 1900's, ground-water flow directions have changed significantly from pre-development conditions. Recharge areas and the interaction between the PRM and the Schuylkill and Delaware Rivers also changed as a result of the withdrawals.

Pre-Development System

Barksdale and others (1958) theorized that before development of ground-water supplies began around 1900, regional ground-water flow was from high-altitude outcrop areas east of Trenton, N.J., towards the Delaware River. Ground-water flow was localized; precipitation recharged areas of high altitude and discharged to nearby streams and rivers. Vertical hydraulic gradients were upward in the discharge zones. Thus, before development of ground water, a large part of the water-table aquifer in south Philadelphia was a ground-water discharge zone. The hydraulic head in the lower sand unit was higher than the head in the middle and upper sand units and the Trenton gravel. Water flowed partly from the lower sand unit through and around confining units, especially in areas where the confining units pinched out into the middle and upper sand units, and subsequently into the alluvial water-table aquifer. Also, the rivers were gaining reaches in these areas. Greenman and others (1961, p. 54) constructed a pre-development representation of the potentiometric-surface map of the lower sand unit. Sloto (1988, p. 20) presented a pre-development, simulated potentiometric-surface map of the lower sand unit generated from a calibrated ground-water-flow model. Navoy and Carleton (1995) presented a simulated, pre-development potentiometric-surface map of the middle sand unit that was modified from Martin (1998, fig. 30).

Historical Ground-Water Withdrawals

By the 1920's, pumping in the City of Philadelphia had changed the natural ground-water-flow patterns. The principal change in the direction of ground-water flow from pre-development to the 1920's was in the area near the Walt Whitman Bridge (fig. 1), where the greatest withdrawals from the lower sand unit were made (Paulachok, 1991, p. 40). Withdrawals created water-level declines in this area, and ground water flowed toward these pumping centers. By 1940, continued and increasing pumping from the lower sand unit near the Walt Whitman Bridge had caused greater water-level declines in the lower aquifers and caused a still steeper hydraulic gradient towards these pumping centers. Also, lower heads in the lower sand unit relative to the heads in the alluvial and upper and middle sand units began to develop, which created a downward vertical ground-water-flow component. Recharge areas changed to areas near the Fall Line because of pumping from areas east of Trenton (Greenman and others, 1961, plates 21 and 22). Because of the increasing withdrawals from the unconfined alluvium and the confined upper, middle, and lower sand units, hydraulic heads were lowered below the levels of the Delaware and Schuylkill Rivers. Barksdale and others (1958) and Greenman and others (1961) document induced recharge from these rivers. Navoy and Carleton (1995, p. 35) give a detailed characterization of the Delaware River and the PRM aquifer interaction. These factors most likely have the same controlling effect on the interaction of the Schuylkill River and the underlying aquifer system. The rate and magnitude of flow from the rivers 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.

Ground-water development for supply at the PNSY started in 1940, and heavy pumping at the facility continued until the mid 1960's. Large cones of depression in the lower sand unit were documented by Greenman and others (1961, fig. 16). According to Paulachok (1991), between 1943 and 1960, vertical leakage was the most important source of recharge to the lower sand unit in the vicinity of the PNSY. The downward vertical hydraulic gradients were more pronounced between 1943 and 1960 than prior to ground-water development in 1940 because of large withdrawals at the PNSY.

Because of poor water quality, mainly excessive concentrations of iron and manganese, ground-water withdrawals at the PNSY were discontinued in the mid-1960's. The decrease in pumping allowed water levels to recover. Coincident with decreasing pumpage and eventual shutdown of pumping at the PNSY, ground-water withdrawals on the New Jersey side of the Delaware River began to increase. According to Vowinkel (1984), total annual pumpage from the PRM in New Jersey in 1956 was 120 Mgal/d. The pumpage increased to 195 Mgal/d by 1966 and to 245 Mgal/d by 1980. Even though pumping stopped at the PNSY and water levels in the lower sand unit recovered in the PBR, DSCP, and PHD vicinity, the increased pumping in New Jersey maintained the downward vertical gradients.

In the modeled area, a total of 131 pumped wells are in Pennsylvania. Significant pumping in Pennsylvania began in the 1920's and steadily increased until 1941. A marked increase occurred after 1941, and pumpage in the modeled area peaked in 1948 at greater than 7 Bgal/yr or 20 Mgal/d. Overall pumpage steadily decreased until 1974 when pumping was slightly greater than 3 Bgal/yr or 8.5 Mgal/d because of increased use of public water supplies. From 1975 to 1982, pumping decreased to virtually nothing.

In the modeled area, a total of 125 pumped wells are in New Jersey. Significant pumping in New Jersey also began in the 1920's and slowly increased until 1946 with pumpage nearing 3 Bgal/yr or 8 Mgal/d. A dramatic increase occurred from 1947 and continued until it peaked in 1974 at greater than 16 Bgal/yr or 45 Mgal/d. Pumpage decreased from the peak until 1982 to almost 14 Bgal/yr or 38 Mgal/d. A sharp decline in pumpage occurred in 1984 with a slow decline continuing until 1995 when withdrawals totaled just less than 10 Bgal/yr or 27 Mgal/d. For the modeled area, annual pumpage from 1904 to 1995 in Pennsylvania and New Jersey is shown in figure 16.

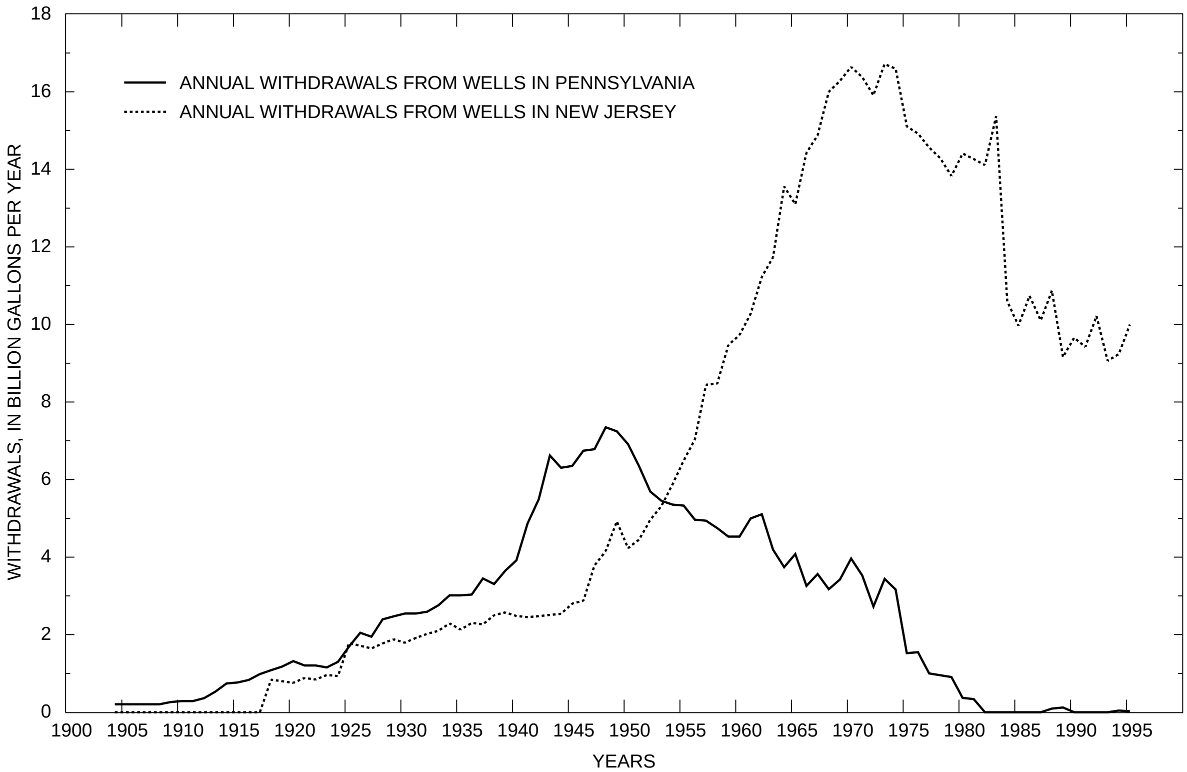


Figure 16. Annual ground-water withdrawals in the modeled area from the Potomac-Raritan-Magothy aquifer in Pennsylvania and New Jersey, 1904–95.

SIMULATION OF THE GROUND-WATER SYSTEM

An accurate understanding of the hydrogeologic system in the study area is needed to estimate historical water-level altitudes in the vicinity of the DSCP/PBR. This understanding or conceptualization of the flow system must then be constructed into a three-dimensional numerical ground-water-flow model. Boundary conditions of the model must be reasonably estimated to simulate the flow system and satisfy the objective. The geologic structure of the PRM and coinciding hydrologic parameters of the units, simulation of pinch-out units, spatial distribution of recharge, interactions of aquifers with the Schuylkill and Delaware Rivers, and historical withdrawal information all must be identified and defined to reasonably simulate the ground-water-flow system.

Model Structure and Boundary Conditions

The model is a seven-layer three-dimensional representation of the hydrogeologic units of the study area. The three-dimensional, numerical flow model, MODFLOW (McDonald and Harbaugh, 1988), was used to simulate ground-water flow. The hydrogeologic units and corresponding model layers are shown in figure 2. The layer thicknesses and altitudes were described earlier in the section "Aquifer and Confining Unit Thicknesses and Altitudes." In the DSCP/PBR vicinity, the spatial discretization per grid cell was 328 ft (100 m) on a side. The spatial discretization was increased outward from the DSCP/PBR vicinity to a maximum cell size of 1,640 ft (500 m) on a side (fig. 17).

In all model layers, the Fall Line boundary was simulated as a no-flow boundary. In all model layers, the lateral northern, eastern, southern, and western boundaries were defined by use of time-variable general head boundaries. The heads in each layer at each boundary were approximated by use of water-level data in wells near those boundaries at time periods corresponding to simulated stress periods. The bedrock interface beneath layer 7 was simulated as a no-flow boundary.

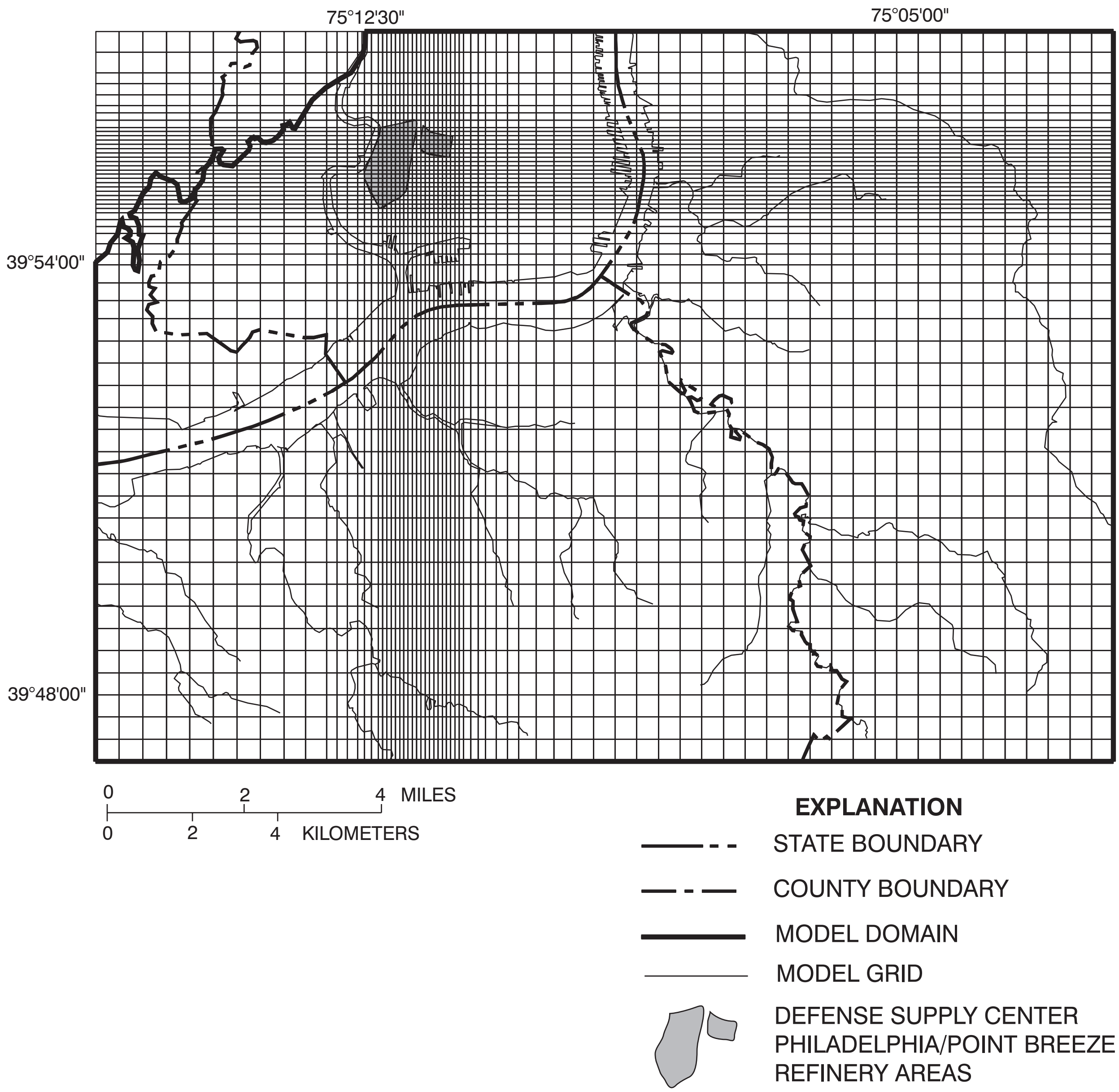


Figure 17. Finite-difference grid for the model.

Spatial Distribution of Aquifer and Confining Unit Hydraulic Properties

Aquifer and confining unit hydraulic properties of conductivity and specific storage varied spatially in all units except the lower sand unit, layer 7. The values for these parameters were obtained from the literature (Sloto, 1988; Navoy and Carleton, 1995). Using the pre-processing software (Argus Interware, 1997), different zones were used to represent the varying hydraulic parameters of the different units. The initial spatial aspect of the zonation was obtained from Navoy and Carleton (1995). Zones were changed in the model-calibration process. The zonation for hydraulic conductivity and specific storage are shown in figures 18 through 24. Because layer 7 did not pinch out, only one zone for hydraulic conductivity and specific storage was used.

All model layers were modeled as confined units. Although the alluvial unit in some locations is unconfined, the unit was modeled as a confined aquifer because of model instability, but the specific storage value for areas in Pennsylvania was increased to represent unconfined storage. Hydraulic parameters used in the model are listed in table 2.

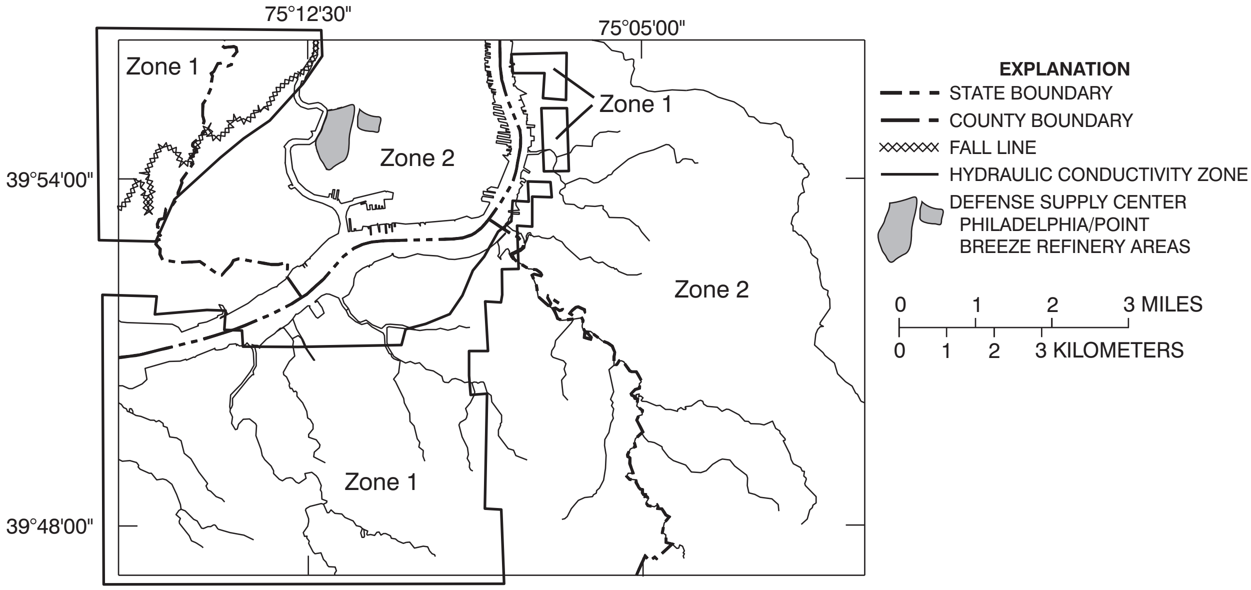


Figure 18. Hydraulic conductivity zones used in the model for the alluvial and Trenton gravel unit (layer 1).

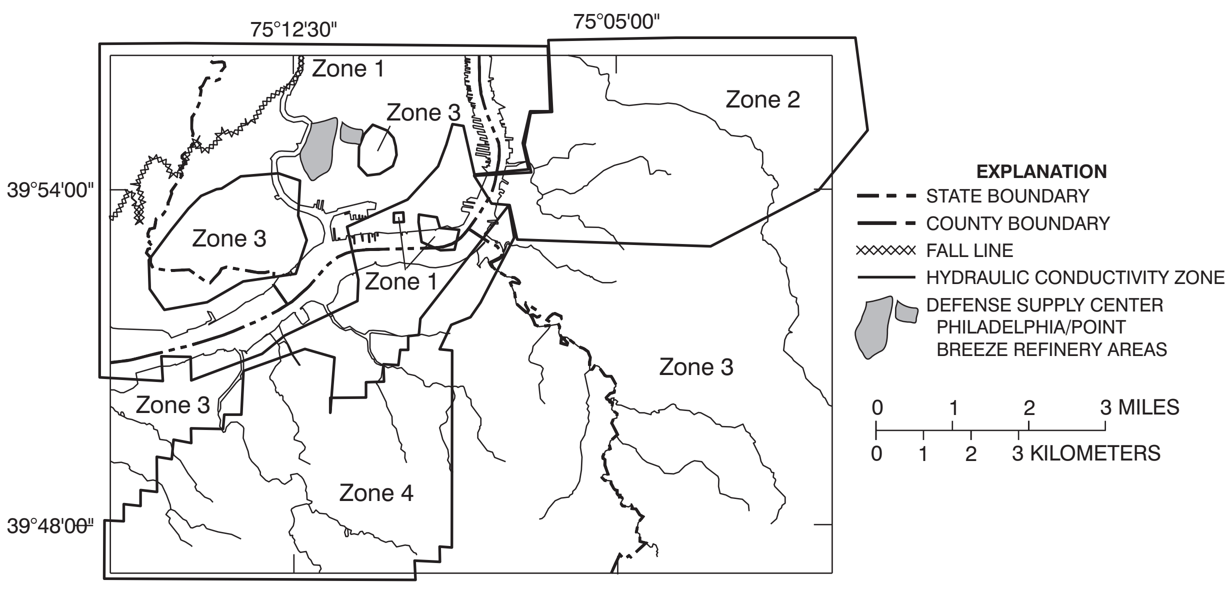


Figure 19. Hydraulic conductivity zones used in the model for the upper clay unit (layer 2) of the Potomac-Raritan-Magothy aquifer system.

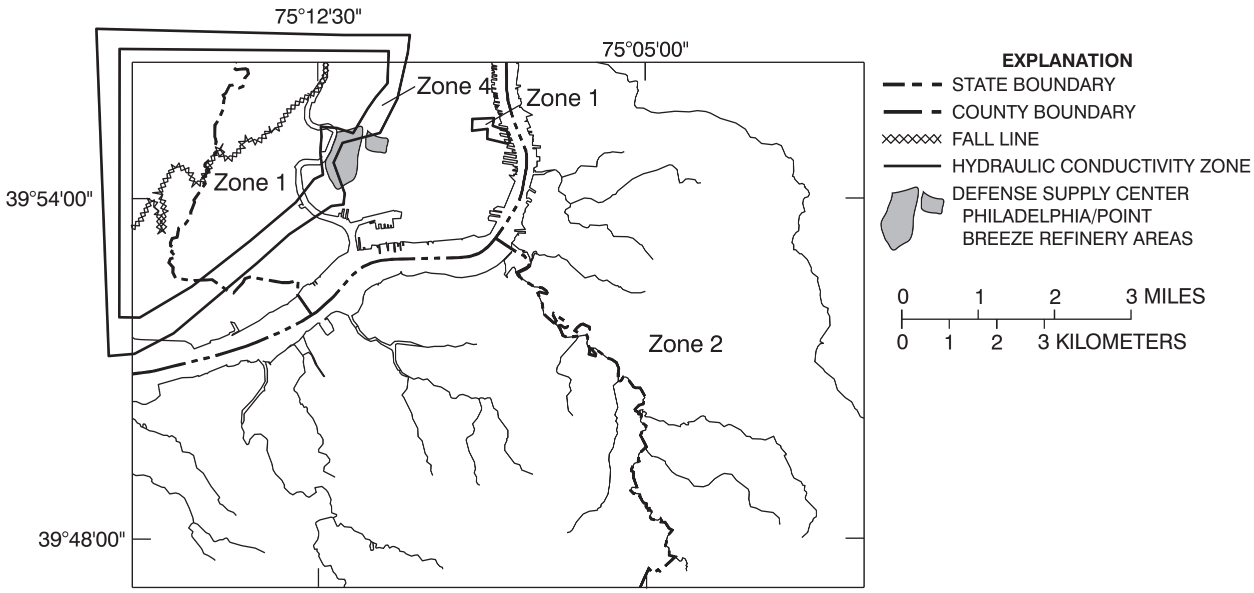


Figure 20. Hydraulic conductivity zones used in the model for the upper sand unit (layer 3) of the Potomac-Raritan-Magothy aquifer system.

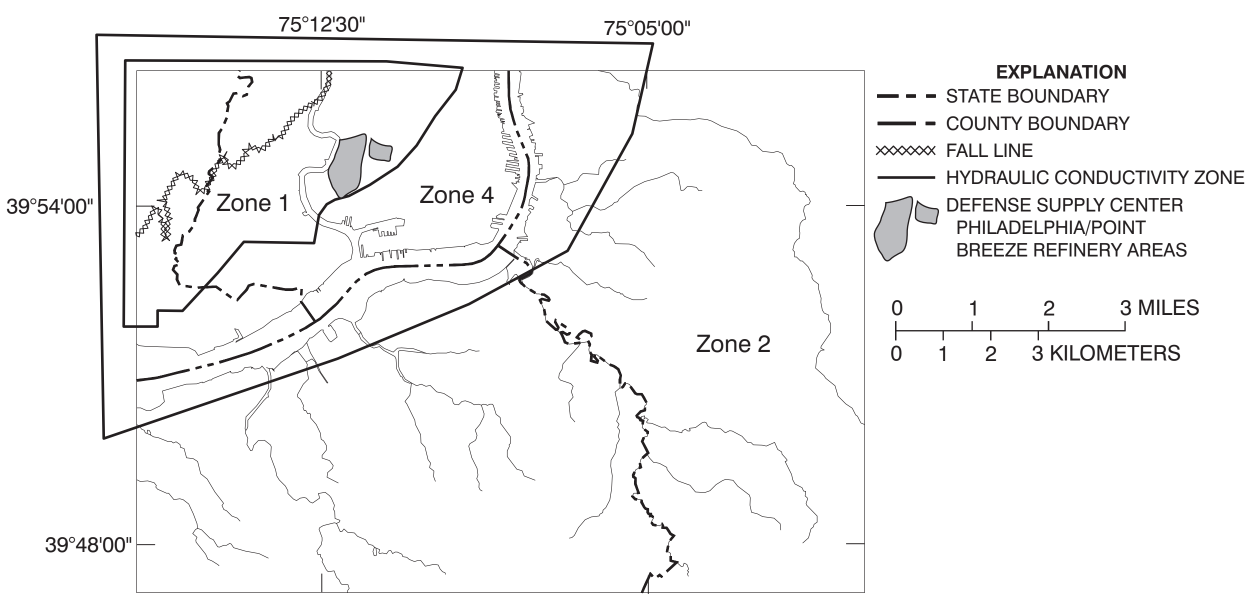


Figure 21. Hydraulic conductivity zones used in the model for the middle clay unit (layer 4) of the Potomac-Raritan-Magothy aquifer system.

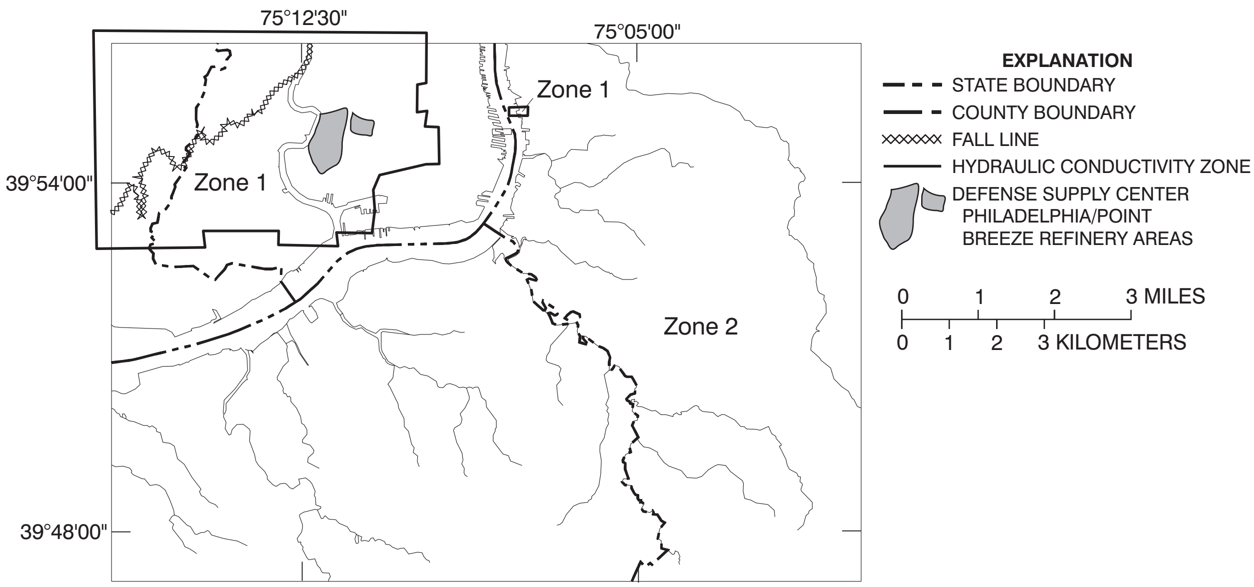


Figure 22. Hydraulic conductivity zones used in the model for the middle sand unit (layer 5) of the Potomac-Raritan-Magothy aquifer system.

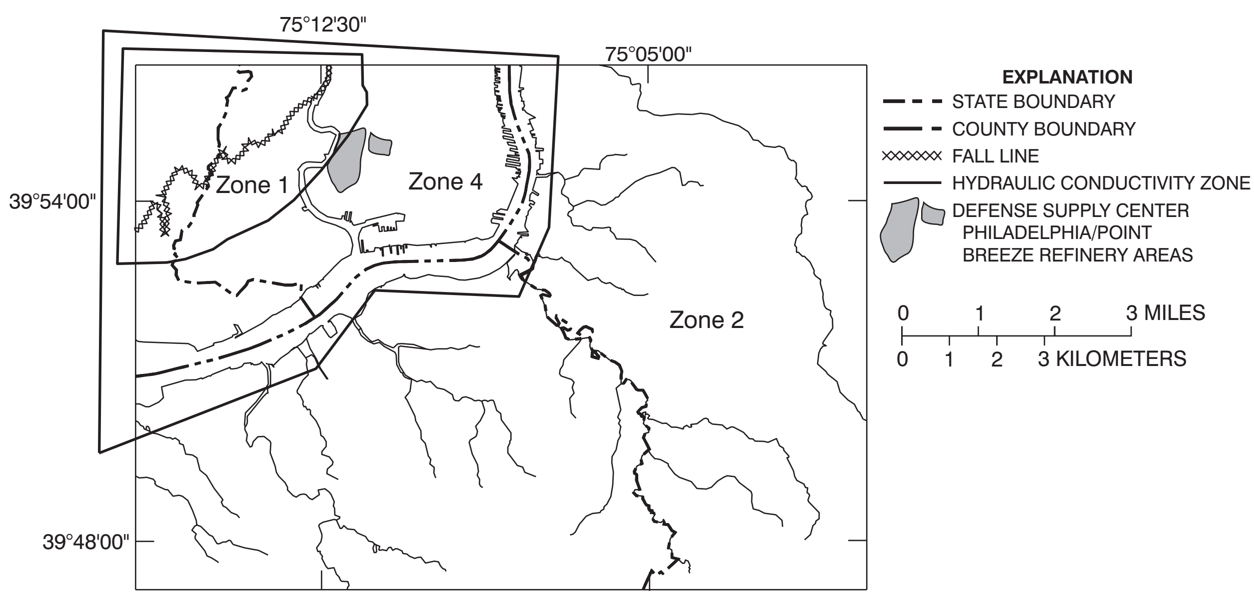


Figure 23. Hydraulic conductivity zones used in the model for the lower clay unit (layer 6) of the Potomac-Raritan-Magothy aquifer system.

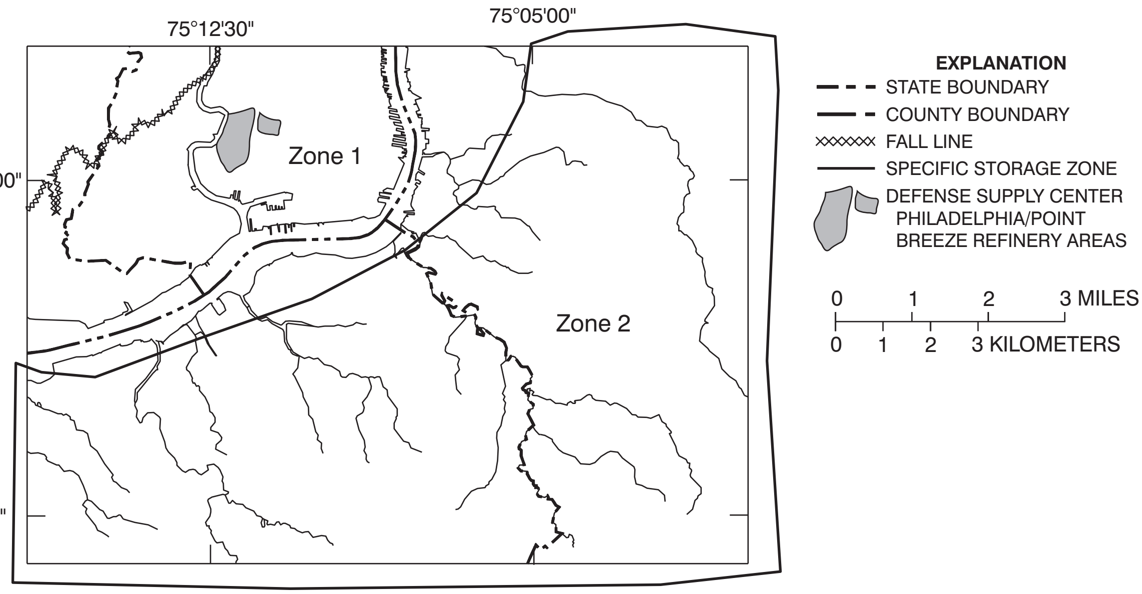


Figure 24. Specific storage zones used in the model for the alluvium and Trenton gravel (layer 1).

Table 2. *Summary of zonation of hydraulic conductivity and specific storage values used in the model*

[--, not defined]

Model layer	Zone	Hydraulic conductivity				Specific storage
		Horizontal		Vertical		
		feet per day	meters per day	feet per day	meters per day	
Layer 1	1	3.28×10^{-5}	1.0×10^{-5}	32,808	10,000	0.1
	2	5.472	1.668	5.472	1.668	.0001
Layer 2	1	3.28×10^{-5}	1.0×10^{-5}	32,808	10,000	1.0×10^{-7}
	2	.35	.10668	.35	.10668	--
	3	3.5×10^{-4}	1.067×10^{-4}	3.5×10^{-4}	1.067×10^{-4}	--
	4	.328	.1	.328	.1	--
Layer 3	1	3.28×10^{-5}	1.0×10^{-5}	32,808	10,000	1.0×10^{-4}
	2	35	10.668	35	10.668	--
	4	3.28×10^{-2}	.01	35	10.668	--
Layer 4	1	3.28×10^{-5}	1.0×10^{-5}	32,808	10,000	1.0×10^{-7}
	2	.35	.10668	.35	.10668	--
	4	1.2×10^{-2}	3.657×10^{-3}	1.2×10^{-2}	3.657×10^{-3}	--
Layer 5	1	3.28×10^{-5}	1.0×10^{-5}	32,808	10,000	1.0×10^{-4}
	2	98	30	98	30	--
Layer 6	1	3.28×10^{-5}	1.0×10^{-5}	32,808	10,000	1.0×10^{-7}
	2	.35	.10668	.35	.10668	--
	4	4.0×10^{-3}	1.219×10^{-3}	4.0×10^{-3}	1.219×10^{-3}	--
Layer 7	--	164	50	164	50	1.0×10^{-4}

Simulation of Pinched-Out Units

Because of the depositional environment and the underlying dipping bedrock, many units pinch out near the Fall Line in the northeastern part of the study area. Also, many units are discontinuous throughout the study area. In order to simulate these discontinuities, the method established was to determine from the isopach maps the zero thickness areas of individual units. The zero thickness areas were determined using the pre-processing software and the zero thicknesses were assigned a value of 0.328 ft (0.1 m). The horizontal hydraulic conductivity was set to 3.28×10^{-5} ft/d (1.0×10^{-5} m/d), and the vertical hydraulic conductivity was set to 32,808 ft/d (10,000 m/d). This procedure permitted water (in the model) to freely flow downward through the pinched out units to underlying units. On figures 17–23, zone 1 represented areas of pinched out or discontinuous units.

Spatial and Temporal Distribution of Recharge

Water directly enters the aquifer system as recharge from precipitation only on an outcrop area (Navoy and Carleton, 1995, p. 60). The outcrop areas are near the Fall Line in the northern part of the modeled area. Recharge was assigned to the uppermost active model layer. The spatial distribution of recharge for this model is shown on figure 25. The spatial distribution for the zoning of recharge parameters was obtained from Navoy and Carleton (1995, fig. 45). Navoy and Carleton (1995) used recharge estimates on the Pennsylvania side of the river in their calibrated model in the Camden, N.J., area that ranged from 4 to 9 in/yr (2.78×10^{-4}m/d to 6.26×10^{-4}m/d). In order to calibrate this model, recharge rates were changed temporally. The recharge values, zonation for spatial distribution, and temporal distribution of recharge rates are listed in table 3.

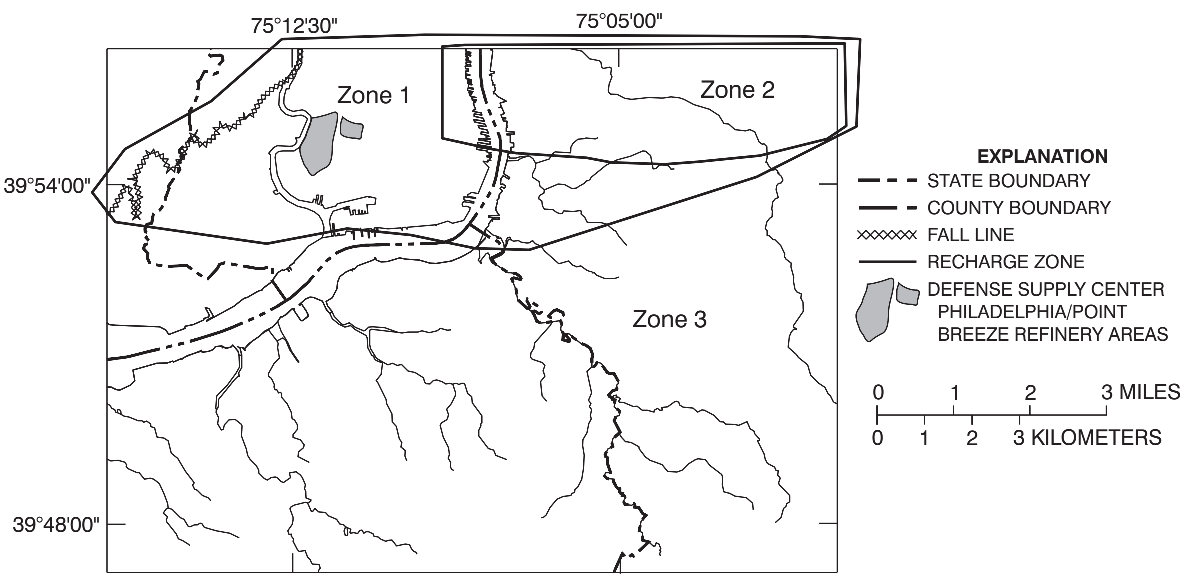


Figure 25. Recharge zones used in the model.

Table 3. *Summary of assigned recharge rates associated with spatial and temporal variability*

[Zones are shown in figure 25.]

Zone	Stress periods[1]	Recharge rate (inches per year)	Recharge rate (meter per day)
1	1 - 16	4	2.784×10^{-4}
	17 - 21	6	4.175×10^{-4}
2	1 - 16	6	4.175×10^{-4}
	17 - 21	8	5.552×10^{-4}
3	1 - 16	0	0
	17 - 21	0	0

[1] See table 5 for stress period time intervals.

River Interactions

The interaction between the Delaware and Schuylkill Rivers and the aquifer system is an important factor because the rivers changed from gaining streams to losing streams from pre- to post-development of ground-water resources. Factors that effect the aquifer/river interaction in the model are the vertical hydraulic conductivity of the riverbed, the altitude of the bottom of the river, the stage of the river, and the thickness of the riverbed. Because of the local hydrogeology, the bottoms of the rivers are in different units. For this model, the rivers were zoned spatially on the basis of which model layer the bottom of the river was located. Different riverbed hydraulic conductivities were assigned to each river area unit (fig. 26). The riverbed hydraulic conductivities are spatially variable and are based on work done by Navoy and Carleton (1995, fig. 23). Riverbed hydraulic conductivities were initially set to values used by Navoy and Carleton (1995) but were adjusted in the calibration process. The rivers in the study area are tidal, but only average river stages were used. The average river stage was held constant for all stress periods. The riverbed thickness was assigned 10 ft (3.048 m) for all area river units. The riverbed hydraulic conductivities, river-bottom altitudes, and average river stages for each river area unit are summarized in table 4.

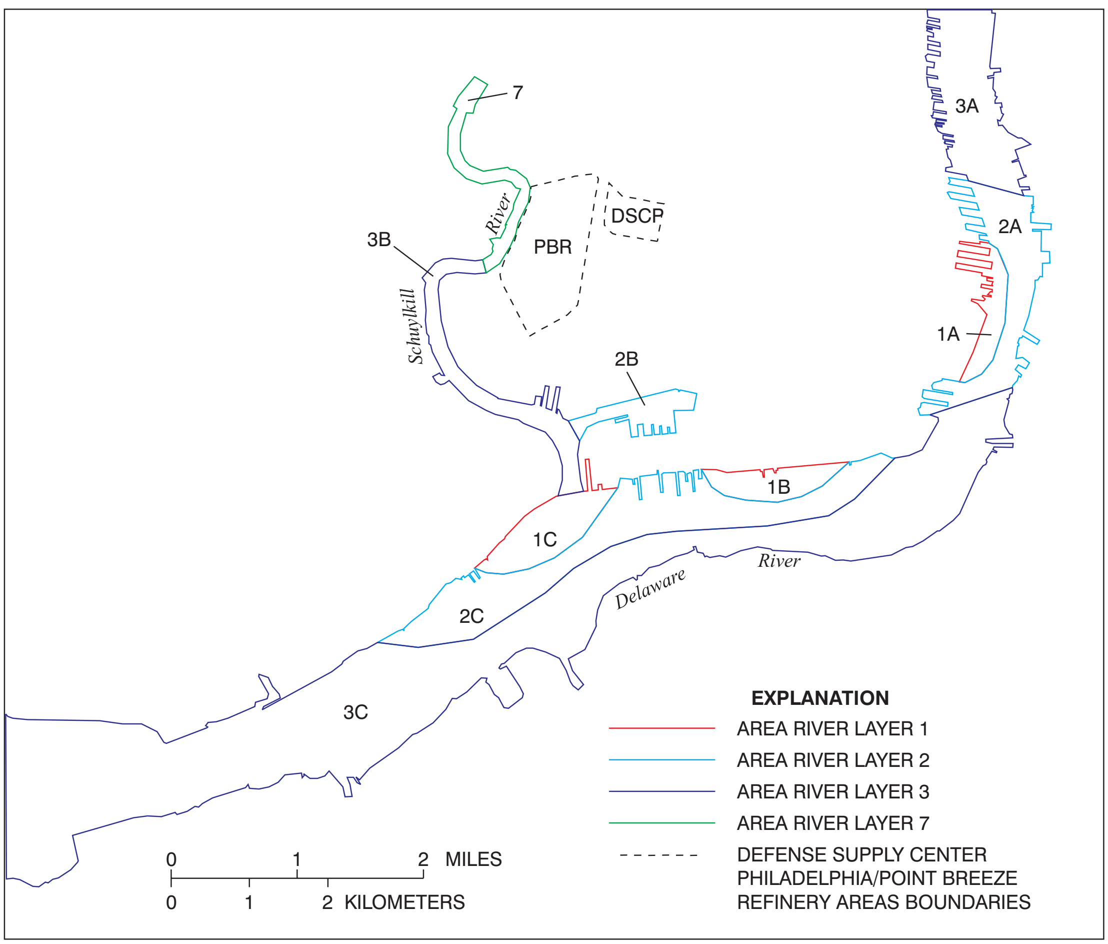


Figure 26. River area layers used in the model.

Table 4. Summary of area riverbed hydraulic conductivities, average river stages, and altitudes of the bottom of the rivers

River area	Model layer	Riverbed hydraulic conductivity		Average river stage		Altitude of river bottom	
		meters per day	feet per day	meter	feet	meter	feet
1A	1	1.299×10^{-2}	4.26×10^{-2}	0.1524	0.5	-3.0	-9.84
1B	1	1.299×10^{-2}	4.26×10^{-2}	.1524	.5	-3.0	-9.84
1C	1	1.299×10^{-2}	4.26×10^{-2}	.1524	.5	-3.0	-9.84
2A	2	2.60×10^{-5}	8.53×10^{-5}	.1524	.5	-6.5	-21.3
2B	2	2.60×10^{-5}	8.53×10^{-5}	.1524	.5	-16.6	-54.5
2C	2	2.60×10^{-5}	8.53×10^{-5}	.1524	.5	-12.0	-39.4
3A	3	6.40×10^{-3}	2.10×10^{-2}	.3048	1.0	-2.0	-6.56
3B	3	6.40×10^{-3}	2.10×10^{-2}	.1524	.5	-14.0	-45.9
3C	3	6.40×10^{-3}	2.10×10^{-2}	.1524	.5	-15.0	-49.2
7	7	1.299×10^{-2}	4.26×10^{-2}	.3048	1.0	-1.0	-3.28

Time Discretization and Stress Periods

The starting point for the model simulations was set to pre-development conditions. Withdrawals before 1900 are assumed to be insignificant; significant pumping started after 1904. The model used 21 stress periods that represented different time intervals from 1900 through 1995. Each stress period was based on changes in annual withdrawal rates. The stress periods and the corresponding simulated years are summarized in table 5. The first stress period was a steady-state simulation and the subsequent 20 stress periods were transient simulations. For each transient stress period, an average withdrawal rate was used to represent pumping. The annual withdrawals and corresponding assigned model stress-period withdrawal rates are shown in figure 27.

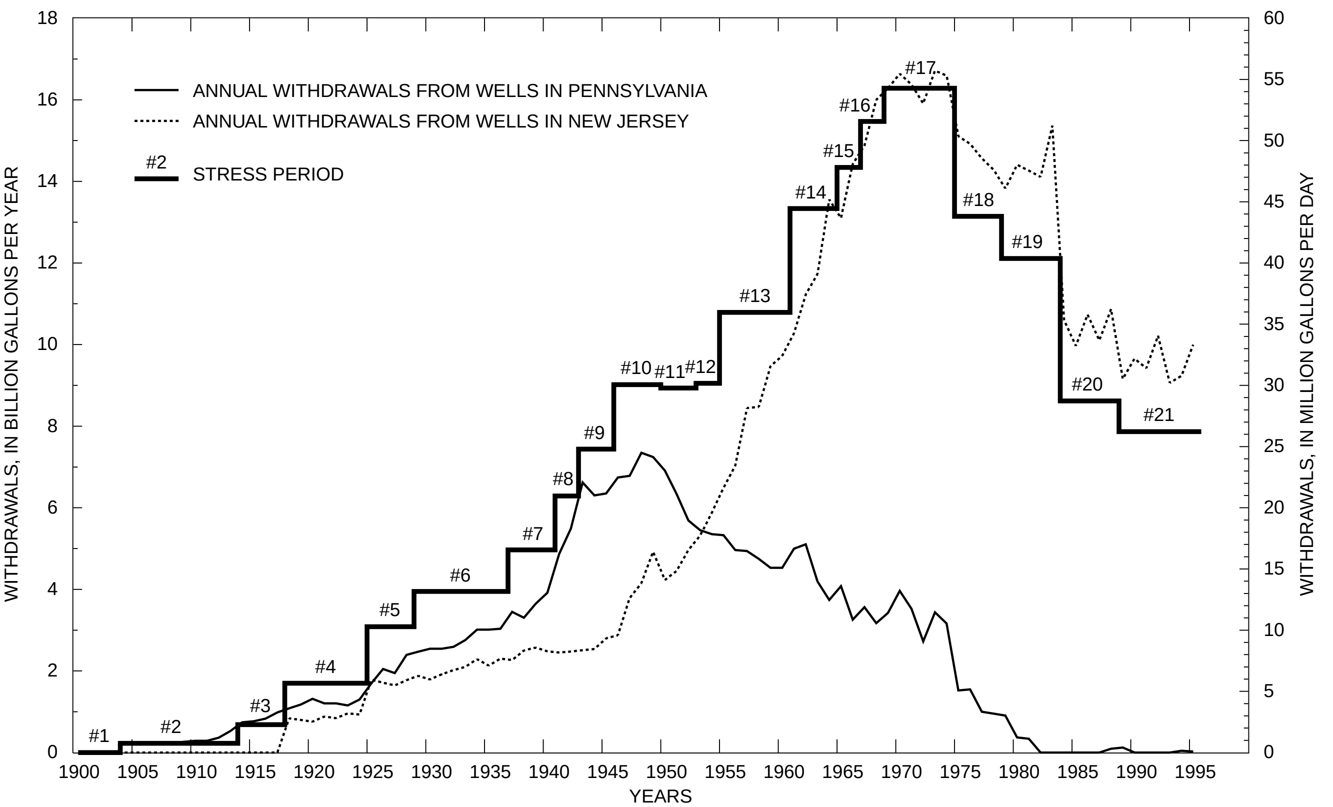


Figure 27. Annual ground-water withdrawals in the modeled area from the Potomac-Raritan-Magothy aquifer in Pennsylvania and New Jersey from 1904-95 and model stress-period withdrawals.

Table 5. *Summary of simulated stress periods and represented years*

Stress period	Represented years	Stress period	Represented years
1	1900–03	12	1953–54
2	1904–13	13	1955–60
3	1914–17	14	1961–64
4	1918–24	15	1965–66
5	1925–28	16	1967–68
6	1929–36	17	1969–74
7	1937–40	18	1975–78
8	1941–42	19	1979–83
9	1943–45	20	1984–88
10	1946–49	21	1989–95
11	1950–52		

MODEL CALIBRATION

In order to adequately simulate historical water-level altitudes, parameters such as hydraulic conductivities of the aquifer units and riverbed must be adjusted to reflect results of available observed data in the literature. The model parameters were adjusted by a trial-and-error approach to match the observed data.

The model was calibrated, meaning that input parameters were adjusted until simulated water levels matched published potentiometric-surface maps. Most potentiometric-surface maps done in Pennsylvania are of the lower sand unit (layer 7) of the PRM. Greenman and others (1961) published a potentiometric-surface map of the lower sand unit in the south Philadelphia area for August 1945. They also published a potentiometric-surface map of the lower sand unit in the south Philadelphia area for March 1954. Gill and Farlekas (1976) published a potentiometric-surface map of the PRM aquifer system in the New Jersey Coastal Plain that included part of south Philadelphia for 1968. Sloto (1988) published a potentiometric-surface map of the lower sand unit in south Philadelphia and southwestern New Jersey compiled from Walker (1983, pl. 1) and Paulachok (U.S. Geological Survey, written commun., 1982). Rosman (1997) published a potentiometric-surface map of the PRM aquifer system near National Park, N.J., for 1996, which included part of south Philadelphia.

The model was considered to be calibrated if altitudes on the simulated potentiometric-surface maps were within +/- 15 ft of altitudes on the published potentiometric-surface maps listed above. Navoy and Carleton (1995) set a 15-ft calibration accuracy for their model of the PRM in the Camden area. They based the 15-ft accuracy on several factors that included seasonal variations in water levels caused by seasonal variations in withdrawals and climatic factors, error in altitude data from the DEM, and error associated with synoptic water-level measurements. Because the purpose of the model was to simulate water-level altitudes over several decades, model stress periods were several years long. Thus, seasonal variations due to seasonal withdrawals and climatic factors were not incorporated into the model. Navoy and Carleton set a range attributable to the seasonal water-level variation of +/- 5 ft. The DEM error for level 2 DEM's is set at one-half the contour interval, which would yield a range of +/- 5 ft. Associated error attributable from synoptic water-level measurements is related to the accuracy of the measurement-site altitude (Navoy and Carleton, 1995, p.53). Most water-level measurement site altitudes were derived from USGS topographic maps with 10-ft contour intervals that would yield a range of +/- 5 ft.

Available water-level data near the DSCP/PBR area were compared to simulated water-level altitudes in grid cells that contained those wells for a check of model fit. Model parameters were not adjusted in order to match these water-level data, however, because the data were limited spatially and temporally.

The purpose of the model was to simulate water-level altitudes over several decades. A result of the simulation shows that water-level altitudes were consistently below the bottom of the Packer Avenue sewer from 1940 through 1990 is acceptable when that result is put in the context that the model is simulating conditions over several years and seasonal variations in the water table were not simulated. Navoy and Carleton (1995) in their report on modeling ground-water flow in the PRM aquifer system of the Camden area state that seasonal variations in water levels in the aquifer system, caused by seasonal variations in withdrawals and climatic factors, can range from +/- 5 ft over several years.

Initial Conditions

In order to simulate pre-development conditions, a steady-state simulation was run with initial water levels for all layers placed at the land surface. The resulting steady-state potentiometric surface of the lower sand unit (layer 7) is shown in figure 28. The potentiometric surface agrees with pre-development conditions theorized by Barksdale and others (1958) that describe the pre-pumping, regional ground-water-flow system having upward vertical gradients with local recharge in upland areas and discharging to nearby rivers.

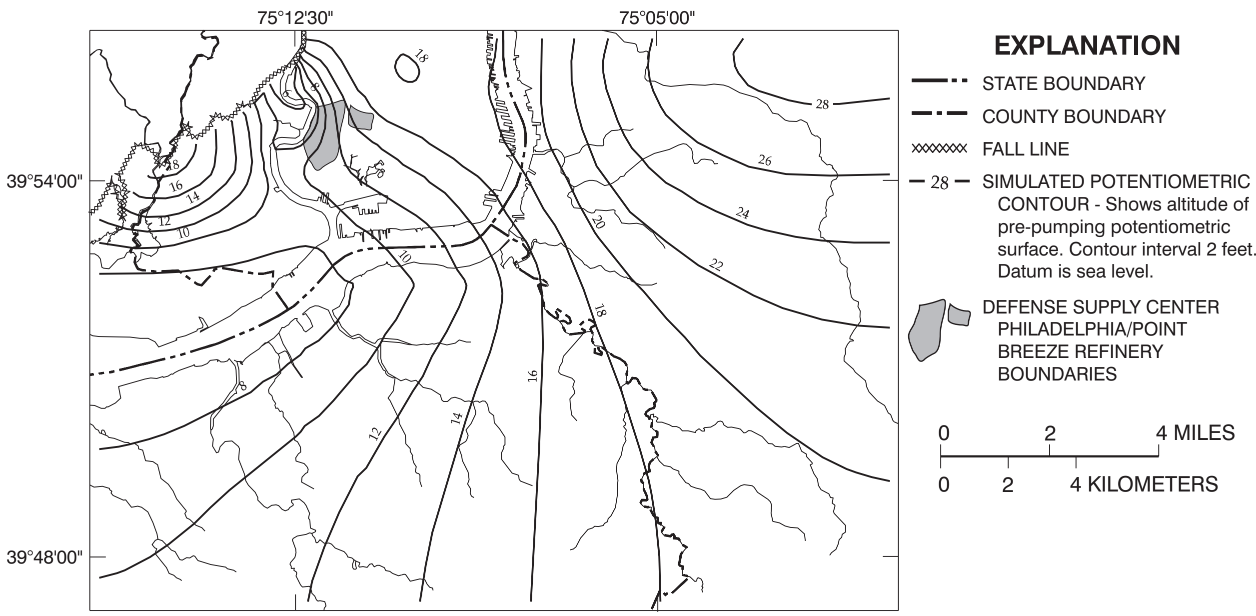


Figure 28. Simulated pre-development potentiometric surface of lower sand unit (model layer 7) of the Potomac-Raritan-Magothy aquifer system.

Comparison of Simulated Heads to Potentiometric Surface Maps

The simulated potentiometric surface of the south Philadelphia area for August 1945 is shown in figure 29. The August 1945 potentiometric-surface map of Greenman and others (1961) is shown in figure 30. The potentiometric-surface configurations are in agreement, but maximum drawdowns at the pumping centers are not. This could be the result of water-level data collected in pumping wells in which well-loss effects increase drawdown. Well-loss effects are negligible in non-pumping wells. Also, the grid-cell size may be too large to adequately represent drawdowns in the aquifer, especially in areas near large withdrawals.

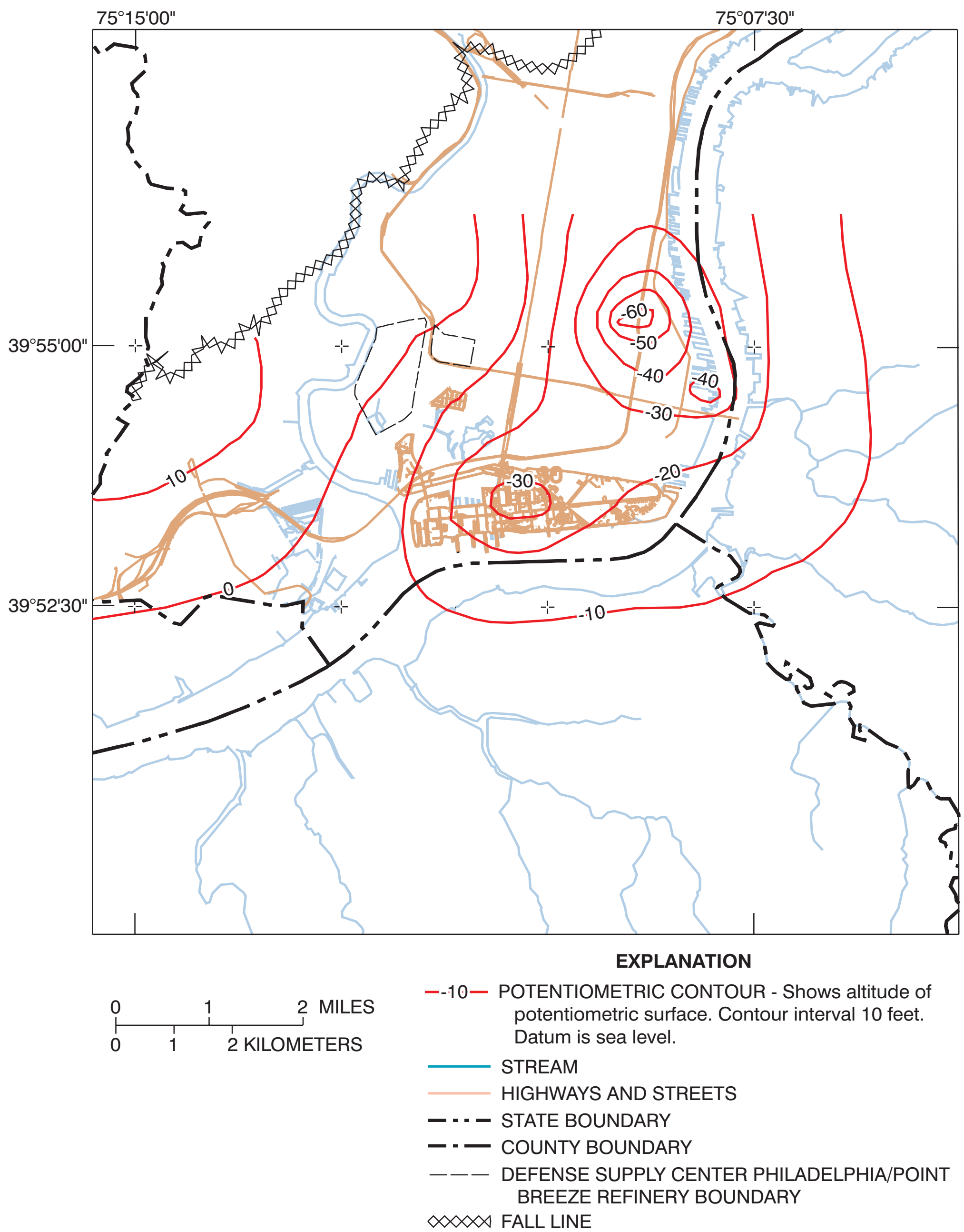


Figure 29. Simulated potentiometric surface for the lower sand unit of the Potomac-Raritan-Magothy aquifer system, August 1945.

For August 1945, simulated horizontal ground-water-flow direction in the lower sand unit (layer 7) near the area of concern was to the southeast towards areas with large cones of depression along the Delaware River. Simulated water-level altitudes in the lower sand unit (layer 7) ranged from 0 to -10 ft sea level, which caused downward vertical flow gradients in the upper units.

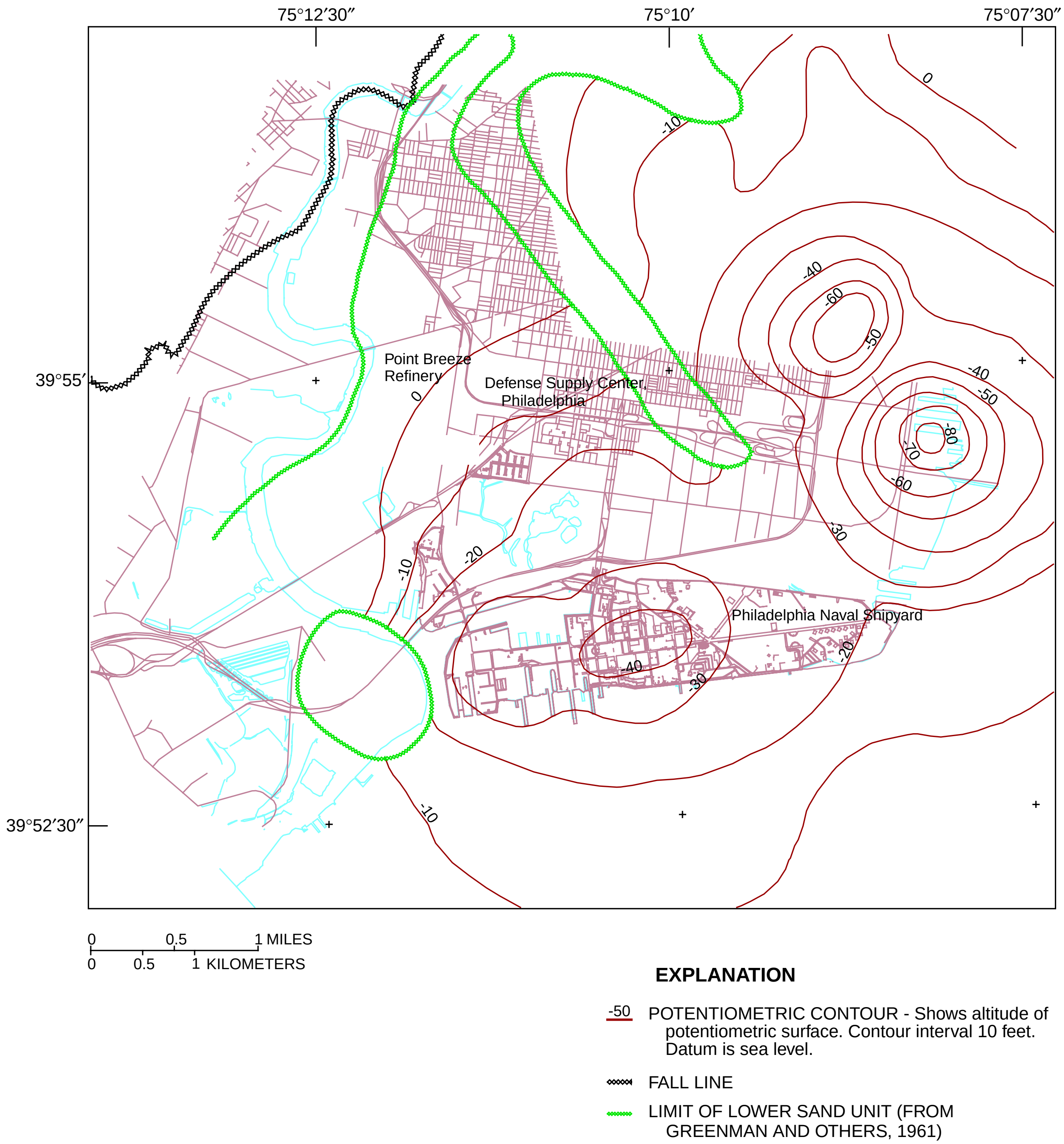


Figure 30. Potentiometric surface of the lower sand unit, August 1945 (modified from Greenman and others, 1961).

The simulated potentiometric surface of the south Philadelphia area for March 1954 is shown in figure 31. The March 1954 potentiometric-surface map of Greenman and others (1961) is shown in figure 32. The potentiometric-surface configurations are in agreement, but maximum drawdowns at the pumping centers once again are not. As described earlier, this could result from well-loss effects in pumping wells, and the large grid-cell size in areas of large withdrawals.

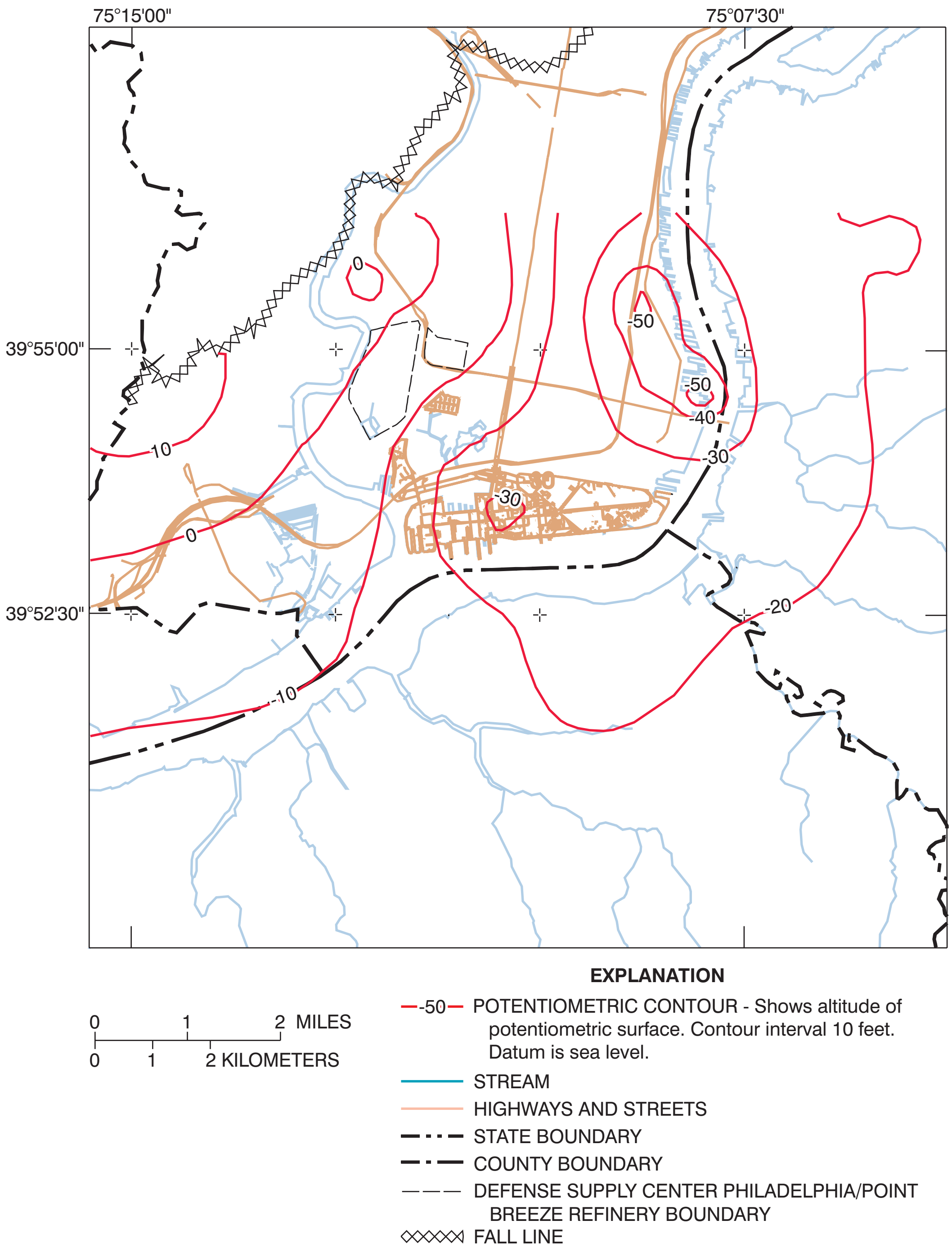


Figure 31. Simulated potentiometric surface for the lower sand unit of the Potomac-Raritan-Magothy aquifer system, March 1954.

For March 1954, simulated horizontal ground-water-flow direction in the lower sand unit (layer 7) near the area of concern was to the southeast towards areas with large cones of depression along the Delaware River. Simulated water-level altitudes in the lower sand unit (layer 7) ranged from 0 to -10 ft sea level, which caused downward vertical flow gradients in the upper units.

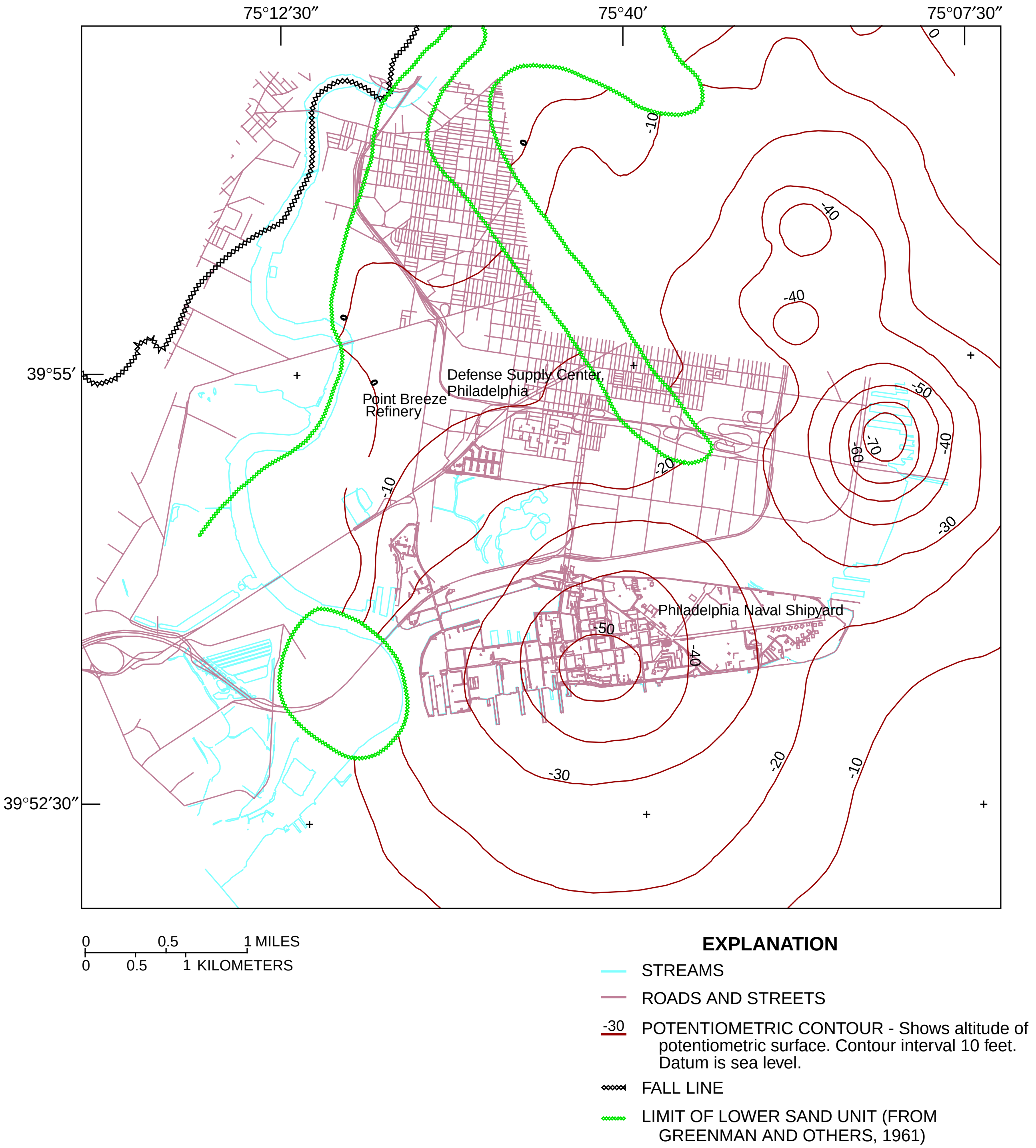


Figure 32. Potentiometric surface of the lower sand unit, March 24, 1954 (modified from Greenman and others, (1961).

The simulated potentiometric-surface map of the south Philadelphia area for 1968 is shown in figure 33. The 1968 potentiometric-surface map of Gill and Farlekas (1976) is shown in figure 34. The directions of ground-water flow are in agreement. However, maximum drawdowns of the simulated water surface near pumping centers are not in agreement. This could be the result of inaccurate water-withdrawal data; perhaps the withdrawals at these pumping centers were substantially less than reported.

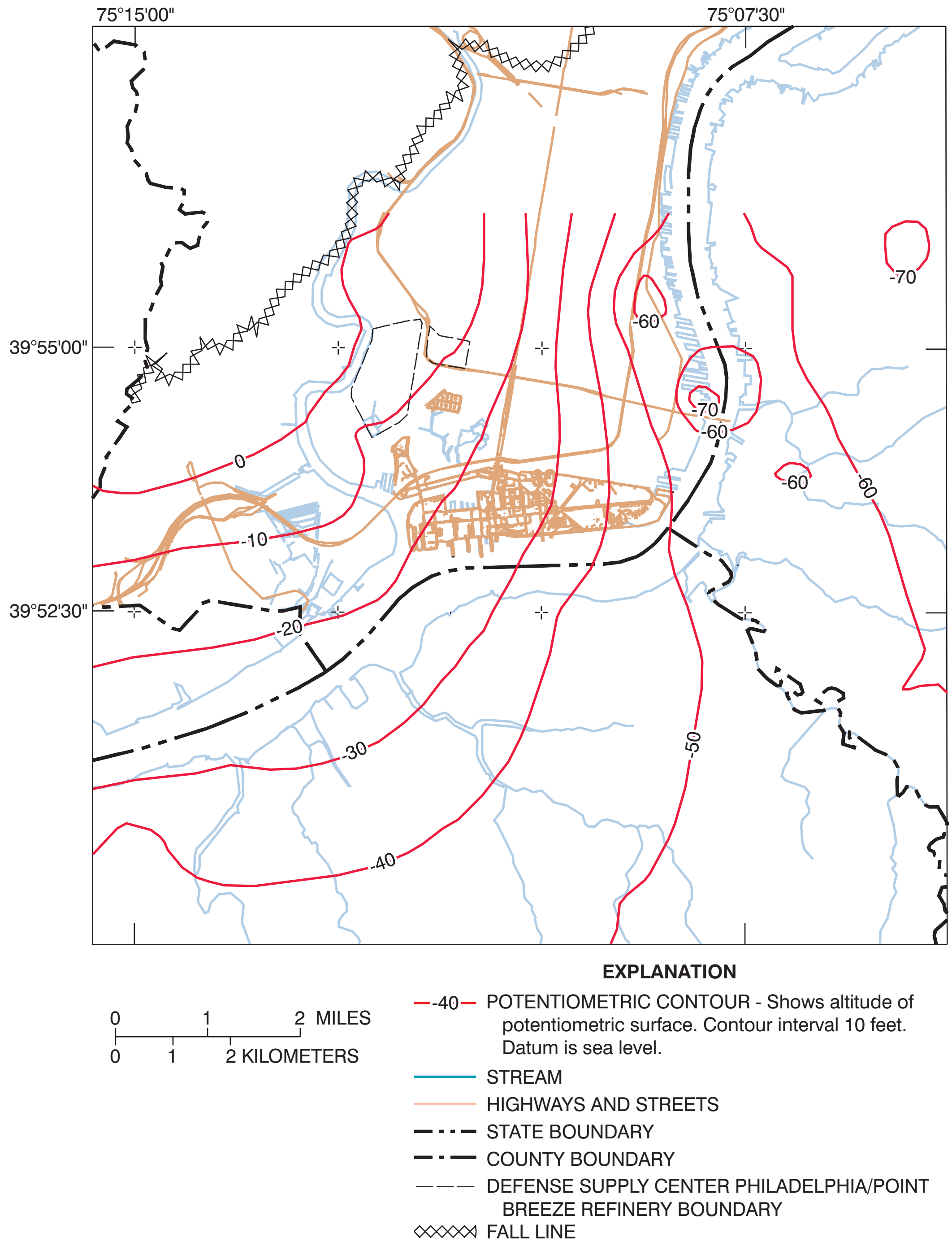


Figure 33. Simulated potentiometric surface for the lower sand unit of the Potomac-Raritan-Magothy aquifer system, December 1968.

For 1968, simulated horizontal ground-water-flow direction in the lower sand unit (layer 7) near the area of concern was to the east towards areas with large cones of depression in New Jersey and along the Delaware River. Simulated water-level altitudes in the lower sand unit (layer 7) ranged from -10 to -20 ft sea level, which caused a downward vertical flow gradients in the upper units.

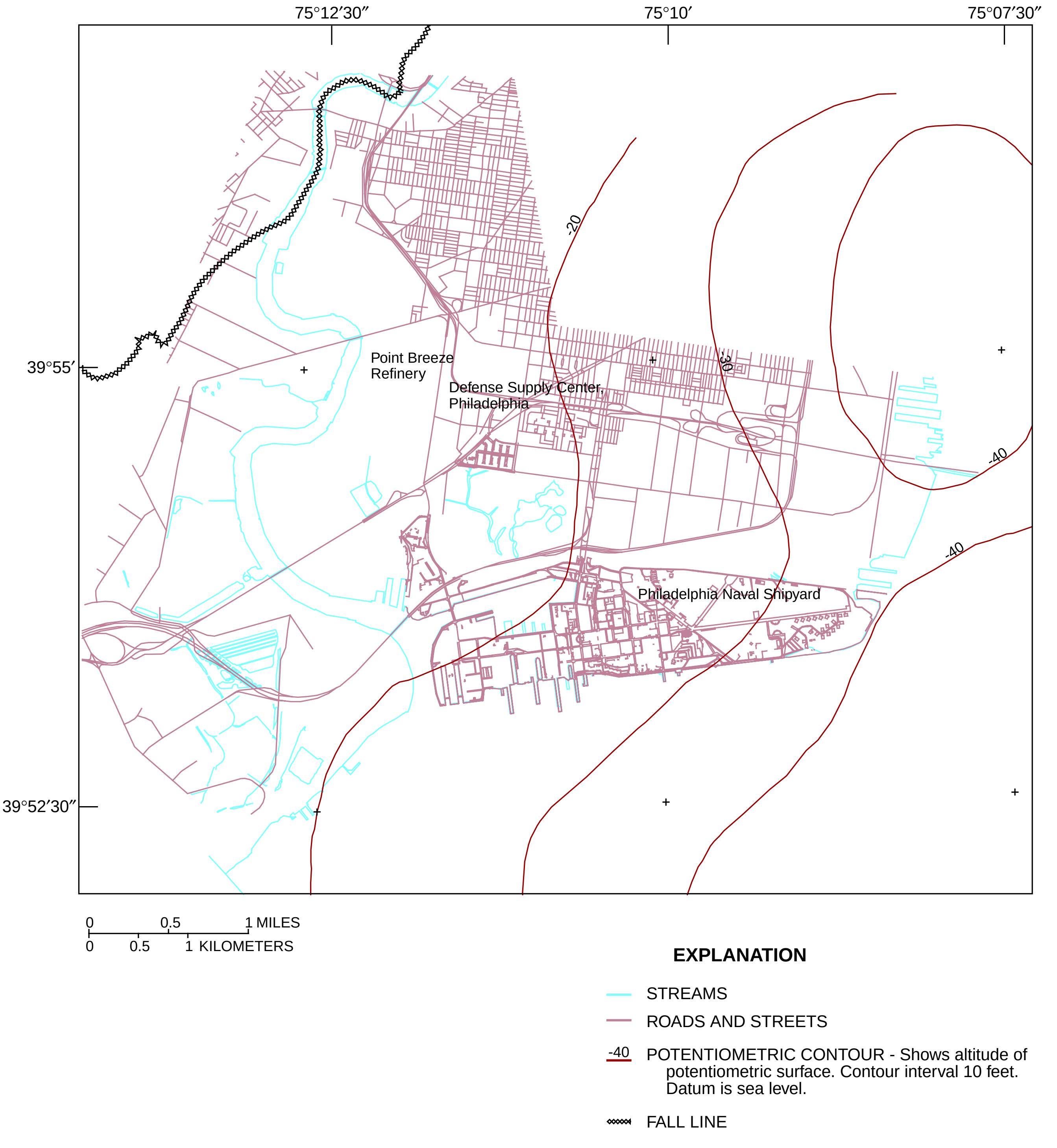


Figure 34. Potentiometric surface of the lower sand unit, 1968 (modified from Gill and Farlekas, 1976).

The simulated potentiometric-surface map of the south Philadelphia area for 1978 is shown in figure 35. The 1978 potentiometric-surface map of Sloto (1981) is shown in figure 36. The directions of ground-water flow indicated by the contour lines on the two maps are similar but not in agreement, and the water-level altitude contours are not in agreement. This could be the result of a small number of data points used to construct the original map, particularly on the Pennsylvania side of the river. Walker (1983) did not measure wells on the Pennsylvania side of the river to construct the map, and Paulachok (1991) measured only a few wells in the northwest corner of the study area.

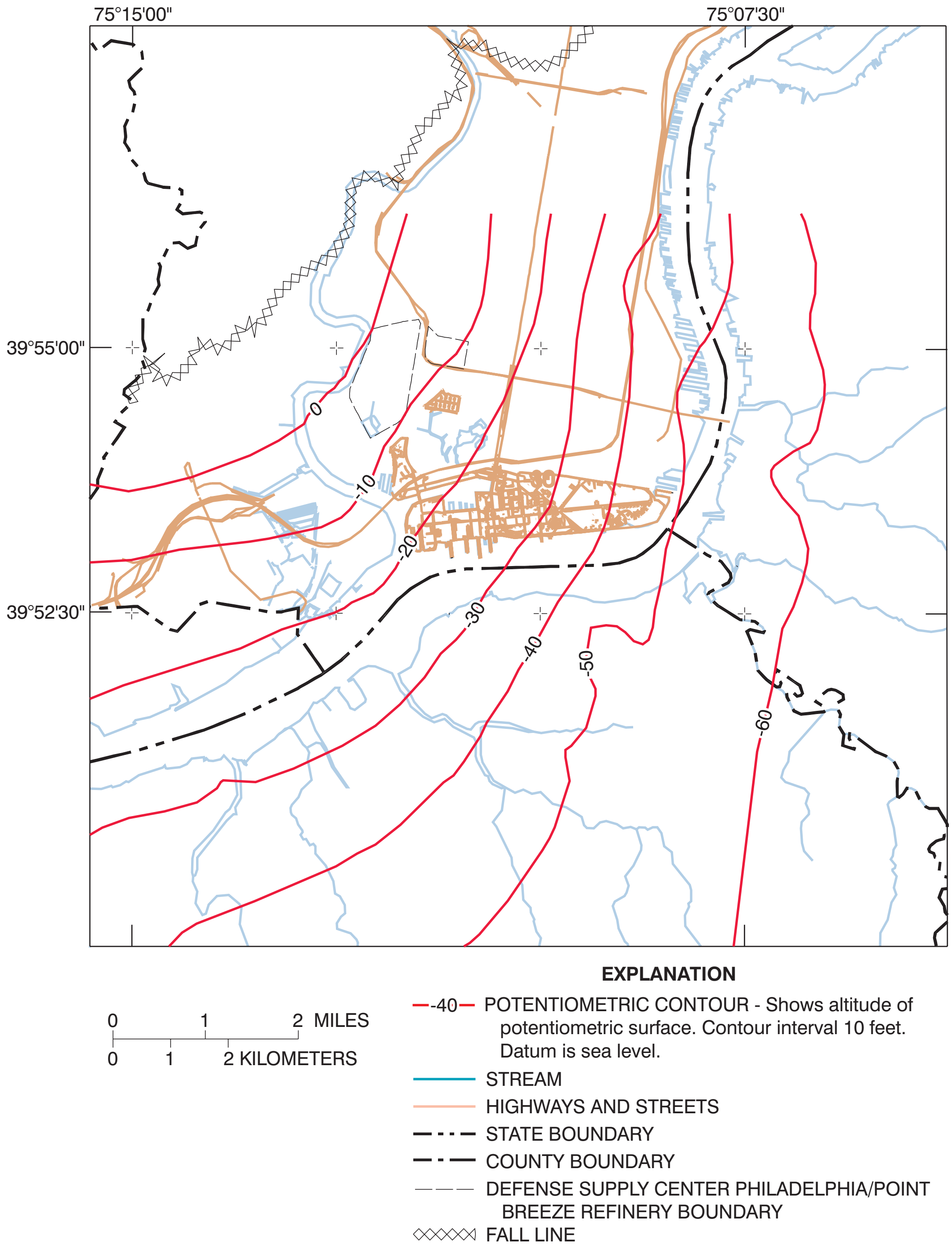


Figure 35. Simulated potentiometric surface for the lower sand unit of the Potomac-Raritan-Magothy aquifer system, December 1978.

For 1978, simulated horizontal ground-water-flow direction in the lower sand unit (layer 7) near the area of concern was to the east towards areas in New Jersey. Simulated water-level altitudes in the lower sand unit (layer 7) ranged from -10 to -20 ft sea level, which caused downward vertical flow gradients in the upper units.

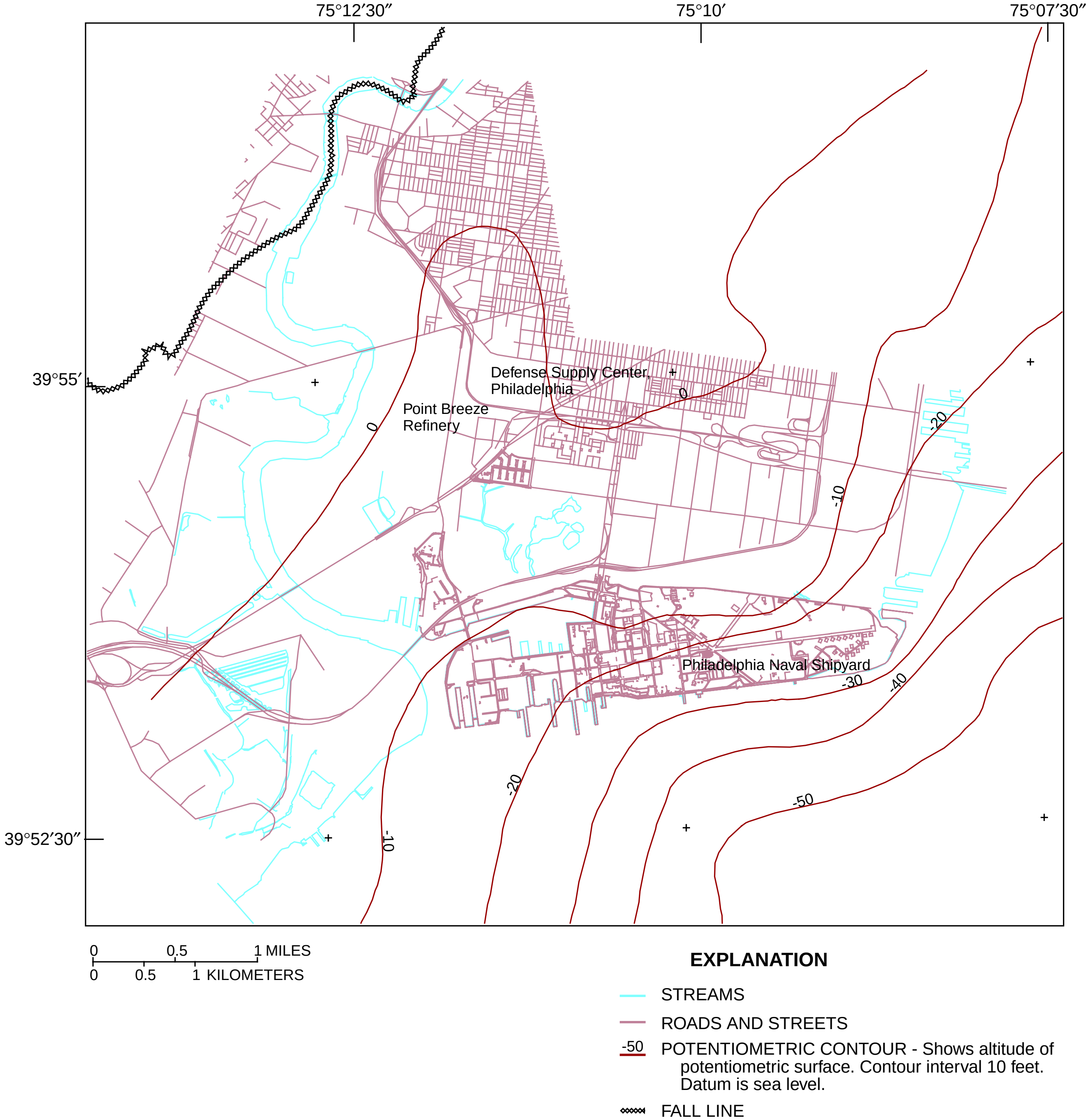


Figure 36. Potentiometric surface of the lower sand unit, 1978 (modified from Sloto, 1988).

The simulated potentiometric-surface map of the south Philadelphia area for 1995 is shown in figure 37. The potentiometric-surface map for 1996 of Rosman (1997) is shown in figure 38. The potentiometric-surface map configurations and the directions of ground-water flow indicated by the contour lines are in agreement. The simulated potentiometric contours are slightly west of the contour lines constructed from measured water levels.

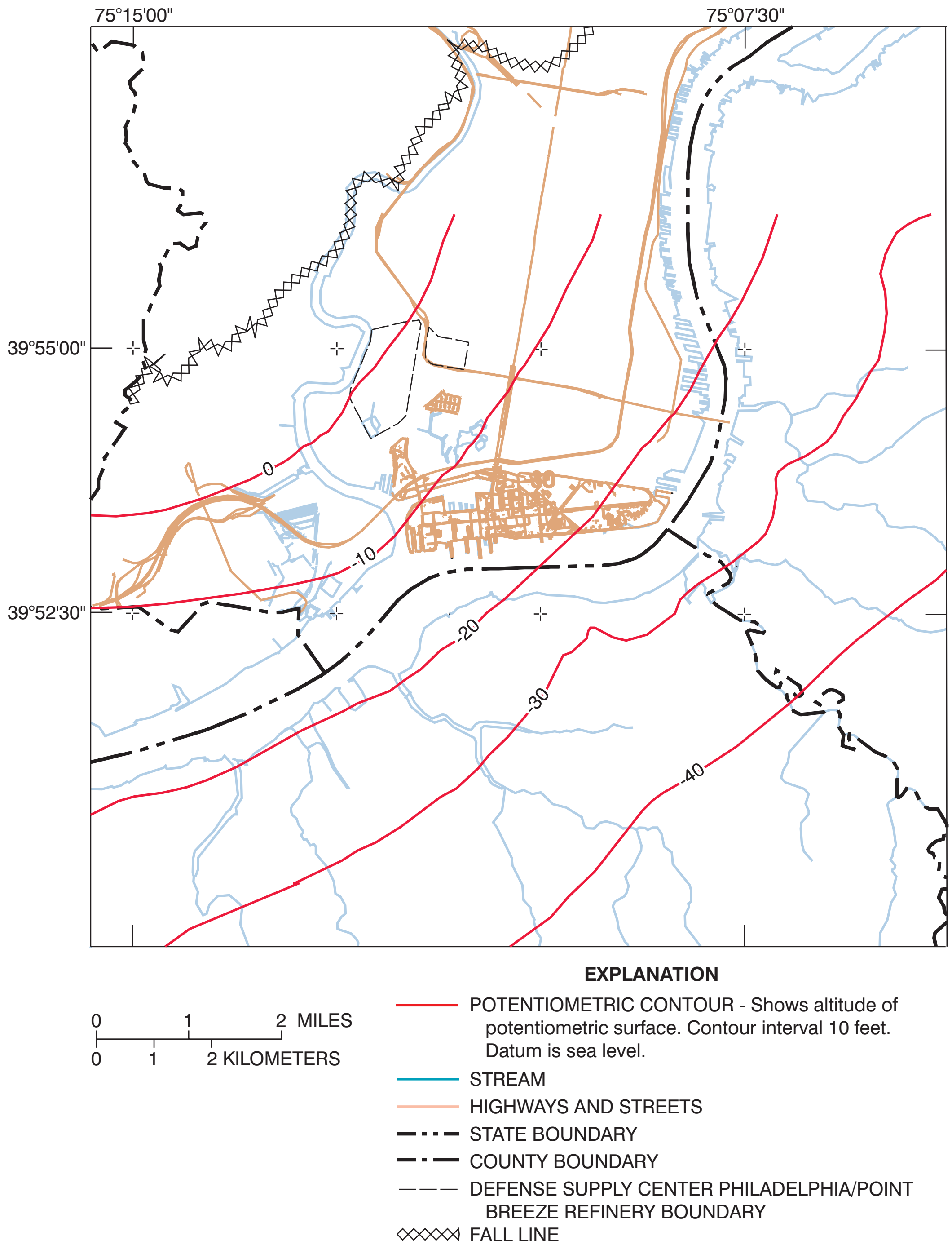


Figure 37. Simulated potentiometric surface for the lower sand unit of the Potomac-Raritan-Magothy aquifer system, December 1995.

For 1996, simulated horizontal ground-water-flow direction in the lower sand unit (layer 7) near the area of concern was to the southeast towards areas in New Jersey. Simulated water-level altitudes in the lower sand unit (layer 7) ranged from 0 to -10 ft sea level, which caused downward vertical flow gradients in the upper units.

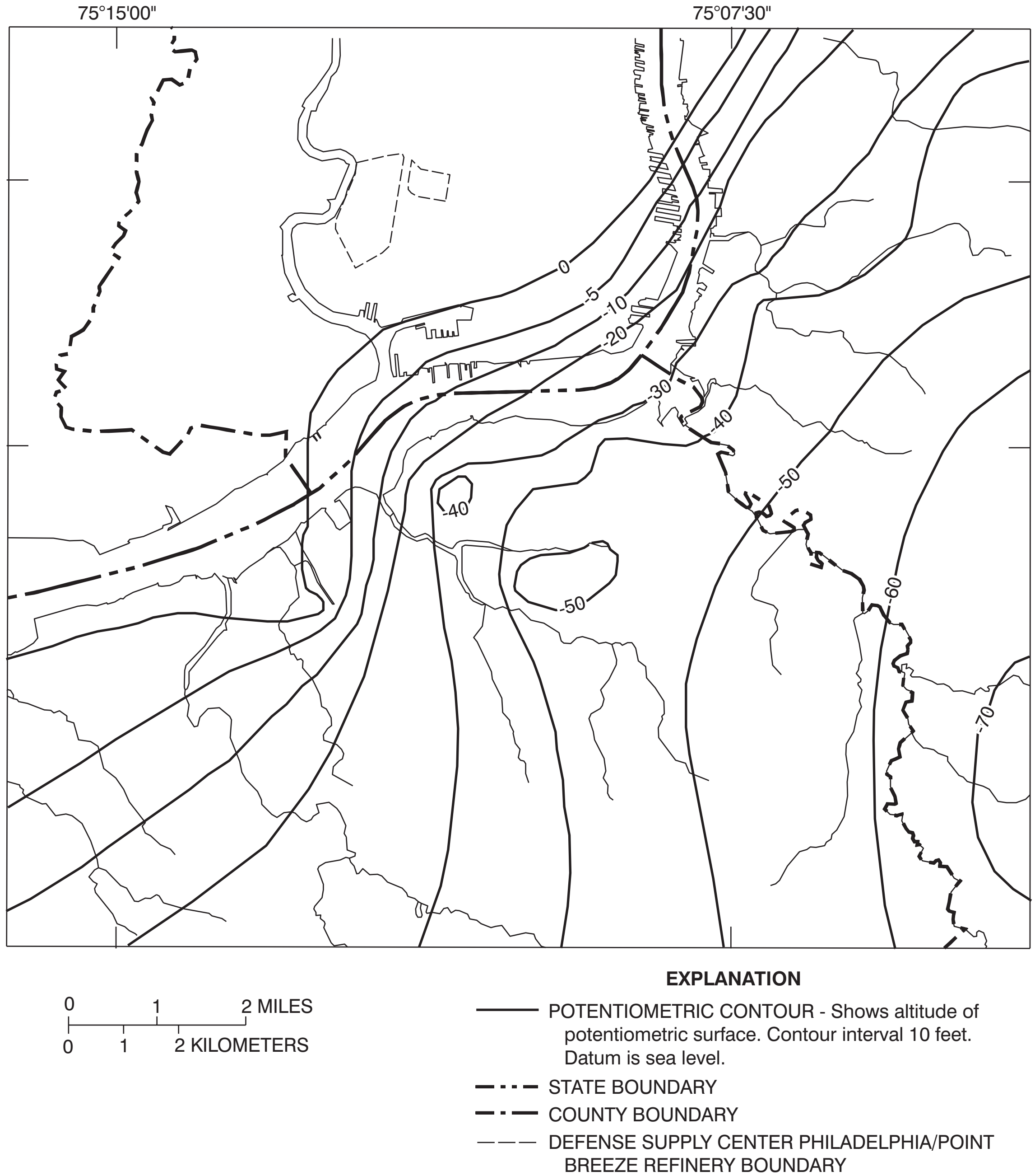


Figure 38. Potentiometric surface map of the lower sand unit, 1996 (from Rosman, 1997)

Comparison of Simulated and Measured Water-Level Hydrographs

Simulated water-level hydrographs were compared to measured water levels from wells near the DSCP/PBR area. Limited historical water-level data were available for comparison from wells Ph-32, Ph-61, Ph-77, Ph-85, and Ph-87 (fig. 39). When comparing simulated and measured hydrographs, some assumptions must be made. For this model, withdrawal rates were averaged on an annual basis. Therefore, seasonal water-level fluctuations exhibited in the hydrographs are not simulated. Measured water levels have more frequent and larger fluctuations than simulated water levels if the wells are near unknown pumping wells. On a regional basis, the effects of pumping on water-level altitudes would be insignificant, but locally, large fluctuations in water levels could occur. Also, the location of simulated water-level altitudes are at the center of the model grid cell, which most commonly does not coincide with the geographic location of the well. Starting elevation data were from the USGS DEM, not surveyed data. For example, for grid cell 15,29 containing well MW-6D, the land-surface elevation in the model cell is 22.43 ft above sea level; however, the surveyed land-surface elevation of well MW-6D is 21.45 ft above sea level.

Wells Ph-32, Ph-77, and Ph-87 are completed in the underlying crystalline rocks. Wells Ph-61 and Ph-85 are completed in the lower sand unit of the PRM. Hydrographic comparisons for the wells completed in the bedrock can be made because water levels in the crystalline rock and the unconsolidated sediments are about the same where a confining unit that lies on top of the crystalline rocks is either absent or thin (Greenman and others, 1961, p. 27-28). On the basis of available geologic logs in the DSCP/PBR area, the clay confining layer is thin. The geographic location of the wells and the corresponding grid cells are shown in figure 39.

The comparison between simulated and measured hydrographs for wells Ph-32, Ph-61, Ph-77, Ph-85, and Ph-87 are shown in figures 40 to 44, respectively. The top graph depicts the hydrograph for the entire simulation and the bottom graph focuses on the time periods when water-level data were collected. Most simulated hydrographs match the measured data to within 10 ft.

All hydrographs of measured wells show fluctuations caused by nearby withdrawals not incorporated into the model. Documented data for these withdrawals are not available, so the timing and the amount of withdrawal are unknown. These unknown withdrawals have an effect on the ground-water flow system but have not been simulated.

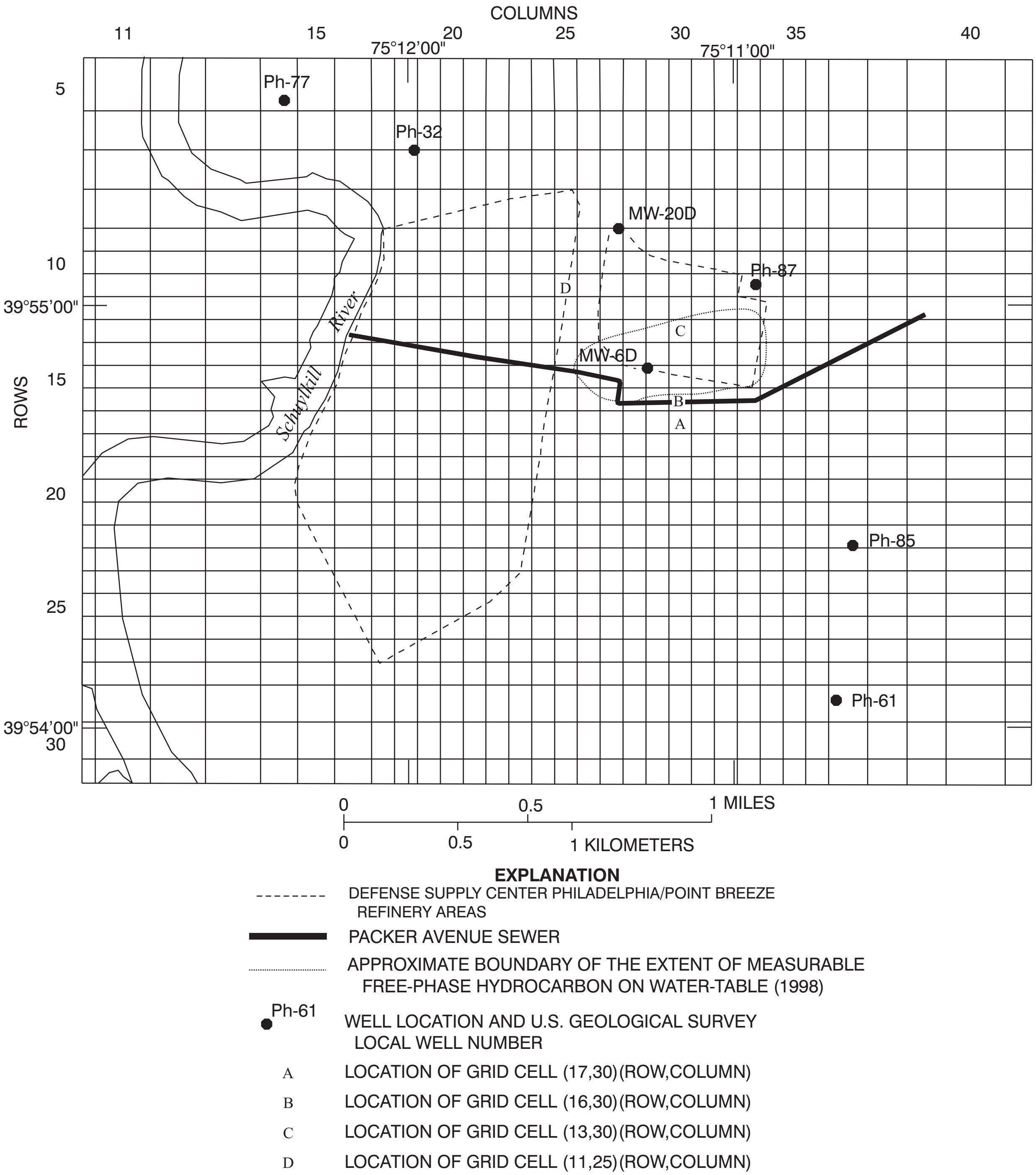


Figure 39. The Defense Supply Center Philadelphia/Point Breeze Refinery area showing selected observation wells, selected grid cell locations, and the Packer Avenue sewer.

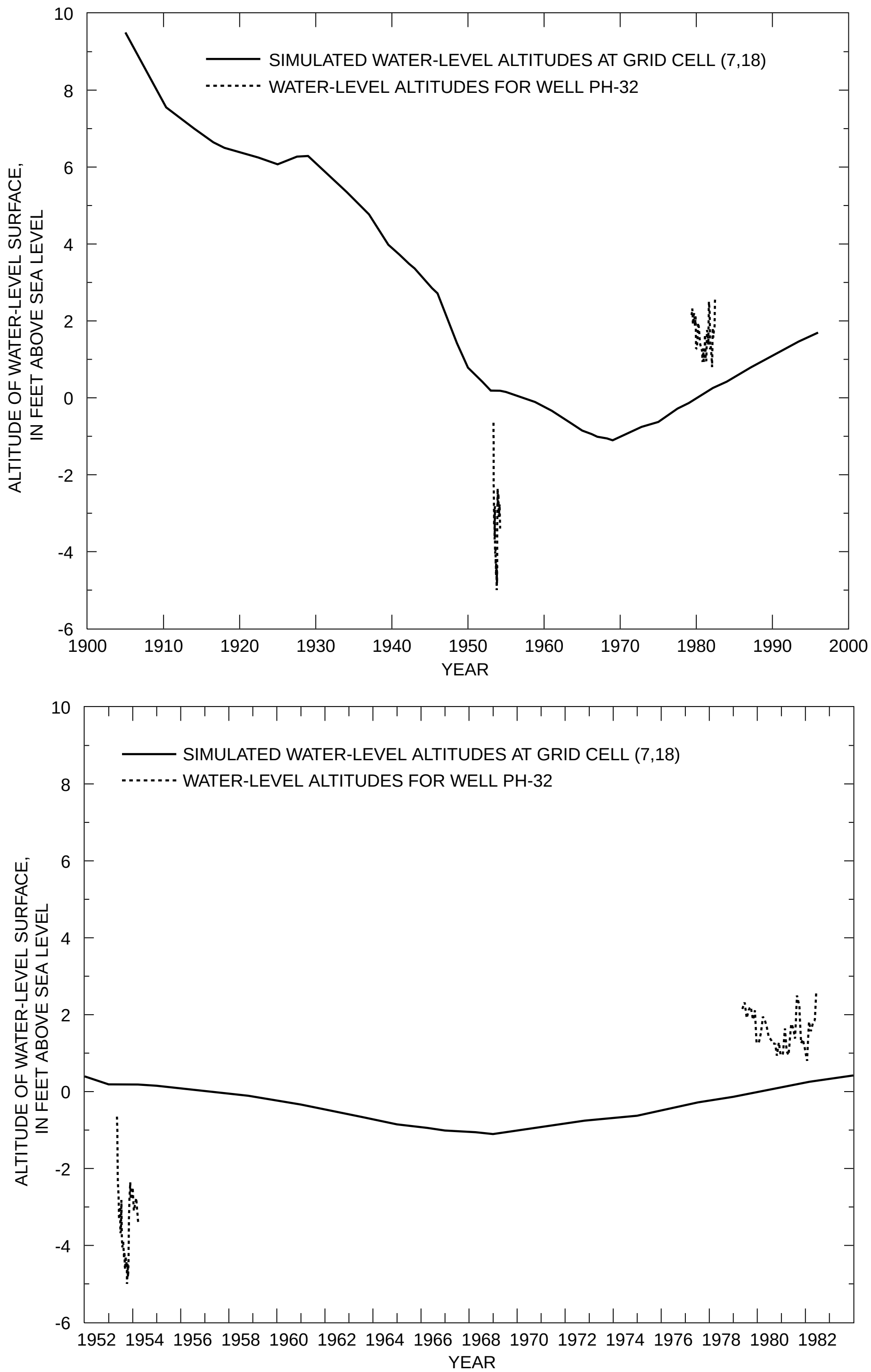


Figure 40. Simulated and measured water-level altitudes for well Ph-32.

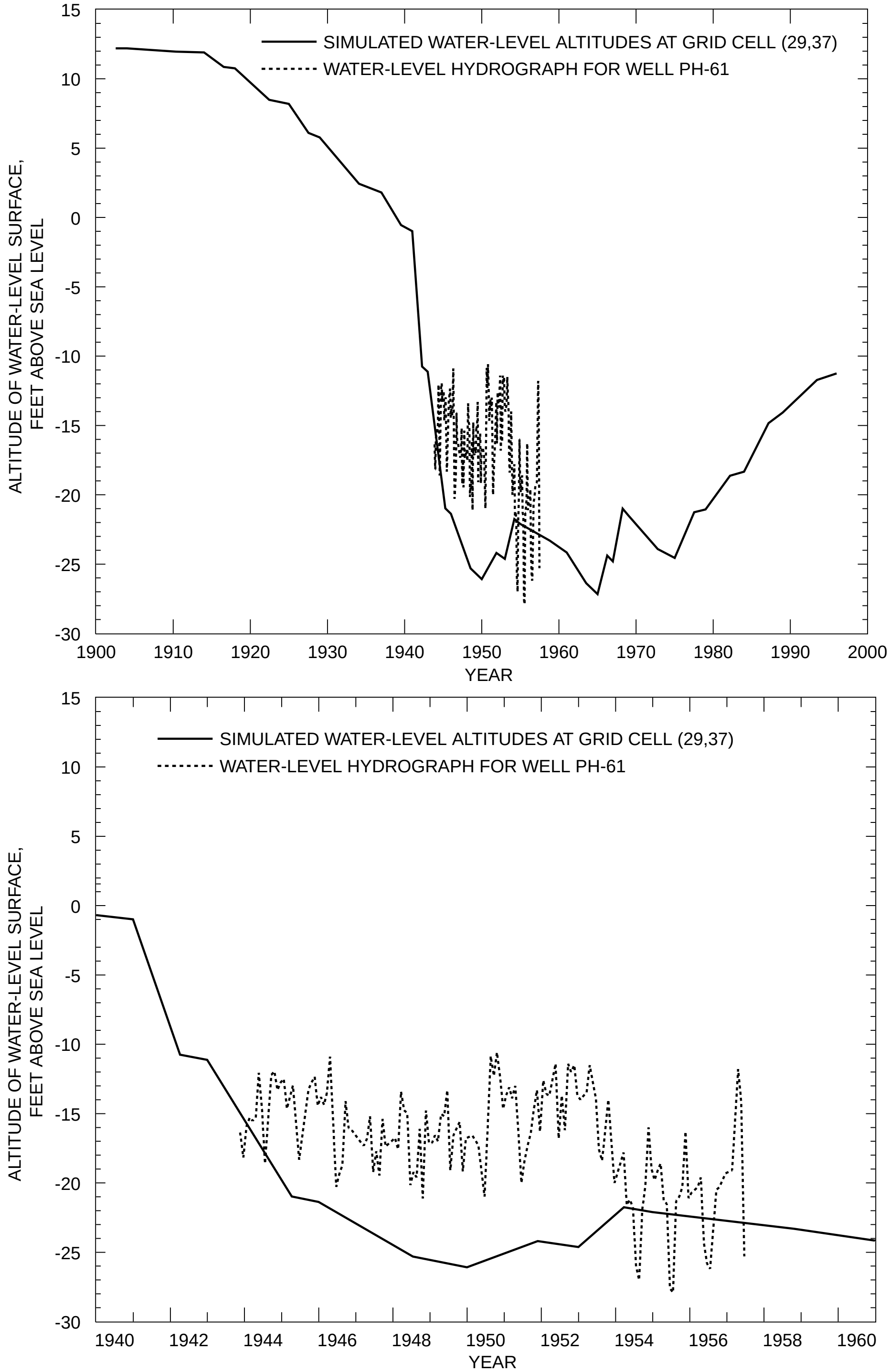


Figure 41. Simulated and measured water-level altitudes for well Ph-61.

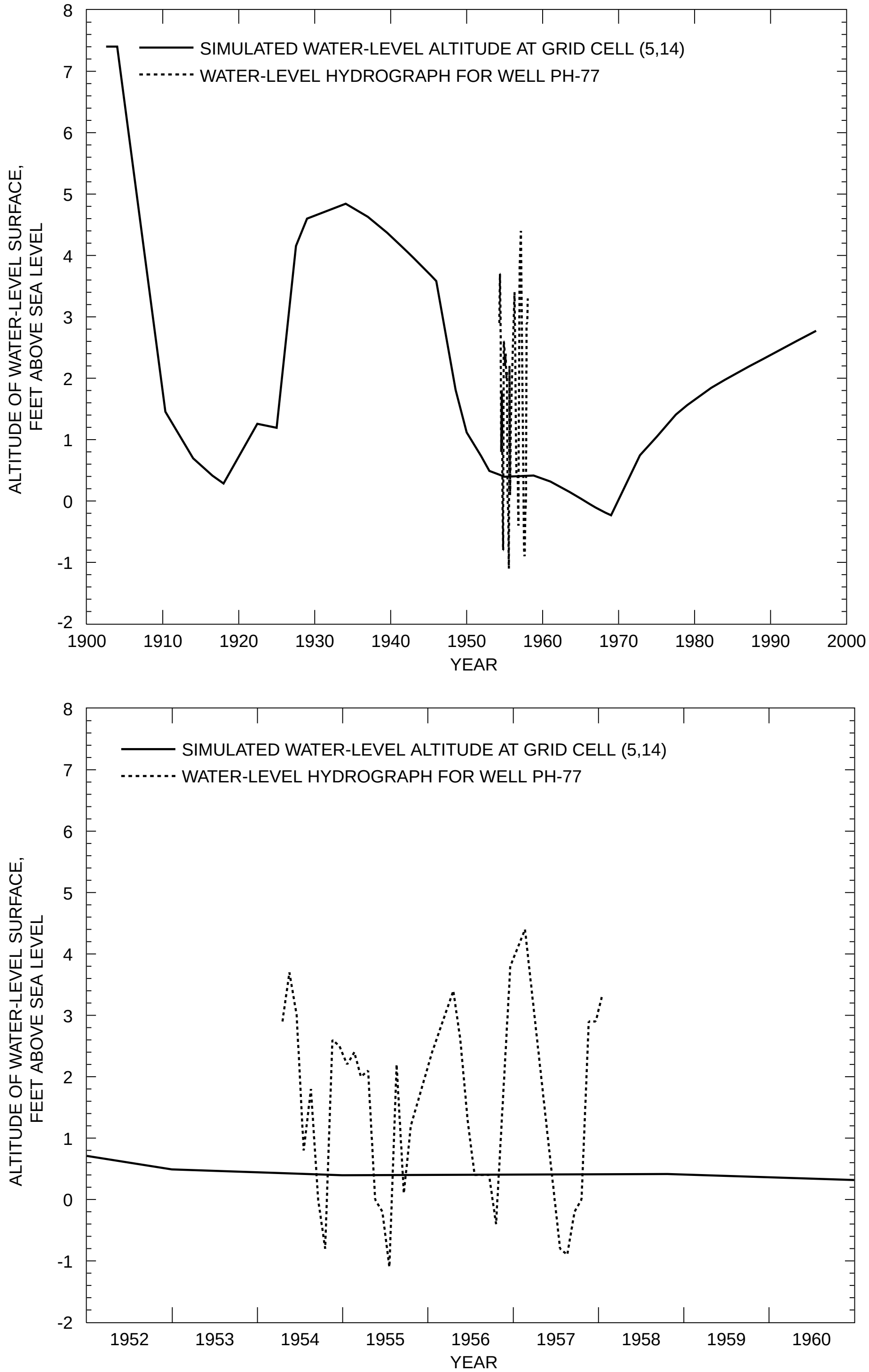


Figure 42. Simulated and measured water-level altitudes for well Ph-77.

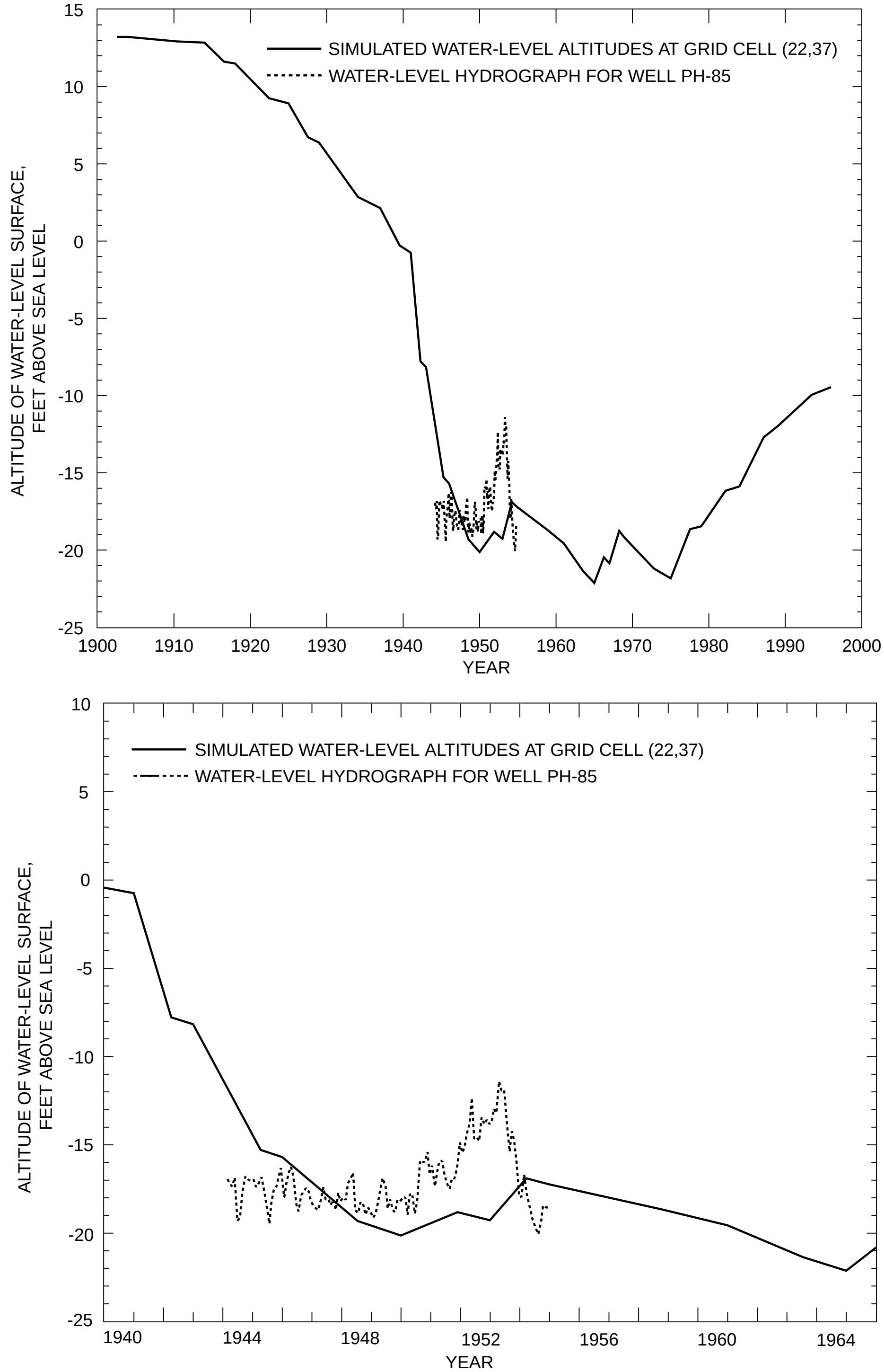
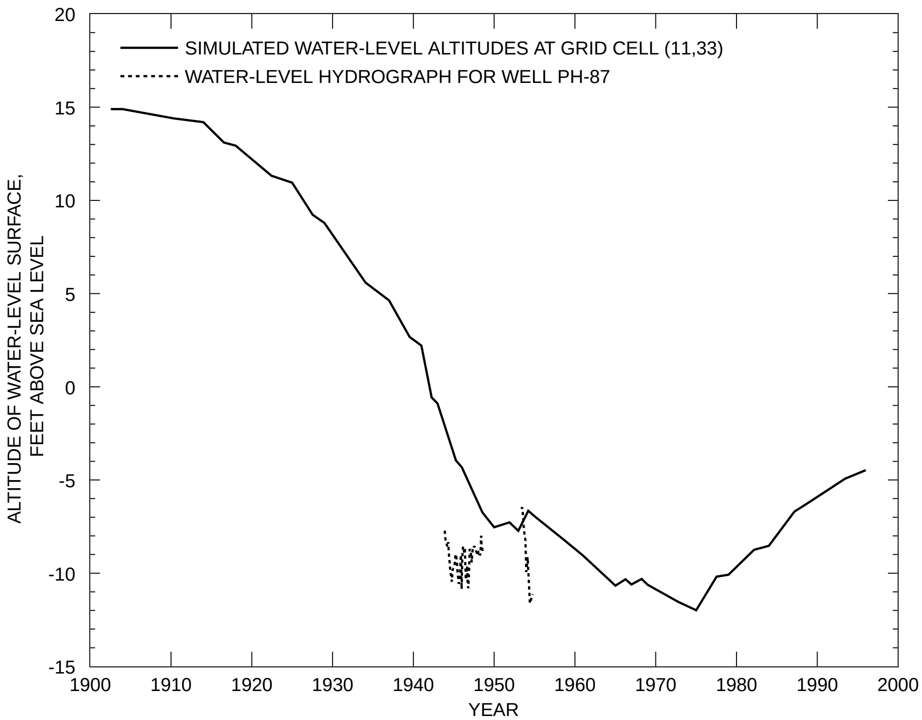


Figure 43. Simulated and measured water-level altitudes for well Ph-85.



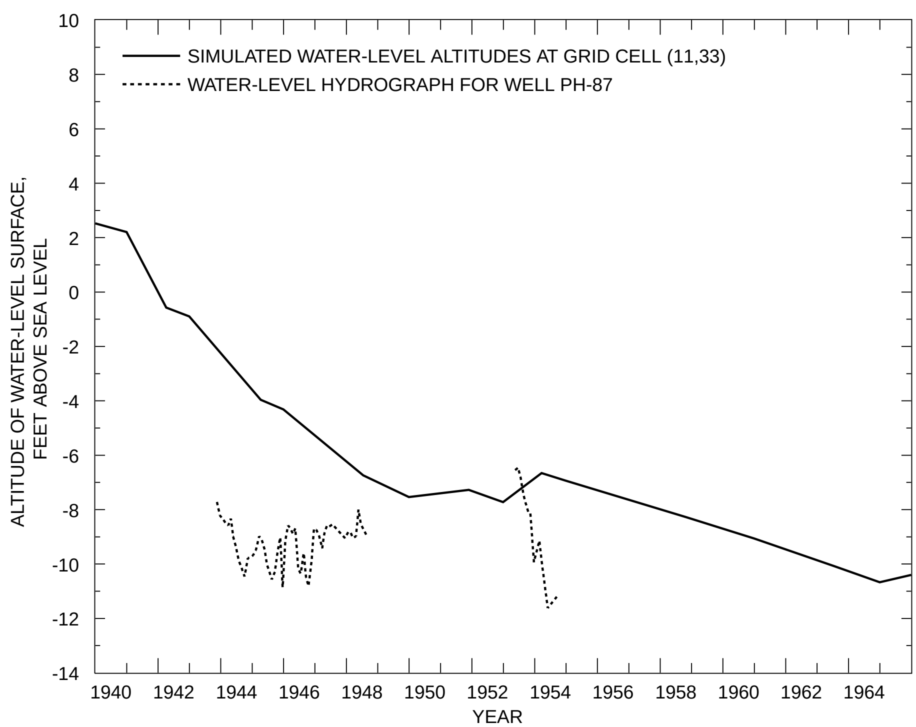


Figure 44. Simulated and measured water-level altitudes for well Ph-87.

SIMULATED WATER-LEVEL ALTITUDES IN THE DSCP/PBR AREA

The ground-water-flow system in the Defense Supply Center, Philadelphia, and the Point Breeze Refinery area was simulated in order to use the model results to estimate water-level altitudes in and near the area of concern and to determine the effect the Packer Avenue sewer may have had on water levels and hydrocarbon plume migration. The apparent location of the hydrocarbon plume in the area of concern is shown on figure 39. In comparing simulated water-level altitudes to altitudes of residual hydrocarbon-stained soils, a range in years of possible hydrocarbon release times can be deduced.

An assumption is made that the simulated water-level altitudes in layer 7 closely represent water-level altitudes of the actual water-table surface. The assumption is valid because the intervening confining units between the water-table aquifer and the lower sand unit are not continuous near the area of concern. Geologic logs from wells MW-6D and MW-20D show no distinct, continuous confining clay near the area of concern. Well MW-6D was drilled to 88 ft below land surface (-66.55 ft below sea level). Well MW-20D was drilled to 92 ft below land surface (-66.20 ft below sea level). Locally, clay layers or lenses are present but are discontinuous. From a regional perspective, however, the alluvial aquifer may lie directly on the lower sand unit, and water-level altitudes in the alluvial aquifer could be reasonably represented by simulated water-level altitudes in the lower sand unit (layer 7).

The author estimated water-level altitudes in the lower sand unit (layer 7) near the area of concern from all available historical measured water levels for time periods prior to 1945, 1946-54, 1955-68, and 1969-78 (fig. 45). This was done in order to determine the timing of the maximum depth to water near the area of concern and relate that to the maximum depth of the residual hydrocarbon smear zone detected below the current (2001) water table.

The author estimated water-level altitudes prior to 1945 ranged from slightly less than 8 ft below sea level to 11 ft below sea level, from 1946 to 1954 ranged from 7 to 12 ft below sea level, from 1955 to 1968 ranged from 7 to 14 ft below sea level, and from 1969 to 1978 ranged from 2 to 8 ft below sea level.

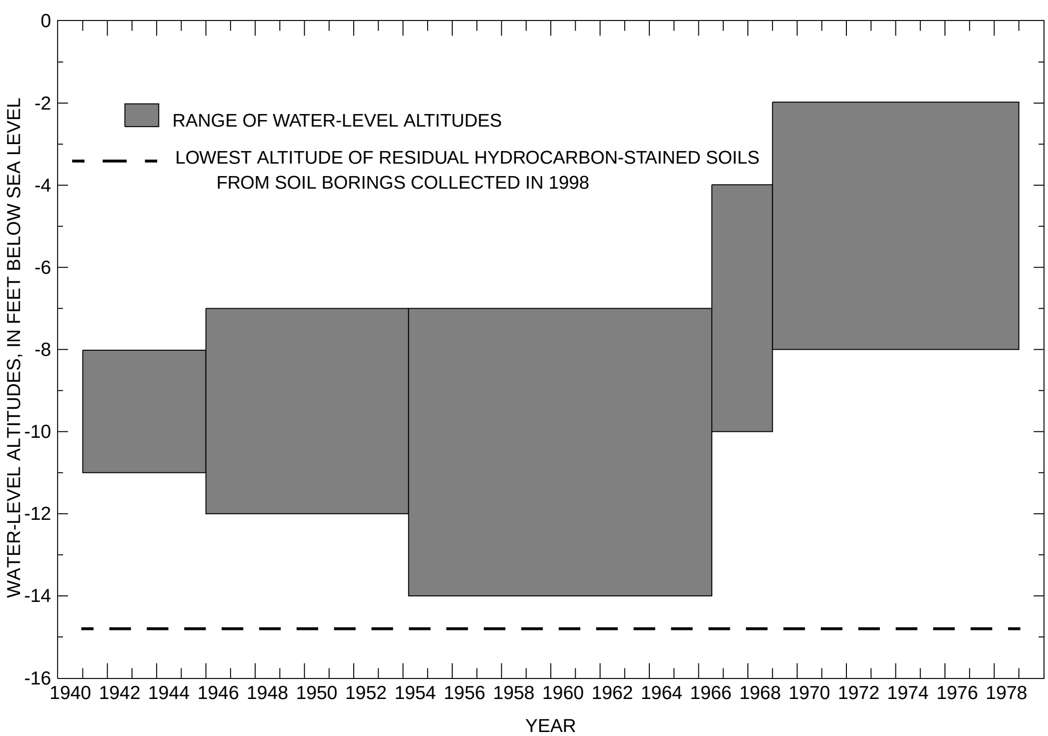


Figure 45. Range in water-level altitudes for time periods January 1941–December 1945, January 1946–March 1954, April 1954–April 1966, May 1966–December 1968, and January 1969–December 1978 in the Defense Supply Center Philadelphia, Point Breeze Refinery, and Passyunk Housing Development area, south Philadelphia, Pennsylvania.

Simulated water-level altitudes in model layers 1 and 7 near the center of the DSCP represented by grid cell 13,30 are shown on figure 46. Grid cell 13,30 is shown as location C on figure 39. Simulated water-level altitudes for layer 1 mimicked simulated water-level altitudes in layer 7, but they consistently were 3 to 5 ft higher in altitude. Simulated water-level altitudes for layer 7 prior to 1945 ranged from pre-development unstressed levels to 3 ft below sea level. Simulated water-level altitudes for layer 7 from 1946 to 1954 ranged from 3 to 7 ft below sea level, from 1955 to 1968 ranged from 6 to 10 ft below sea level, and from 1969 to 1978 ranged from 9 to 11 ft below sea level. The lowest water-level altitude, 10.69 ft below sea level, was during 1969-78, roughly near the end of 1974. The lowest altitude of residual hydrocarbon-stained soils on the DSCP property is 14.88[1] ft below sea level. Assuming that the lowest altitude of hydrocarbon staining occurred when water levels were lowest, some release of hydrocarbon had to occur prior to the end of 1974. The simulated hydrographs on figure 46 show the head in layer 7 (at cell 13,30) to be consistently below the head in layer 1, which indicates downward vertical ground-water-flow gradients.

Simulated water-level altitudes between the DSCP and PBR represented by grid cell 11,25 also are shown on figure 46. Grid cell 11,25 is shown as location D on figure 39. Simulated water-level altitudes for layer 7 prior to 1945 ranged from pre-development unstressed levels to 0.5 ft below sea level, from 1946 to 1954 ranged from 0.5 to 3.5 ft below sea level, from 1955 to 1968 ranged from 3 to 6 ft below sea level, and from 1969 to 1978 ranged from 5 to 6.5 ft below sea level. The lowest water-level altitude, 6.18 ft below sea level, was during 1969-78, roughly near the end of 1974.

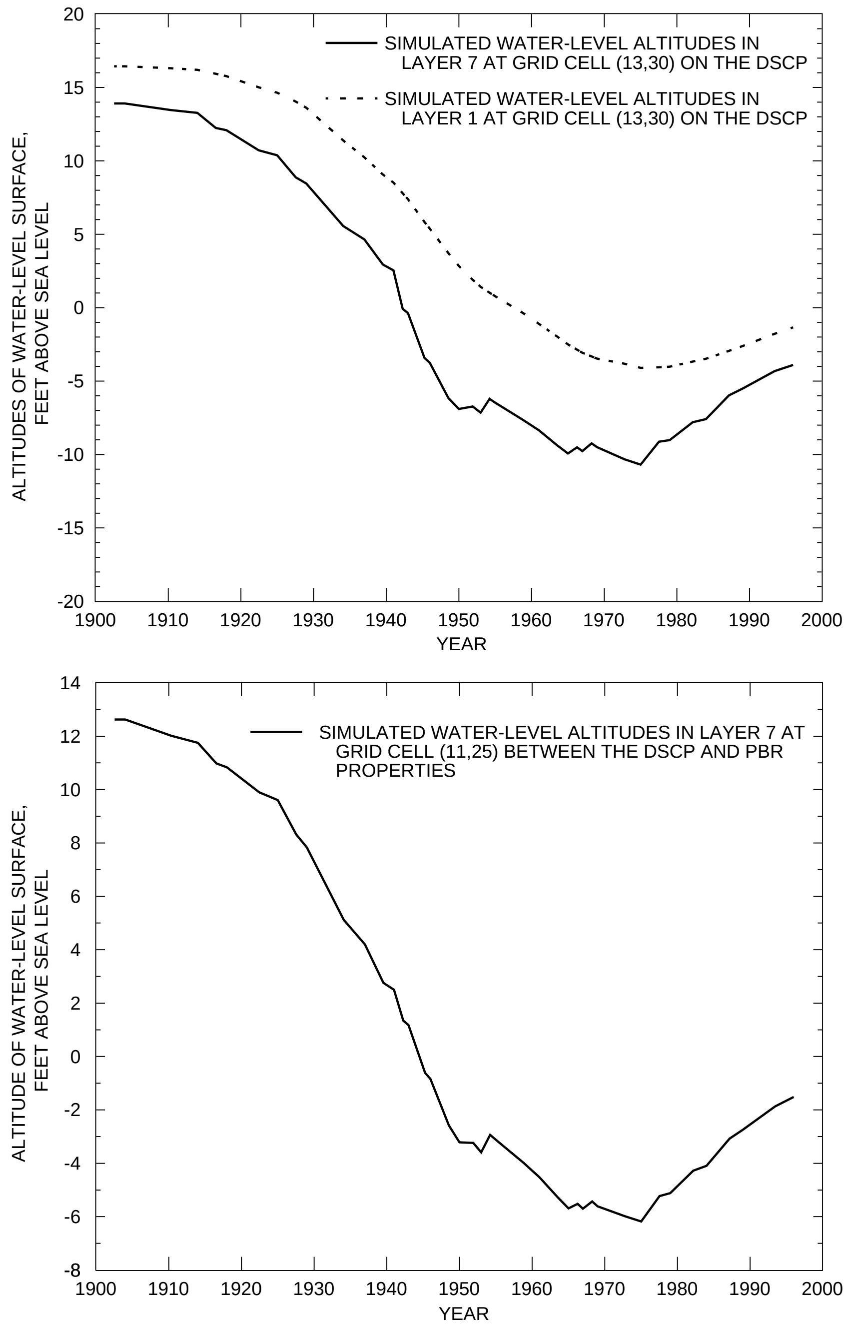


Figure 46. Simulated water-level altitudes in layers 1 and 7 for model grid cells row 13, column 30 on the Defense Supply Center Philadelphia property and in layer 7 row 11, column 25 between the Defense Supply Center Philadelphia and Point Breeze Refinery properties.

[1] Source of data Sun Company, Inc., 1998, Technical third party neutral, empirical data request, May 1998.

Simulation of Packer Avenue Sewer and its Effect on Water Levels

The Packer Avenue sewer is important because if water-level altitudes are lower than the bottom of the sewer then any NAPL floating on the ground-water surface could migrate under the sewer. If water-level altitudes are higher than the bottom of the sewer, however, ground water can infiltrate the sewer and the sewer can be a barrier to hydrocarbon plume movement. The Packer avenue sewer is a 12-ft wide by 8-ft high concrete box culvert that was constructed in the early 1920's. Hydrocarbon vapors have been detected in the Packer Avenue sewer, and NAPL has been observed infiltrating into the sewer in the area just south of the DSCP (D. Burke, Pennsylvania Department of Environmental Protection, written commun., March 12, 1997). On March 11, 1997, Philadelphia Water Department personnel walked through the sewer in the area just south of the DSCP and NAPL was observed infiltrating the sewer along the north facing sewer wall at the floor of the sewer.

The sewer was simulated in the model by use of the drain package in MODFLOW-2000. Twenty-five point drains were used to simulate the sewer. The location of the sewer with respect to the area of concern is shown on figure 39. Point drains were used in order to change the bottom elevation of the sewer as it traversed from east to west. The grid-cell location, conductance, and bottom altitude of the point drains are summarized in table 6.

Simulated water-level altitudes for layers 1 and 7 at grid cells 16,30 and 17,30 are shown on figure 47. The locations of grid cells 16,30 and 17,30 are shown as locations B and A, respectively, on figure 39. The simulated water-level altitude in layer 7 was lower than the bottom of the sewer starting in 1943. The simulated water-level altitude in layer 1 was lower than the bottom of the sewer starting in 1957.

If the simulated water-level altitude of layer 7 closely represents the actual water-table altitude, then the time when water-table altitudes were below the sewer would be nearer to 1943 than 1957. A conservative estimate of the year when water-table altitudes receded below the bottom of the sewer would be sometime around 1947 or 1948. Therefore, the water-table altitude was below the Packer Avenue sewer from approximately 1947 or 1948 through 1995.

Table 6. *Summary of point drain locations, conductances, and bottom altitudes*

Grid cell (row,col)	Conductances (meters)	Altitude drain bottom	
		meters	feet
12,39	0.6999	0.56596	1.8568
13,38	2.651	.48324	1.5824
14,37	2.803	.40	1.3123
15,36	1.37	.3178	1.0426
15,35	1.638	.23511	.77135
16,34	1.424	.1524	.50
16,33	1.497	.10885	.3571
16,32	1.46	.06536	.21443
16,31	1.46	.02177	.07142
16,30	1.46	-.02177	-.07142
16,29	1.46	-.0653	-.2142
16,28	1.46	-.10885	-.3571
16,27	1.399	-.1524	-.50
15,27	1.693	-.1624	-.5328
15,26	1.495	-.22058	-.7237
15,25	1.476	-.2787	-.9148
15,24	1.457	-.3369	-1.1053
14,23	1.476	-.3951	-1.2962
14,22	1.476	-.4533	-1.4872
14,21	1.479	-.5115	-1.678
14,20	1.482	-.5696	-1.8687
14,19	1.482	-.6278	-2.059
14,18	1.482	-.686	-2.25
13,17	1.357	-.7442	-2.442
13,16	1.446	-.8024	-2.632

Because historical ground-water-flow directions were predominately to the southeast, the Packer Avenue sewer would have been a barrier to hydrocarbon plume migration to the southeast from 1900 to 1947. Subsequent to 1947 through 1995 the hydrocarbon plume could have been migrating to the southeast, unimpeded by the sewer. Also, the simulated hydrographs on figure 47 show the consistent lower head in layer 7 (compared to layer 1) at cells 16,30 and 17,30, which indicates downward vertical ground-water-flow gradients.

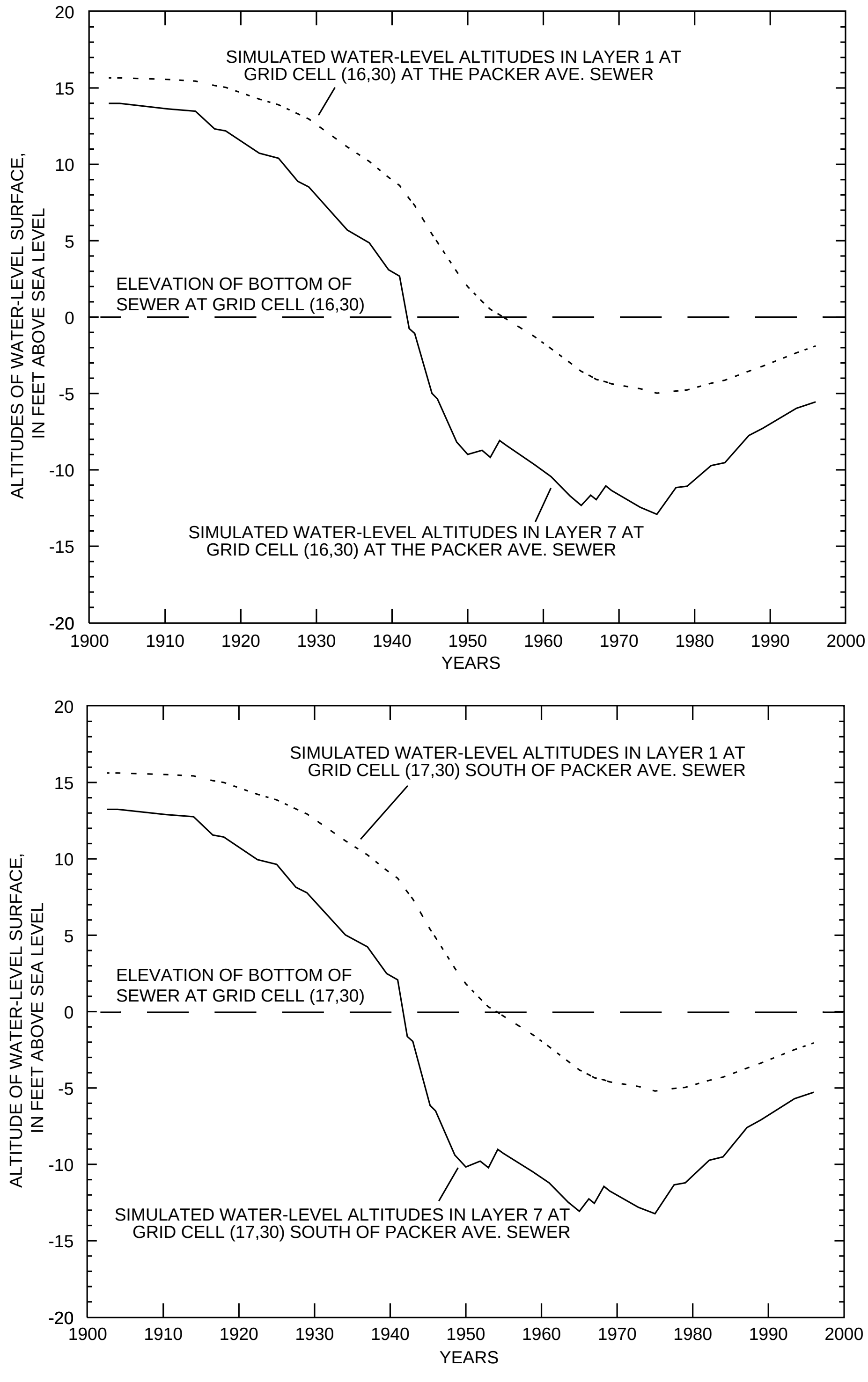


Figure 47. Simulated water-level altitudes in layers 1 and 7 for model grid cells row 16, column 30 and row 17, column 30 near the Packer Avenue sewer.

SUMMARY

The Potamac-Raritan-Magothy (PRM) aquifer system in south Philadelphia historically has been a major water-supply source in the south Philadelphia region. The Philadelphia Naval Shipyard and other industries in the area withdrew large amounts of water from the PRM for day-to-day operations in the past. A result of this past development in the area is that the ground-water quality of the PRM aquifer system has been degraded. Some degradation in the upper part of the aquifer is the result of numerous hydrocarbon plumes. Since the early 1990's, the Pennsylvania Department of Environmental Protection (PaDEP) has been overseeing investigations of multiple localized hydrocarbon plumes floating on the water-table surface in the south Philadelphia area. Although localized NAPL is a major concern, a more regional look at the entire area was needed to assess problems. The U.S. Geological Survey was tasked with assessing the historical ground-water-flow system using a more regional perspective while also focusing on an area of concern for the PaDEP near the Point Breeze Refinery and the Defense Logistics Agency's Defense Supply Center, Philadelphia.

The ground-water-flow system of the PRM in south Philadelphia and adjacent southwestern New Jersey was simulated by use of a 3-dimensional, 7-layer finite-difference numerical flow model. The simulation was run from 1900, prior to ground-water development, through 1995. The modeled area comprised parts of Philadelphia and Delaware Counties in Pennsylvania and Gloucester and Camden Counties in New Jersey. In order to adequately simulate the ground-water-flow system in the area of concern, a much larger area was modeled that included parts of New Jersey where significant ground-water withdrawals affecting water levels in south Philadelphia occurred in the past. At issue in an area of concern is a current (2001) hydrocarbon plume of unknown origin with an unknown time of release.

The ground-water flow system was simulated to estimate past water-level altitudes in and near the area of concern and to determine the effect of the Packer Avenue sewer, which lies south of the DSCP, on the ground-water-flow system. The model was calibrated to match five potentiometric-surface maps of the lower sand unit for 1945, 1954, 1968, 1978, and 1996.

Simulated water-level altitudes from the model for the lower sand unit of the PRM on the DSCP ranged from pre-development, unstressed altitudes to 3 feet below sea level prior to 1945, from 3 to 7 feet below sea level from 1946 to 1954, from 6 to 10 feet below sea level from 1955 to 1968, and from 9 to 11 feet below sea level from 1969 to 1978.

The lowest simulated water-level altitude on the DSCP, 10.69 ft below sea level, occurred near the end of 1974. The lowest altitude of residual hydrocarbon-stained soil on the DSCP is approximately 15 ft below sea level. Thus, if the lowest altitude of hydrocarbon staining were coincident with the lowest water levels, a hydrocarbon plume must have been present prior to the end of 1974.

Model simulations indicate that ground water in layer 7 was infiltrating the Packer Avenue sewer prior to approximately 1943, and ground water in layer 1 was infiltrating prior to approximately 1957. Assuming that simulated water-level altitudes in layer 7 closely represent actual water-table altitude at the sewer because of the absence of intervening confining layers, a conservative estimate of the year when altitudes were below the sewer would be 1947 or 1948. Because the historical ground-water-flow directions were predominately to the southeast, the Packer Avenue sewer would have been a barrier to hydrocarbon plume migration to the southeast from 1900 to 1947. Subsequent to 1947 through 1995, the hydrocarbon plume would be migrating to the southeast unimpeded by the sewer.

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