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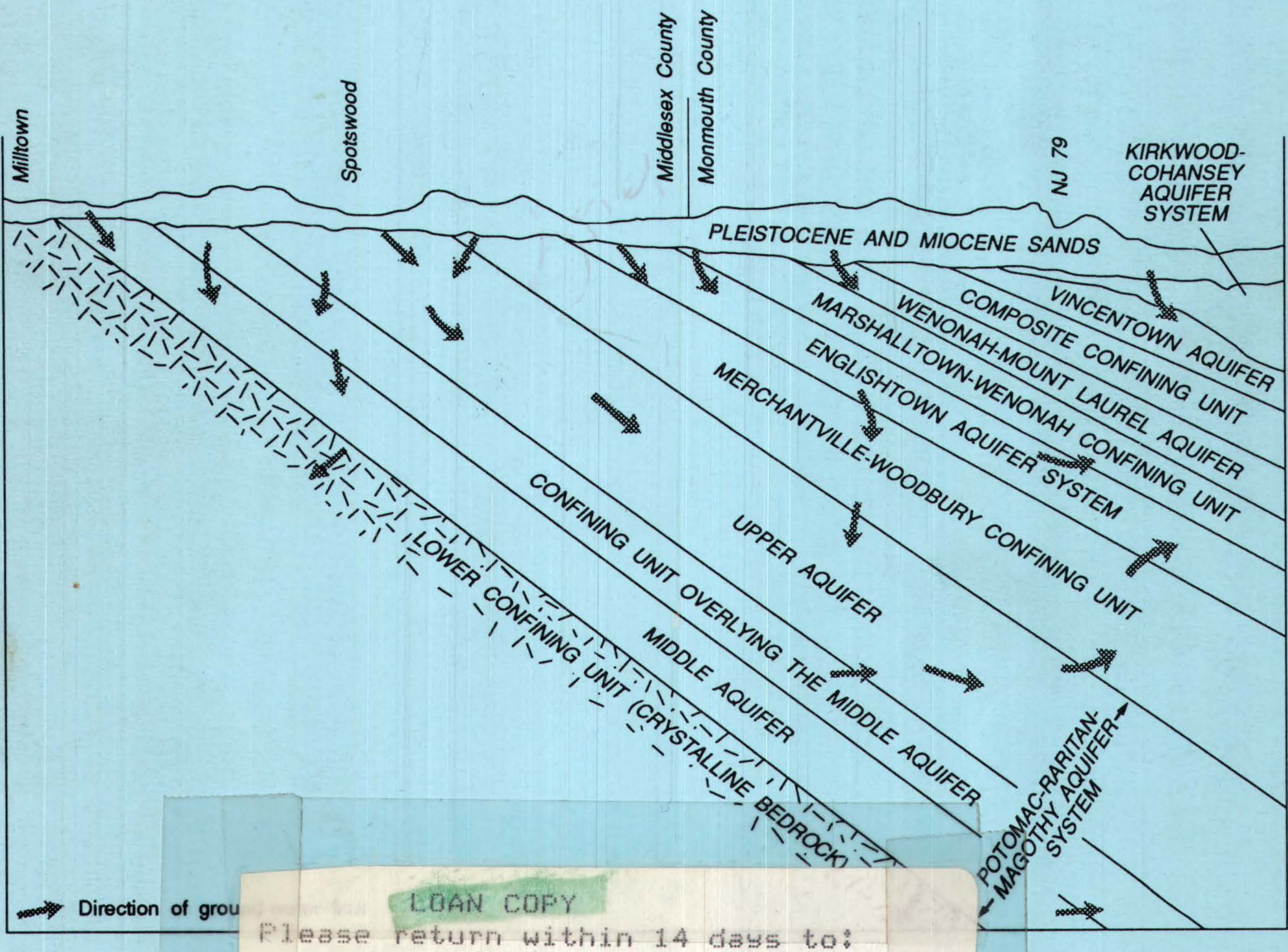
Geological Survey Report GSR 36

HYDROGEOLOGY, SIMULATION OF REGIONAL GROUND-WATER FLOW, AND SALTWATER INTRUSION, POTOMAC-RARITAN-MAGOTHY AQUIFER SYSTEM, NORTHERN COASTAL PLAIN OF NEW JERSEY



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Cover illustration: Diagrammatic cross section through the hydrogeologic units in the Northern Coastal Plain of New Jersey showing directions of water movement. Not to scale. Vertical scale greatly exaggerated.

New Jersey Geological Survey
Geological Survey Report GSR 36

Hydrogeology, Simulation of Regional Ground-Water Flow, and Saltwater Intrusion, Potomac-Raritan-Magothy Aquifer System, Northern Coastal Plain of New Jersey

by
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Prepared by the United States Geological Survey
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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
inch (in.)	2.54	centimeter
inch per year (in/yr)	2.54	centimeter per year
foot (ft)	0.3048	meter
foot per mile (ft/mi)	0.1894	meter per kilometer
foot per day (ft/d)	0.3048	meter per day
foot per year (ft/yr)	0.3048	meter per year
foot squared per day (ft^2/d)	0.0929	meter squared per day
acre	43,560	feet squared
cubic foot per second (ft^3/s)	0.3048	cubic meter per second
foot per day per foot ((ft/d)/ft)	1.00	meter per day per meter
gallon per minute (gal/min)	0.06309	liter per second
gallons per acre per day	3.7854	liter per acre per day
million gallons (Mgal)	3,785	cubic meter
million gallons per day (Mgal/d)	3,785	cubic meter per day
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

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.

Abbreviated water-quality units used in report:

Chemical concentrations, specific conductance, and water density are given in metric units. Chemical concentration is given in milligrams per liter (mg/L) or micrograms per liter ($\mu g/L$). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million.

Specific conductance of water is expressed in microsiemens per centimeter at 25 degrees Celsius (μS/cm). This unit is identical to micromhos per centimeter at 25 degrees Celsius, formerly used by the U.S. Geological Survey.

Water density is given in grams per milliliter (g/mL).

HYDROGEOLOGY, SILMULATION OF REGIONAL GROUND-WATER FLOW, AND SALTWATER INTRUSION, POTOMAC-RARITAN-MAGOTHY AQUIFER SYSTEM, NORTHERN COASTAL PLAIN OF NEW JERSEY

by Amleto A. Pucci, Jr., Daryll A. Pope, and JoAnn M. Gronberg

ABSTRACT

The Potomac-Raritan-Magothy aquifer system in Middlesex and Monmouth Counties in the northern Coastal Plain of New Jersey consists primarily of unconsolidated Cretaceous sediments, which are divided into the upper and middle aquifers and confining units. These units, which strike northeast-southwest along the Fall Line, dip and thicken to the southeast. The upper aquifer consists primarily of the Old Bridge Sand Member of the Magothy Formation, which is composed of coarse-grained sands, localized thin clay beds, and younger surficial sands and gravels in and near the outcrop. Transmissivity ranges from 1,760 to 19,400 ft^2/d (feet squared per day) and tends to be higher in updip areas. Estimated withdrawals from the upper aquifer in the northern Coastal Plain were approximately 42 Mgal/d (million gallons per day) in 1986. Cones of depression whose centers range from 36 to 42 ft (feet) below sea level have developed as a result of these withdrawals.

The upper aquifer is confined throughout most of the northern New Jersey Coastal Plain by clays and silts of the Cretaceous Woodbury Clay and Merchantville Formation and younger sediments of the Magothy Formation. This confining unit generally is greater than 200 ft thick. The simulated vertical hydraulic conductivity for the confining unit ranges from 8.4×10^{-5} to 5.6×10^{-3} feet per day; interpreted vertical hydraulic conductivities generally are lower except in southwestern Middlesex County, where the vertical hydraulic conductivities of the confining unit are higher.

The middle aquifer consists primarily of the Farrington Sand Member of the Cretaceous Raritan Formation and surficial Holocene and Miocene sands and gravels in its outcrop area. It also can include the uppermost sands of the Cretaceous Potomac Group in parts of Monmouth County. The middle aquifer is composed of fine to coarse sand that contains some lignite and pyrite, and, locally, some clay beds. It pinches out in the northern part of Sayreville Township, near Raritan River. The transmissivity of the aquifer ranges from 2,140 to 13,800 ft^2/d and tends to decrease in the northern part of the northern Coastal Plain of New Jersey where the aquifer thins. A poorly permeable confining unit composed mostly of clays and silts of the Woodbridge Clay Member of the Raritan Formation overlies the aquifer in most of this area. The confining unit generally is greater than 100 ft thick, although it thins and is sandy in the southwestern part of Middlesex County, where a good hydraulic connection exists between the middle and upper aquifers. Estimated withdrawals from the middle aquifer in the northern Coastal Plain were about 22 Mgal/d in 1986. These withdrawals have caused cones of depression whose centers range from 77 to 93 ft below sea level.

A finite-difference, quasi-three-dimensional ground-water flow model was developed to simulate ground-water flow in the aquifer system. The confined and unconfined areas of the upper and middle aquifers were modeled as separate layers. The model was calibrated primarily by adjusting vertical hydraulic conductivity in the confining units and horizontal hydraulic conductivity in the aquifers, then matching simulated and measured ground-water levels for the period 1896-1986 and simulated and interpreted potentiometric surfaces under predevelopment conditions and in 1984.

For the predevelopment period, the total flow into and out of the upper and middle aquifers is 35 and 21 Mgal/d, respectively. Recharge to the aquifer system is from direct recharge in the unconfined areas and from vertical leakage through overlying confining units. The main recharge areas are the topographically high areas in southwestern Middlesex County for both aquifers, in the eastern Sayreville area for the upper aquifer, and north of the Raritan River for the middle aquifer. Most ground water discharges to low-lying regional surface-water drains (streams), which flow into the South River.

For 1984 transient conditions, the total ground-water flow into and out of the upper and middle aquifers is 61 and 34 Mgal/d, respectively. The largest amount of recharge is from direct recharge in the unconfined areas, but some recharge also is derived from vertical leakage through the Merchantville-Woodbury confining unit, captured ground-water discharge to streams, and induced inflow at artificial-recharge facilities. Regional flow is from recharge areas toward major cones of depression.

Sensitivity analysis showed that the model was useful for representing flow in the system, especially in the confined-aquifer areas. Model representation of lateral and vertical boundary conditions was judged acceptable. Simulation results were less sensitive to changes in aquifer properties in the unconfined areas of the aquifers and to changes in storage in the confining units. Sensitivity analysis and calibration of hydraulic parameters and conditions showed that the distribution of hydraulic head was sensitive to changes in horizontal hydraulic conductivity in the aquifers, vertical hydraulic conductivity in the confining units, magnitudes of ground-water withdrawals, and initial hydraulic head in aquifer outcrop areas.

Two scenarios were simulated to determine the effects of ground-water withdrawals from 1986 through 2019. For the scenario in which ground-water withdrawals increase to about 69 Mgal/d in the upper aquifer and 37 Mgal/d in the middle aquifer, centers of cones of depression are as deep as 100 ft below sea level in the upper aquifer and 170 ft below sea level in the middle aquifer. For this scenario, most of the additional water comes from captured surface-water discharge, induced cross-formational flow from overlying aquifers, and increases in induced flow from artificial-recharge areas. Induced flow from Raritan Bay also increases. For the scenario in which ground water withdrawals are reduced to 42.5 Mgal/d in the upper aquifer and 15 Mgal/d in the middle aquifer, water levels recover to above sea level nearly everywhere. In each aquifer, ground-water discharge to streams increases and induced flow through the confining units and from the overlying sediments decreases, and discharge of ground water to Raritan Bay in the upper aquifer exceeds the induced recharge from Raritan Bay.

Reversal of ground-water gradients has caused saltwater intrusion in the two aquifers. Chloride concentrations in water from the upper aquifer in Keyport and Union Beach Boroughs were as high as 2,100 mg/L (milligrams per liter) in 1986. The intrusion has not increased significantly since well fields in the area were closed in the late 1970's. Elevated chloride concentrations also were measured in Keanesburg Borough in 1986. In both of these areas, saltwater has entered the upper aquifer from the Bay because of movement of the freshwater-saltwater interface in response to increasing ground-water withdrawals.

Chloride concentrations in well-water samples from the middle aquifer were as high as 6,000 mg/L in Sayreville Borough in 1987; concentrations in samples from drive-point wells from the same aquifer near the Washington Canal, the main source of saltwater, were as high as 7,100 mg/L. The migration of the saltwater front at about 470 feet per year to the southeast is influenced mainly by a thinning of the middle aquifer, which constrains flow, and by the locations of regional cones of depression caused by ground-water withdrawals.

INTRODUCTION

The first wells through which water was withdrawn from the Potomac-Raritan-Magothy aquifer system in Middlesex and Monmouth Counties in the northern Coastal Plain were drilled in the late 1800's. Since that time, ground-water use generally has increased. The Potomac-Raritan-Magothy aquifer system is the major source of ground-water supply in the northern Coastal Plain of New Jersey. In 1989, this aquifer system supplied about 95 percent of the potable ground water used in Middlesex County and about 76 percent of ground-water supply in Monmouth County, where shallower, less productive aquifers also are used as a source of water.

This historical increase in ground-water withdrawals from the aquifer system has caused water levels to decline and saltwater to intrude from Raritan Bay and its estuaries into the aquifer system. Ground-water withdrawals have caused cones of depression whose centers exceeded depths of 90 ft below sea level in the middle aquifer and 40 ft below sea level in the upper aquifer by 1986. Measured chloride concentrations were as high as 6,000 mg/L in well-water from the middle aquifer in 1987 and 2,100 mg/L in water from the upper aquifer in 1986.

An extensive data base and a thorough understanding of this complex aquifer system, particularly its response to ground-water withdrawals, are critical to ensure the long-term availability of ground water in the study area. Until the initiation of this study, information on the Potomac-Raritan-Magothy aquifer system within Middlesex and Monmouth Counties was incomplete and scattered. For these reasons, the New Jersey Department of Environmental Protection and Energy targeted this area for an intensive 5-year study. This study, done by the U.S. Geological Survey in cooperation with the New Jersey Department of Environmental Protection and Energy, was funded by the New Jersey Water Supply Bond Issue of 1981 and 1983. The study was designed to collect and analyze hydrogeologic data in an effort to develop an understanding of the dynamics of the Potomac-Raritan-Magothy aquifer system in an area of approximately 600 mi^2 in the northern Coastal Plain of New Jersey.

Purpose and Scope

This report presents data on, and interpretations of, the hydrogeology and hydraulic properties of, ground-water withdrawals from, and ground-water flow and intrusion of saltwater in the Potomac-Raritan-Magothy aquifer system in the study area. Sources of ground water, flow of ground water before and after development, and relations between intrusion of saltwater and ground-water withdrawals are discussed.

In the first part of this report, the location of the study area is described, and previous investigations are summarized. A general discussion of the hydrologic system also is presented.

In the second part of the report, the hydrogeology of the Potomac-Raritan-Magothy aquifer system in the northern Coastal Plain of New Jersey is discussed. Information is presented on the lithology, stratigraphy, structure and thickness, and hydraulic properties of, water levels in, and withdrawals of ground water from the hydrogeologic units; streamflow and ground-water/surface-water interactions; precipitation; and ground-water recharge. This information was gathered from several sources, including previously published data, unpublished data, and data-collection programs that were part of this study.

In the third part of the report, the hydrogeology of the Potomac-Raritan-Magothy aquifer system is analyzed by use of a digital modular ground-water flow model. The purpose of the model is to augment the understanding of the hydrology of the Potomac-Raritan-Magothy aquifer system in the northern Coastal Plain of New Jersey. The model, referred to hereafter as the "South River model," quantitatively represents the hydrologic system and was used to examine the hydraulic properties of the Potomac-Raritan-Magothy aquifer system, flow into and out of the aquifer system, and the effects of development and (or) management of the aquifer system within the study area. The ground-water-model area is slightly different from the primary study area, as is described later in the report. It includes all of the Coastal Plain in Middlesex County, much of Monmouth County, and parts of Ocean and Mercer Counties. Calibrated digital models can be effectively used to assess responses of water levels and flow in aquifer systems to ground-water withdrawals. Digital-modeling methods can also be used to evaluate the hydrogeologic and hydraulic complexities of aquifer systems.

In the fourth part of the report, intrusion of saltwater into the aquifer system is described, as is the migration of saltwater as a result of ground-water withdrawals and canal construction.

Description of Study Area

The study area is located in east-central New Jersey and comprises the northern part of the Coastal Plain physiographic province in New Jersey (fig. 1). It encompasses approximately 600 mi^2, including parts of Mercer, Middlesex, and Monmouth Counties in New Jersey. The study area is bounded on the northwest by the Fall Line, which separates the consolidated rocks of the Piedmont physiographic province from the unconsolidated sediments of the Coastal Plain; on the north by Staten Island (Richmond County), New York;

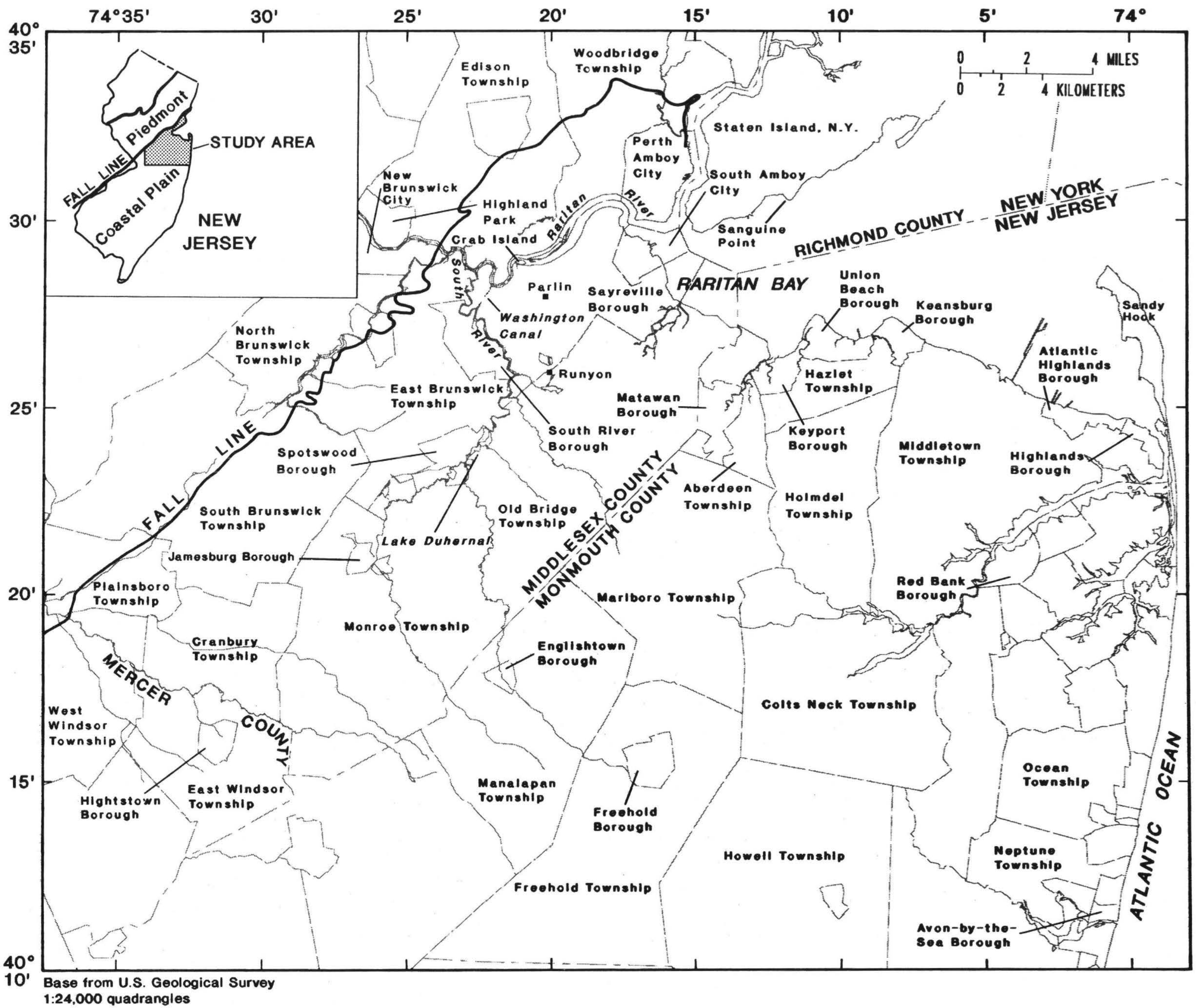

Figure 1.--Location of the study area and physiographic provinces. (Modified from Fenneman, 1938)

and on the east by the Atlantic Ocean. The southern boundary extends west from the Atlantic Ocean in southern Monmouth County to Mercer County; the southwestern boundary extends from this point north to the Fall Line.

Elevations in the study area range from sea level to 360 ft above sea level. The higher elevations generally are in central Monmouth County. Locally, the study area is deeply dissected by streams and is hilly, particularly in the northeast near the Raritan River. The remaining area is relatively flat with sandy soils. River basins with drainage areas greater than 5 mi^2 include Raritan River, South River, Navesink River, Millstone River, Lawrence Brook, Cheesequake Creek, and Matawan Creek basins (Velnich, 1984). Major surface-water bodies are Raritan Bay to the north and the Atlantic Ocean to the east.

Geologic Setting

The New Jersey Coastal Plain is underlain by unconsolidated deposits of clay, silt, sand, and gravel that range in age from Cretaceous to Holocene (table 1) (Zapecza, 1989, p. B5). These sediments unconformably overlie Triassic and Jurassic sedimentary and igneous rocks in the northern part of the study area; these in turn overlie Precambrian and lower Paleozoic bedrock (Zapecza, 1989, p. B5). A thick diabase sill of Jurassic age (Palisades sill) is present within the Triassic sequence (Barksdale and others, 1943).

Three tectonic features--the Raritan embayment, the South New Jersey uplift, and the Salisbury embayment--dominate the basement topography beneath the Coastal Plain of New Jersey. The Raritan embayment, centered in the Raritan Bay area, is the main structural feature of the northern Coastal Plain. These structural features directly affected the deposition of Coastal Plain sediments (Owens and Sohl, 1969, p. 237). In general, individual units are thickest in the embayment areas, and depositional facies changes are common between adjacent tectonic features (Olsson, 1978, p. 941); some sedimentary sequences are thin or absent in uplifted or high areas (Owens and Gohn, 1985, p. 26).

The Coastal Plain sediments form a wedge-shaped mass that strikes northeast-southwest and dips toward the southeast. The thickness of the deposits in the study area ranges from zero along the Fall Line to 1,100 ft near the southeastern border of Monmouth County.

The Potomac Group (Lower and Upper Cretaceous) comprises the oldest unconsolidated sediments of the Coastal Plain of New Jersey. These sediments consist of alternating beds of clay, silt, sand, and gravel that were deposited by meandering streams (Owens and Gohn, 1985, p. 41) on the bedrock (Zapecza, 1989, p. B5). Although the individual formations of the Potomac Group are mappable beyond New Jersey, the Potomac Group sediments are considered to be a single unit in New Jersey because the boundaries of the individual formations are indefinite (Owens and others, 1977, p. 7).

Table 1. Geologic and hydrogeologic units in the Coastal Plain of New Jersey

(Modified from Zapecza, 1989, table 2)

SYSTEM	SERIES	GEOLOGIC UNIT	LITHOLOGY	HYDROGEOLOGIC UNIT	HYDROLOGIC CHARACTERISTICS
Quaternary	Holocene	Alluvial deposits	Sand, silt, and black mud.	Undifferentiated	Surficial material, commonly hydraulically connected to underlying aquifers. Locally some units may act as confining units. Thicker sands are capable of yielding large quantities of water.
		Beach sand and gravel	Sand, quartz, light-colored, medium- to coarse-grained, pebbly.		
	Pleistocene	Cape May Formation	Sand, quartz, light-colored, heterogeneous, clayey, pebbly.		
Tertiary	Miocene	Pensauken Formation			
		Bridgeton Formation		Kirkwood-Cohansey aquifer system	A major aquifer system. Ground water occurs generally under water-table conditions. In Cape May County, the Cohansey Sand is under artesian conditions.
		Beacon Hill Gravel	Gravel, quartz, light-colored, sandy.		
		Cohansey Sand	Sand, quartz, light-colored, medium- to coarse-grained, pebbly; local clay beds.		
		Kirkwood Formation	Sand, quartz, gray and tan, very fine to medium-grained, micaceous, and dark-colored diatomaceous clay.	Confining unit	Thick diatomaceous clay bed occurs along coast and for a short distance inland. A thin water-bearing sand is present in the middle of this unit.
				Rio Grande water-bearing zone	
				Confining unit	
				Atlantic City 800-foot sand	A major aquifer along the coast.
				Composite confining unit	Poorly permeable sediments.
	Oligocene	Piney Point Formation[1]	Sand, quartz and glauconite, fine- to coarse-grained.	Composite confining unit: Piney Point aquifer	Yields moderate quantities of water.
	Eocene	Shark River Formation			
		Manasquan Formation	Clay, silty and sandy, glauconitic, green, gray, and brown, contains fine-grained quartz sand.	Composite confining unit	Poorly permeable sediments.
	Paleocene	Vincentown Formation	Sand, quartz, gray and green, fine- to coarse-grained, glauconitic, and brown clayey, very fossiliferous, glauconite and quartz calcarenite.	Composite confining unit: Vincentown aquifer	Yields small to moderate quantities of water in and near its outcrop area.
		Hornerstown Sand	Sand, clayey, glauconitic, dark-green, fine- to coarse-grained.	Composite confining unit	Poorly permeable sediments.
Cretaceous	Upper Cretaceous	Tinton Sand	Sand, quartz and glauconite, brown and gray, fine- to coarse-grained, clayey, micaceous.		
		Red Bank Sand		Composite confining unit: Red Bank Sand	Yields small quantities of water in and near its outcrop area.
		Navesink Formation	Sand, clayey, silty, glauconitic, green and black, medium- to coarse-grained.	Composite confining unit	Poorly permeable sediments.
		Mount Laurel Sand	Sand, quartz, brown and gray, fine- to coarse-grained, slightly glauconitic.	Wenonah-Mount Laurel aquifer	A major aquifer.
		Wenonah Formation	Sand, very fine- to fine-grained, gray and brown, silty, slightly glauconitic.	Marshalltown-Wenonah confining unit	A leaky confining unit.
		Marshalltown Formation	Clay, silty, dark-greenish-gray; contains glauconitic quartz sand.		
		Englishtown Formation	Sand, quartz, tan and gray, fine- to medium-grained; local clay beds.	Englishtown aquifer system	A major aquifer. Two sand units in Monmouth and Ocean Counties.
		Woodbury Clay	Clay, gray and black, and micaceous silt.	Merchantville-Woodbury confining unit	A major confining unit. Locally the Merchantville Formation may contain a thin water-bearing sand.
		Merchantville Formation	Clay, glauconitic, micaceous, gray and black; locally very fine grained quartz and glauconitic sand are present.		
		Magothy Formation	Sand, quartz, light-gray, fine- to coarse-grained. Local beds of drak gray lignitic clay. Includes Old Bridge Sand Member.	Potomac-Raritan-Magothy aquifer system: Upper aquifer	A major aquifer system. In the northern Coastal Plain, the upper aquifer is equivalent to the Old Bridge aquifer and the middle aquifer is equivalent to the Farrington aquifer. In the Delaware River Valley, three aquifers are recognized. In the deeper subsurface, units below the upper aquifer are undifferentiated.
		Raritan Formation	Sand, quartz, light-gray, fine- to coarse-grained, pebbly, arkosic; contains red, white, and variegated clay. Includes Farrington Sand Member.	Confining unit	
				Middle aquifer	
	Lower Cretaceous	Potomac Group	Alternating clay, silt, sand, and gravel.	Confining unit	
				Lower aquifer	
Pre-Cretaceous		Bedrock	Precambrian and lower Paleozic crystalline rocks, metamorphic schist, and gneiss; locally Triassic sandstone and shale and Jurassic diabase are present.	Bedrock confining unit	No wells obtain water from these consolidated rocks, except along Fall Line.

[1] of Olsson and others, 1980

Upper Cretaceous sediments of only the Raritan and Magothy Formations have been found in outcrop near the Fall Line; sediments of the Potomac Group are absent. The Raritan and Magothy Formations have been subdivided into nine geologic units on the basis of their lithology and economic importance (Christopher, 1979, fig. 2; Zapecza, 1989, p. B8). The geologic subdivision of the Raritan and Magothy Formations near the Fall Line in the northern part of the study area is shown in table 2.

The Raritan Formation consists of the Raritan fire clay (an informal unit), the Farrington Sand Member, the Woodbridge Clay Member, the Sayreville Sand Member, and the South Amboy Fire Clay Member. The sediments of the Raritan Formation represent a wide variety of depositional conditions and indicate deposition in a subaerial deltaic plain (Owens and Sohl, 1969, p. 239). Along the coast, the Raritan Formation was deposited in a predominantly marine environment (Perry and others, 1975, p. 1535). Where present, the Raritan fire clay is a massive, multicolored clay that forms a gradational contact with saprolite overlying bedrock (Ries and others, 1904, p. 192). The Farrington Sand Member, which lies above it, is characterized by sand, gravel, and lenses of clay. The overlying Woodbridge Clay Member consists of micaceous silts and clays and contains lignite and siderite concretions. The marine fossils present in this unit indicate that the Woodbridge Clay Member was deposited in marginal marine swamps (Owens and Sohl, 1969, p. 239). Overlying the Woodbridge Clay Member, the Sayreville Sand Member is a light-colored, cross-stratified, medium-grained sand interbedded with light- to dark-colored clayey silt (Owens and others, 1977, p. 16). The cross-stratification indicates deposition in river channels, possibly as point bars (Owens and Sohl, 1969, p. 239). The South Amboy Fire Clay Member is similar to the Woodbridge Clay Member except that it lacks siderite concretions and marine fossils (Owens and Sohl, 1969, p. 239).

The Magothy Formation, which lies unconformably on the Raritan Formation, includes the Old Bridge Sand Member, the Amboy Stoneware Clay Member, and the informal Morgan and Cliffwood beds. The Magothy Formation consists largely of coarse beach sand and associated marine and lagoonal sediments (Perry and others, 1975, p. 1535). The cross-stratification of the Old Bridge Sand Member indicates deposition in river channels (Owens and Sohl, 1969, p. 239). The Amboy Stoneware Clay Member is a dark, micaceous silt containing white to pale-blue clay. The Morgan beds of interbedded clay, silt, and sand lie unconformably on the Amboy Stoneware Clay Member; these beds grade laterally into cross-stratified sand. The Cliffwood beds range from a light-gray, clayey silt to very fine sand.

The Merchantville Formation lies unconformably on the Magothy Formation (Owens and Sohl, 1969, p. 242). This marine deposit consists chiefly of interstratified, massive, thick glauconite sand and thinly bedded, very micaceous, carbonaceous clayey silt (Owens and Sohl, 1969, p. 242). The Merchantville Formation is the oldest glauconite unit that crops out in the New Jersey Coastal Plain.

The Woodbury Clay lies conformably on the Merchantville Formation. The contact is gradational, and it is considered to be the point at which glauconite becomes a minor constituent and clay becomes a major constituent

Table 2.--Lithologic subdivisions of the Raritan and Magothy Formations and hydrogeologic units in and near the outcrop in the study area

System	Geologic unit		Lithology	Hydrogeologic unit	
Cretaceous	Magothy Formation	Cliffwood beds	Sand, quartz, light-gray, fine- to coarse-grained; local beds of dark-gray lignitic clay.	Potomac-Raritan-Magothy aquifer system[1]	Confining unit
		Morgan beds			
		Amboy Stoneware Clay Member			
		Old Bridge Sand Member			Upper aquifer[2]
	Raritan Formation	South Amboy Fire Clay Member	Sand, quartz, light-gray, fine to coarse-grained, pebbly, arkosic, red white and variegated clay, and saprolitic clay developed on bedrock.		Confining unit
		Sayreville Sand Member			
		Woodbridge Clay Member			
		Farrington Sand Member			Middle aquifer
		Fire Clay Member			Confining unit
Pre-Cretaceous	Bedrock		Precambrian and lower Paleozoic crystalline rocks, metamorphic shist and gneiss; locally Triassic, sandstone, shale and Jurassic basalt.	Bedrock confining unit	

Modified from Christopher, 1979, figure and Zapecza, 1984, table 2.

[1]To maintain consistent terminology, the aquifer-system name commonly used throughout New Jersey is used in this report. The lower aquifer is not mappable within the study area.

[2]Locally the upper aquifer can include the Sayreville Sand Member where the South Amboy Fire Clay Member is thin or missing

(Owens and others, 1977, p. 31). The Woodbury Clay is a thick, massive, clayey silt. The calcareous fauna present in the formation indicate deposition in a marine environment (Owens and Sohl, 1969, p. 243).

The ages and lithologies of younger geologic formations in the Coastal Plain are described in table 1. Geologic units within the study area include (from oldest to youngest): the Englishtown Formation, Marshalltown Formation, Wenonah Formation, Mount Laurel Sand, Navesink Formation, Red Bank Sand, Tinton Sand (all of Late Cretaceous age), and the Hornerstown Sand, Vincentown Formation, Manasquan Formation, and Kirkwood Formation (all of Tertiary age). Although they are shown in the general geologic table for the Coastal Plain (Zapecza, 1989), the Piney Point and Shark River Formations are not present in the study area (table 2). Zapecza (1989) described the lithology and distribution of these sediments throughout the Coastal Plain of New Jersey.

The Aquifer System in the Hydrologic Cycle

The Potomac-Raritan-Magothy aquifer system responds to physical processes through which water is transmitted between it, the land surface, surface-water bodies, and other hydrogeologic units in the ground-water system of the Coastal Plain of New Jersey. The flow and exchange of water as a result of these processes are described by the hydrologic cycle.

Ground water is present under two general conditions: water-table (unconfined) and artesian (confined). Water-table conditions are found where saturated, porous and permeable rocks that make up the ground-water reservoir, or aquifer, are not overlain by rocks of substantially lower permeability. A water-table aquifer is recharged by downward percolation of precipitation, leakage from surface-water bodies, upward flow from underlying geologic strata, or a combination of these sources. Under artesian conditions, water in the aquifer is confined beneath poorly permeable rock and is under pressure. Confined aquifers are recharged by slow leakage from above or below through the less permeable strata and by horizontal ground-water flow from the outcrop area of the aquifer. Water in an artesian aquifer is confined by poorly permeable rocks and has no "free" water surface or water table; instead, it has a potentiometric surface, which is the level to which the water rises in tightly cased wells.

The hydrologic cycle is the continuous circulation of water from the atmosphere to the land surface, to the soil and ground water in the underlying rocks, and back to the atmosphere. It includes processes of condensation, precipitation, evaporation, transpiration, infiltration, and runoff. Ground water is constantly exchanged with water in the atmosphere and the surface-water system. The movement of water through these phases of the cycle is variable in both time and space. Precipitation that falls onto the Earth's surface either becomes surface runoff or recharge to the ground-water system or returns to the atmosphere through evaporation or transpiration. Streamflow in the northern Coastal Plain of New Jersey is derived mostly from discharge of shallow ground water, or base flow. Shallow, unconfined ground water that is not captured by these processes can enter the deeper, confined ground-water-flow system.

Development of ground-water resources alters the exchange of water in some of these processes. The extent of the changes that result from the stresses caused by withdrawals and diversions of ground water is considered later in this report. The resulting changes in the hydraulic equilibrium of the ground-water system have also caused two other processes to occur--release of water from storage by compaction and saltwater intrusion.

The lowering of water levels has caused some water to be released from storage in the sediments of the Potomac-Raritan-Magothy aquifer system. In unconfined aquifers, water from storage is derived primarily from dewatering of the pore spaces in the aquifers. In confined aquifers, the released water is derived primarily from reversible compaction of the aquifers and confining units as a result of reduced hydraulic pressure, which increases the grain-to-grain loading; the remainder of the released water (a comparatively small amount) is derived from expansion of the water. The quantity of water released from storage is greatest in areas of greatest reduction in water levels. Irreversible compaction of sediments in the Coastal Plain of New Jersey is considered to be negligible (Martin, 1990) and therefore is not considered in this report.

Ground-water withdrawals from the Potomac-Raritan-Magothy aquifer system during the 1800's to present has lowered water levels in some parts of the aquifers to below sea level. As a result, saltwater has become a source of recharge and flows into parts of the aquifer system in the northern Coastal Plain along estuaries and the coast of Raritan Bay that previously contained freshwater. Saltwater intrusion also is discussed later in this report.

Previous Investigations

The hydrogeology and ground-water resources of the northern Coastal Plain of New Jersey were first studied in the 1800's. Early investigators described the geology from pits that were dug into the clay beds near the South and Raritan Rivers for commercial development of the brick and clay industry. Several investigators described and correlated the water-bearing units, described the general structural features, and mapped the structure of the Coastal Plain (Cook and Smock, 1878; Woolman, 1889-1902; Vermeule, 1894; Knapp, 1903; Ries and others, 1904; Kummel and Poland, 1909). A number of geologic investigations during the early 1900's refined the previously published geologic and hydrogeologic maps of the aquifers and confining units in the study area (M.E., Johnson, New Jersey Geological Survey, written commun., 1925-40; Barksdale, 1937; Barksdale and others, 1943; Richards and others, 1962).

Many subsequent reports included analyses and maps of the geologic formations of the northern Coastal Plain in New Jersey (U.S. Geological Survey, 1967; S.K., Whitney, New Jersey Geological Survey, written commun., 1969; Gill and Farlekas, 1976; Zapecza, 1989; Lyttle and Epstein, 1987; S.K. Sandberg, and others, New Jersey Geological Survey, written commun., 1988; Gronberg and others, 1991). The hydrogeology of the Raritan Bay area has been discussed in several reports (Berkey, 1955; U.S. Army Corps of Engineers, 1963; Edgerton, Germeshausen, & Grier, Inc., 1965; Bokuniewicz and Fray, 1979; Schaefer and Walker, 1981; Declercq, 1986; and Pucci, 1986). Several researchers have investigated the stratigraphy, lithology, and depositional history of the Coastal Plain in the study area (Hawkins and others, 1933; Hawkins, 1935; McCallum, 1957; Owens and Sohl, 1969; Olsson, 1975; Owens and others, 1977; Owens and Gohn, 1985; and Pucci and Owens, 1989). Various investigators have reported geologic data for the area (Kasabach and Scudder, 1961; U.S. Geological Survey, 1979; D.R. Hutchinson, U.S. Geological Survey, written commun., 1985; Epstein, 1986).

Several reports have included discussions of the ground-water resources and hydrology of the Potomac-Raritan-Magothy aquifer system in the northern part of the New Jersey Coastal Plain (Vermeule, 1894; Barksdale and others, 1943; Jablonski, 1959, 1960, and 1968; Hardt and Jablonski, 1959; Parker and others, 1964; Farlekas, 1979; Vowinkel and Foster, 1981; Leahy, 1985; Leahy and others, 1987; Soren, 1988). The hydrogeology of the area near Sayreville Borough has been the focus of several reports (Barksdale, 1937; Appel, 1962; Hasan and others, 1969; Pucci and others, 1988; Pucci and others 1989; S.K. Sandberg, New Jersey Geological Survey, written commun., 1989). Several studies have produced reports and maps of data on water levels and water use in the Coastal Plain of in New Jersey, which includes the study area (Walker, 1983; Eckel and Walker, 1986; and Zapecza and others, 1987).

Results of digital computer analyses of ground-water flow in the Potomac-Raritan-Magothy aquifer system in the study area have been reported by Remson and others (1965) and Farlekas (1979). Three ground-water simulation studies of the Coastal Plain of New Jersey include the Potomac-Raritan-Magothy aquifer system in study area (Luzier, 1980; Harbaugh and others, 1980; Martin, 1990).

Saltwater intrusion in the area of Sayreville Borough has been a focus of several investigations (Barksdale, 1937; Barksdale and others, 1943; U.S. Army Corps of Engineers, 1962; Appel, 1962; Irwin Remson and C.A. Appel, U.S. Geological Survey, written commun., 1963; Hasan and others, 1969; Pucci, 1986; and Ervin and Pucci, 1987). Schaefer and Walker (1981) and Pucci and others (1988) reported on saltwater intrusion in the middle aquifer of the Potomac-Raritan-Magothy aquifer system near Keyport Inlet and Conaskonk Point in Union Beach. The presence of elevated chloride concentrations from saltwater intrusion in the New Jersey Coastal Plain, including the study area, has been described by Seaber (1963), Schaefer (1983), and Pucci (1986).

Unpublished lithologic data and borehole geophysical data throughout the study area were compiled from the well-record archives at the New Jersey Department of Environmental Protection and Energy and U.S. Geological Survey from records of borings for municipal projects. Appendix A (at end of report) is a summary of these and other major sources of information used for this investigation.

Well-Numbering System

The well-numbering system used in this report is based on the numbering system used by the U.S. Geological Survey in New Jersey since 1978. The first part of the number is a two-digit county code: 21 for Mercer, 23 for Middlesex, 25 for Monmouth. The second part is the sequence number of the well within the county. For example, well number 23-137 represents the 137th well inventoried in Middlesex County.

Acknowledgments

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HYDROGEOLOGY

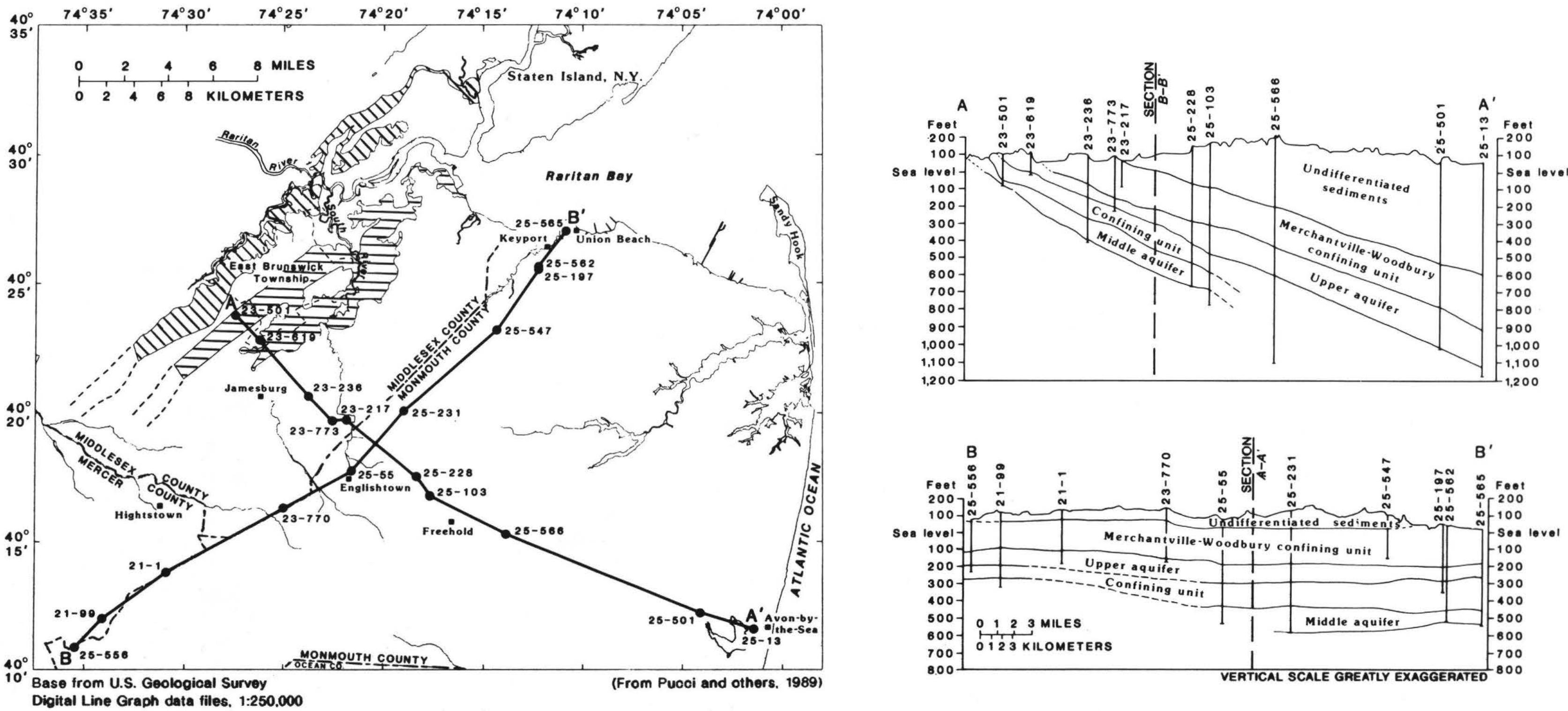
The sediments of the Potomac Group and Raritan and Magothy Formations comprise the Potomac-Raritan-Magothy aquifer system (table 2). In the New Jersey Coastal Plain, this aquifer system generally is divided into the lower, middle, and upper aquifers, which are separated from each other by confining units (Zapecza, 1989, p. B8). In the study area, the middle aquifer is equivalent to the Farrington aquifer, and the upper aquifer is equivalent to the Old Bridge aquifer (Farlekas, 1979). The lower aquifer is not mappable within the study area (Zapecza, 1989, p. 6; Gronberg and others, 1991); although Potomac sediments are present in the southern part of the study area, water-level measurements indicate that these sediments are not connected hydraulically to sediments that comprise the lower aquifer of the Potomac-Raritan-Magothy aquifer system (Zapecza, 1989, p. B8-B12).

The Merchantville-Woodbury confining unit, the main confining unit overlying the Potomac-Raritan-Magothy aquifer system, is discussed in detail in this report. Other hydrogeologic units that overlie the aquifer system in the study area are included in table 1 and are shown as undifferentiated sediments in figure 2. Maps showing the structural contours of the top and thickness of each unit and detailed discussion of each unit are given in Zapecza (1989).

Units Overlying the Potomac-Raritan-Magothy Aquifer System

The water-table system generally consists of horizontally lying fine- to coarse-grained Pleistocene and Miocene sands where they overlie Tertiary and Cretaceous sediments that form confined aquifers (table 1; Zapecza, 1989, p. B5).

The Kirkwood-Cohansey aquifer system is composed of the Kirkwood Formation, the Cohansey Sand, and younger sediments (table 1). This aquifer system is unconfined in southeastern Monmouth County (Zapecza, 1989, pl. 24). Near the coast, the Kirkwood Formation is predominantly made up of clay beds and interbedded zones of sand and gravel. Updip from the coast in the subsurface, the unit consists of fine to medium sand and silty sand, with regionally extensive clay beds only in the basal part of the formation (Zapecza, 1989, p. B19). The Cohansey Sand is predominantly composed of sand and contains minor amounts of pebbly sand, fine- to coarse-grained sand, silty and clayey sand, and interbedded clay. These sediments generally are coarser than those of the underlying Kirkwood Formation (Zapecza, 1989, p. B19).



EXPLANATION

AREAS OF OUTCROP

UPPER AQUIFER OUTCROP

OLD BRIDGE SAND MEMBER OF THE MAGOTHY FORMATION--Dashed where approximately located. (Modified from Barksdale and others, 1943, fig. 6)

MIDDLE AQUIFER OUTCROP

FARRINGTON SAND MEMBER OF THE RARITAN FORMATION--Dashed where approximately located. (Modified from Barksdale and others, 1943, fig. 6)

• 23-770 WELL LOCATION AND U.S. GEOLOGICAL WELL NUMBER

EXPLANATION

21-1 U.S. Geological Survey well number

Hydrogeologic data from Gronberg and others, 1990

Figure 2.--Generalized sections through the major hydrogeologic units in the northern Coastal Plain of New Jersey.

The Vincentown aquifer consists of the sandy part of the Vincentown Formation (table 1). The outcrop area of the Vincentown Formation extends in an irregular and discontinuous band from the northeastern shore of Raritan Bay toward the southwestern corner of Monmouth County (Zapecza, 1989, pl. 19). These permeable sands are found in and near the outcrop area and grade into finer grained silt and clay downdip, where the formation functions as a confining unit. The Vincentown aquifer ranges in thickness from 0 ft in the outcrop area in Monmouth County to more than 140 ft downdip (Zapecza, 1989, p. B16).

In the northern Coastal Plain of New Jersey, the composite confining unit overlying the Wenonah-Mount Laurel aquifer is composed of the basal clay of the Kirkwood Formation, Manasquan Formation, Vincentown Formation (where it consists of fine-grained silt and clay downdip), Hornerstown Sand, Tinton Sand, Red Bank Sand, and Navesink Formation (table 1). These formations crop out in an extensive area of central Monmouth County (Zapecza, 1989, pl. 18). The sediments are predominantly poorly to moderately permeable, silty and clayey, glauconitic quartz sands. The permeable sands of the Vincentown Formation and Red Bank Sand within this confining unit are used locally for water supply. In the study area, the thickness of this confining unit increases considerably over a short distance, from 50 ft in the outcrop area to more than 450 ft near the shore (Zapecza, 1989, p. B14-B16, pl. 18).

The Wenonah-Mount Laurel aquifer, which overlies the Marshalltown-Wenonah confining unit, is composed of the Mount Laurel Sand and the coarse-grained part of the Wenonah Formation (table 1). The sediments that comprise the aquifer crop out in a relatively narrow band that extends from the Atlantic Highlands in Monmouth County toward the area where Middlesex, Monmouth, and Mercer Counties meet in the southwestern part of the study area (Zapecza, 1989, pl. 17). The thickness of the aquifer ranges from 40 ft in the outcrop area to approximately 100 ft near the shore (Zapecza, 1989, p. B14, pl. 17). Eckel and Walker (1986, p. 38 and pl. 5) reported that the water levels in the aquifer in 1983 ranged from more than 140 ft above sea level in southwestern Monmouth County to between 162 and 196 ft below sea level in a deep, extensive cone of depression in southeastern Monmouth County.

The Marshalltown-Wenonah confining unit separates the Wenonah-Mount Laurel aquifer from the Englishtown aquifer system (table 1). It is composed of the fine-grained, lower section of the Wenonah Formation and the Marshalltown Formation. The sediments that make up the confining unit crop out in a continuous band from an area east of Atlantic Highlands Borough toward the southwestern part of the study area (Zapecza, 1989, pl. 15). The Wenonah Formation generally is a dark-gray, poorly sorted, micaceous, silty, fine quartz sand. The lower section also contains much glauconite (Zapecza, 1989, p. B14). The Marshalltown Formation is composed of glauconitic silt and sand ranging from 10 to 20 ft in thickness in the study area (Zapecza, 1989, p. B14).

The Englishtown aquifer system overlies the Merchantville-Woodbury confining unit (table 1). The sediments that comprise the aquifer system crop out from northern Monmouth County to southern Middlesex County. Throughout most of the northern Coastal Plain of New Jersey, it functions as one aquifer; however, in southeastern Monmouth County, its two sand lithofacies are separated by a clayey-silt lithofacies. The aquifer system thickens from 40 ft near the outcrop to 140 ft near Red Bank in northern Monmouth County, where it acts as a single water-bearing unit. In southeastern Monmouth County, it increases in thickness to about 180 ft and includes the clayey-silt lithofacies separating the upper and lower sand units (Zapecza, 1989, p. B13). Eckel and Walker (1986, p. 33 and pl. 4) showed that water levels in this aquifer in this area in 1983 ranged from about 120 ft above sea level in southwestern Monmouth County to between 158 and 249 ft below sea level in a cone of depression in southeastern Monmouth County.

Potomac-Raritan-Magothy Aquifer System

The sediments of the Potomac Group and the Raritan and Magothy Formations, which comprise the Potomac-Raritan-Magothy aquifer system, are the basal sediments of the Coastal Plain (table 1). These sediments have been considered as a single hydrogeologic system because (1) the formations are lithologically indistinguishable throughout large areas of the Coastal Plain (Barksdale and others, 1958, p. 92), and (2) the aquifers within this system have been considered interconnected over some distance (Barksdale and others, 1958, p. 91). In addition, the aquifer system is separated from the overlying hydrogeologic units by the Merchantville-Woodbury confining unit. This massive confining unit, which consists of the sediments of the Merchantville Formation and Woodbury Clay, is considered to be an effective confining unit between the upper aquifer of the Potomac-Raritan-Magothy aquifer system and the overlying Englishtown aquifer system (Barksdale and others, 1958, p. 136; Zapecza, 1989, p. B12). These hydrogeologic units and their relation to the major geologic units, as illustrated in tables 1 and 2, are described below.

The maps of hydrogeologic units in this report show outcrop areas of geologic formations (U.S. Geological Survey, 1967, sheets 3 and 4). The depicted hydrogeologic units of the Potomac-Raritan-Magothy aquifer system and the Merchantville-Woodbury confining unit typically are sandy or clayey parts of respective geologic formations. Strictly defined, the outcrop areas of the geologic formations shown on the hydrogeologic-unit maps are not the outcrop areas of the hydrogeologic units. The outcrop areas of the geologic formations can generally be used, however, to estimate updip limits of aquifers and confining units and to approximate lines of zero thickness of hydrogeologic units in the New Jersey Coastal Plain (Zapecza, 1989, p. B8). In the northern Coastal Plain of New Jersey, the outcrop of the Old Bridge Sand Member of the Magothy Formation coincides closely with the outcrop of the upper aquifer of the Potomac-Raritan-Magothy aquifer system (Barksdale and others, 1943, p. 21). Similarly, the outcrop of the Farrington Sand Member of the Raritan Formation coincides closely with the outcrop of the middle aquifer of the Potomac-Raritan-Magothy aquifer system.

Errors in estimated locations of subsurface contours and thicknesses of hydrogeologic units were caused by differences in reliability and accuracy of diverse sampling methods. For example, the characteristics of the hydrogeologic framework were interpreted from several sources, including geologists' logs, geophysical logs, terrestrial and marine geophysical surveys, and drillers' logs. The regional hydrogeologic framework for the study area presented in this report is considered a refinement of that previously reported in Gronberg and others (1991).

Locations of well drilling and marine geophysical surveys were chosen on the basis of distribution and reliability of available data (Pucci, 1986; Declerq, 1986; Pucci and Murashige, 1987). A summary of information on the wells and test boreholes drilled during this project is presented in table 3. The locations of these wells and boreholes are shown later in the report, in figure 22. Surface geophysical methods also were used to map hydrogeologic units within the study area (S.K. Sandberg, New Jersey Geological Survey, written commun., 1989).

The hydrogeologic framework of the Potomac-Raritan-Magothy aquifer system is described through a series of hydrogeologic sections and maps of the top surface and thickness of each unit. Data on wells and testholes shown in figure 2 were used to generate hydrogeologic section A-A', which is located approximately along dip, and section B-B', which is located approximately along strike (Pucci and others, 1989).

Merchantville-Woodbury Confining Unit

The Merchantville-Woodbury confining unit overlies the upper aquifer of the Potomac-Raritan-Magothy aquifer system. It is composed of the Woodbury Clay, Merchantville Formation, and, locally, members of the Magothy Formation, including the discontinuous Cliffwood and Morgan beds and Amboy Stoneware Clay Member (tables 1 and 2). The Cliffwood and Morgan beds are recognized locally in outcrop and in the subsurface of the Sandy Hook Bay area, in the northeastern part of the study area (Zapecza, 1989, p. B11). These beds interfinger and pinch out within the Merchantville Formation and the Woodbury Clay (Perry and others, 1975, fig. 11). Because the Cliffwood and Morgan beds and Amboy Stoneware Clay Member are part of the confining unit, the updip extent of the confining unit is the outcrop area of the Old Bridge Sand Member of the Magothy Formation near Raritan Bay. In the southwestern part of the study area, these beds are not present near the outcrop area; therefore, the updip extent of the confining unit coincides with the updip extent of the Merchantville Formation.

The thickness map of the Merchantville-Woodbury confining unit (fig. 3) and hydrogeologic section of Coastal Plain sediments through this confining unit (fig. 2) show that it ranges from less than 25 ft in thickness in the outcrop, then increases downdip and to the northeast, and attains a maximum thickness of 369 ft in Atlantic Highlands Borough (well 25-119), in northeastern Monmouth County. According to Zapecza (1989, p. B12), it is the most massive confining unit in the Coastal Plain and is an effective confining layer between the upper aquifer of the Potomac-Raritan-Magothy aquifer system and the Englishtown aquifer system throughout the study area. The hydraulic properties of the Merchantville-Woodbury confining unit are discussed with those of the upper aquifer in the next section.

Upper Aquifer

The upper aquifer is the most extensive unit of the Potomac-Raritan-Magothy aquifer system (Zapecza, 1989, p. B11). It consists primarily of the Old Bridge Sand Member of the Magothy Formation, and includes the Sayreville Sand Member of the Raritan Formation where the South Amboy Fire Clay Member is thin or absent (table 2) (Farlekas, 1979, p. 22). At and near the outcrop area, the aquifer also includes the overlying surficial sands and gravels (Farlekas, 1979, p. 22). The top of the aquifer is clearly defined in well logs because the contact with the overlying Merchantville-Woodbury confining unit is distinct and easily recognized (Gronberg and others, 1991). Near Raritan Bay, the Magothy Formation also includes the Amboy Stoneware Clay Member and the Cliffwood and Morgan beds (table 2); permeability of these units is low, however, and these units are included as part of the Merchantville-Woodbury confining unit (Gronberg and others, 1991). The upper aquifer is characterized by coarse-grained sediments and thin, localized clay beds (Zapecza, 1989, p. B11). This unit can be mapped from the outcrop to the southeastern corner of the study area (fig. 4). In general, the surface of the upper aquifer strikes northeast-southwest and dips about 50 ft/mi.

The thickness of the upper aquifer (fig. 5) ranges from less than 25 ft in the outcrop area to more than 230 ft along the coast in the southeast. In most places, the aquifer is between 75 and 175 ft thick. In the western part of the study area, near the outcrop of the Magothy Formation, it generally is less than 100 ft thick. In the southwestern part of the study area, near Jamesburg and Hightstown Boroughs, the lower boundary of the aquifer is difficult to determine because the underlying confining unit is thin and sandy (Gronberg and others, 1991).

Declercq (1986) reported that the upper aquifer is found beneath Raritan Bay and crops out just south of Staten Island, submerged beneath Raritan Bay. The outcrop of the upper aquifer is submerged at the Raritan Bay shoreline at Morgan, in Sayreville Borough, Middlesex County, N.J., and extends into Raritan Bay. These interpretations are based on available test-borehole data from Raritan Bay (Berkey, 1955; U.S. Army Corps of Engineers, 1963), marine seismic data (D.R. Hutchinson, U.S. Geological Survey, written commun., 1985), a marine seismic-reflection survey of Raritan Bay done during this study (Declercq, 1986), and nearshore test drilling done during this study (Gronberg and others, 1991).

A paleochannel of the ancient Raritan River may serve as a hydraulic connection between the upper aquifer and Raritan Bay. On the basis of cores from Raritan Bay (Berkey, 1955), MacClintock and Richards (1936; from Bokuniewicz and Fray, 1979, p. 14-15) reported a channel that was eroded into Cretaceous sediments by the ancient Raritan River along the northern part of Raritan Bay (fig. 4). The bottom of the ancient channel is approximately 150 ft below sea level. Because the channel is just south of Staten Island (fig. 4), it probably penetrates the sediments of the upper aquifer near the Staten Island shore (fig. 4). Bokuniewicz and Fray (1979, p. 5-14) reported that erosion and filling in of the bay-bottom sediments has probably occurred elsewhere along the ancient channel in Raritan Bay. The Pleistocene channel-fill deposits are highly variable as a result of their fluvial origin. Typically, fluvial channel-fill deposits consist of lag gravel at the channel base, grading upward into sand, silt, clay, and bay-bottom mud (Hack, 1957). As reported by D.D. Drummond (Maryland Geological Survey, written commun., 1987) for the Kent Island, Maryland, area near Chesapeake Bay, these paleochannels may be conduits through which saltwater enters the aquifer.

Holocene sands that directly overlie sands of the Magothy Formation in the eastern part of Raritan Bay also may hydraulically connect the upper aquifer with Raritan Bay (fig. 4). In Kastens and others (1978) and Bokuniewicz and Fray (1979, p. 12), lithologic sections through eastern Raritan Bay show that sediments of the upper aquifer (Magothy Formation) directly underlie glacial (Holocene) outwash sands (Perlmutter and Arnow, 1953) near Staten Island (fig. 4). Minard (1969, pl. 1) reported that Holocene beach sands directly overlie the Magothy Formation in the northern part of Sandy Hook; these sands range in texture from fine to coarse. Kastens and others (1978) mapped these sands over a broad area and showed that they are exposed to the floor of eastern Raritan Bay. Therefore, several hydrogeologic features of the upper aquifer beneath Raritan Bay may serve as conduits of saltwater into the upper aquifer.

Hydraulic properties

Hydraulic properties of the upper aquifer based on aquifer tests (fig. 5) and results of simulations by Martin (1990) are summarized in table 4. The quality of estimates of hydraulic properties of the aquifer depended on the method of data collection and analysis, which is discussed in greater detail by Pucci and others (1989). Aquifer testing is the most reliable method, but specific-capacity data from well-acceptance tests and lithologic logs also were guides in estimating hydraulic properties, especially for the deep confined-aquifer area for which aquifer-test data are sparse. Estimates of vertical hydraulic conductivities of the confining units from aquifer tests could have been affected by variation in the aquifer-test procedures, such as the test duration, which may not have been long enough to detect leakance.

Reported transmissivities for the upper aquifer, as determined from aquifer tests, range from 1,760 to 19,400 ft^2/d. Transmissivities determined from results of the three northernmost tests in the unconfined area of the aquifer (aquifer tests 1, 6, and 11, table 4) range from 1,760 to 5,820 ft^2/d. The lower transmissivities for these tests are likely the result of the thinness of the aquifer in the northern part of the study area. The remaining transmissivities for the unconfined areas of the aquifer range from 9,500 to 19,400 ft^2/d. On the basis of interpretation of well logs, the upper aquifer is believed to be semiconfined at the sites of aquifer tests 2 and 3, although the test sites are in the outcrop area (Pucci and others, 1989). Transmissivity values for the confined, semiconfined, and leaky confined areas of the aquifer range from 4,010 to 15,450 ft^2/d. Of these values, the transmissivities derived from the six aquifer tests in the deepest part of the system (4, 5, 7, 9, 10 and 15, table 4) range from 5,400 to 8,420 ft^2/d.

The horizontal hydraulic conductivity of the upper aquifer, as determined from aquifer tests and well-acceptance tests, ranges from 4 to 483 ft/d (Pucci and others, 1989, tables 5 and 7). Areas where the hydraulic conductivity is less than 100 ft/d are distributed throughout the study area, whereas areas where the hydraulic conductivity is greater than 100 ft/d are concentrated in or near the outcrop area of the Old Bridge Sand Member of the Magothy Formation, which constitutes the unconfined area of the upper aquifer (Pucci and others, 1989).

Table 3.--Records of test boreholes and observation wells drilled, 1985-87

[All well locations shown in figure 22; all wells owned by U.S. Geological Survey; * indicates drive-point well; --, data unavailable; Geophysical logs: J, Gamma; E, electric; NA, not applicable; USGS, U.S. Geological Survey; NJDEP, New Jersey Department of Environmental Protection]

USGS well number	Local iden-ti-fier	Latitude	Longitude	Municipality	Altitude of land surface (feet)	Date drilled	Drilled depth (feet below land surface)
21- 241	NA	401727	743640	West Windsor Township	100	09/18/85	133
23- 790	NA	402627	742247	South River Borough	75	09/05/85	147
23- 791	NA	401940	743353	Plainsboro Township	80	09/12/85	150
23-1058	Hess Bros. 1	402704	742139	Sayreville Borough	25	10/29/86	173
23-1059	Hess Bros. 2	402704	742139	Sayreville Borough	25	11/20/86	167
23-1060	Marsh Ave.	402802	742022	Sayreville Borough	40	12/07/86	251
23-1077	JCP&L Sayreville	402831	742120	Sayreville Borough	7	02/27/87	75
23-1078	Sayre St.	402721	742210	Sayreville Borough	12	02/05/87	84
23-1120*	drive point A	402744	742215	Sayreville Borough	1	11/17/87	11
23-1121*	do.	402744	742215	Sayreville Borough	1	11/17/87	22
23-1122*	do.	402744	742215	Sayreville Borough	1	11/17/87	32
23-1123*	do.	402744	742215	Sayreville Borough	1	11/18/87	37
23-1124*	drive point B	402748	742218	Sayreville Borough	3.5	11/20/87	12
23-1125*	do.	402748	742218	Sayreville Borough	3.5	11/20/87	17
23-1126*	do.	402748	742218	Sayreville Borough	3.5	11/20/87	22
23-1127*	do.	402748	742218	Sayreville Borough	3.5	11/20/87	29
23-1128*	do.	402748	742218	Sayreville Borough	3.5	11/23/87	47
23-1129*	drive point C	402752	742221	Sayreville Borough	6	11/18/87	12
23-1131*	do.	402752	742221	Sayreville Borough	6	11/18/87	22
23-1132*	do.	402752	742221	Sayreville Borough	6	11/18/87	27
23-1133*	do.	402752	742221	Sayreville Borough	6	11/18/87	32
23-1134*	do.	402752	742221	Sayreville Borough	6	11/18/87	42
25- 565	Conaskonk Pt.	402704	741051	Union Beach Borough	10	11/11/85	555
25- 566	Oak Rise Dr.	401517	741351	Freehold Township	200	12/10/85	1,320
25- 567	Union Beach Water Tower	402630	741029	Union Beach Borough	10	04/04/86	297
25- 568	JCP&L Union Beach	402652	741100	Union Beach Borough	0	04/11/86	283

1 Nominal inside diameter

2 Refers to aquifer unit of the Potomac-Raritan-Magothy aquifer system

Table 3.--Records of test boreholes and observation wells drilled, 1985-87--Continued

Construction data						
USGS well number	Casing diameter (inches)[1]	Screened interval feet below land surface)	Core sampling	Geo-phys-ical logs	Driller	Aquifer unit[2]
21- 241	Not completed as well		Every 10 feet	J	NJDEP	--
23- 790	Not completed as well		Every 5 or 10 feet	EJ	NJDEP	--
23- 791	Not completed as well		Every 10 feet	EJ	NJDEP	--
23-1058	4	112-122	--	J	NJDEP	Middle
23-1059	4	138-148	--	E	NJDEP	Middle
23-1060	4	138-148	--	EJ	NJDEP	Middle
23-1077	2	46-56	--	J	NJDEP	Middle
23-1078	2	68-78	--	J	NJDEP	Middle
23-1120*	1	9-11	--	--	USGS	Middle
23-1121*	1	20-22	--	--	USGS	Middle
23-1122*	1	30-32	--	--	USGS	Middle
23-1123*	1	35-37	--	--	USGS	Middle
23-1124*	1	10-12	--	--	USGS	Middle
23-1125*	1	15-17	--	--	USGS	Middle
23-1126*	1	20-22	--	--	USGS	Middle
23-1127*	1	27-29	--	--	USGS	Middle
23-1128*	1	45-47	--	--	USGS	Middle
23-1129*	1	10-12	--	--	USGS	Middle
23-1131*	1	20-22	--	--	USGS	Middle
23-1132*	1	25-27	--	--	USGS	Middle
23-1133*	1	30-32	--	--	USGS	Middle
23-1134*	1	40-42	--	--	USGS	Middle
25- 565	4	201-211	--	EJ	NJDEP	Upper
25- 566	2	716-726	Continuous	EJ	NJDEP	Upper
25- 567	4	250-270	--	EJ	NJDEP	Upper
25- 568	4	245-265	--	EJ	NJDEP	Upper

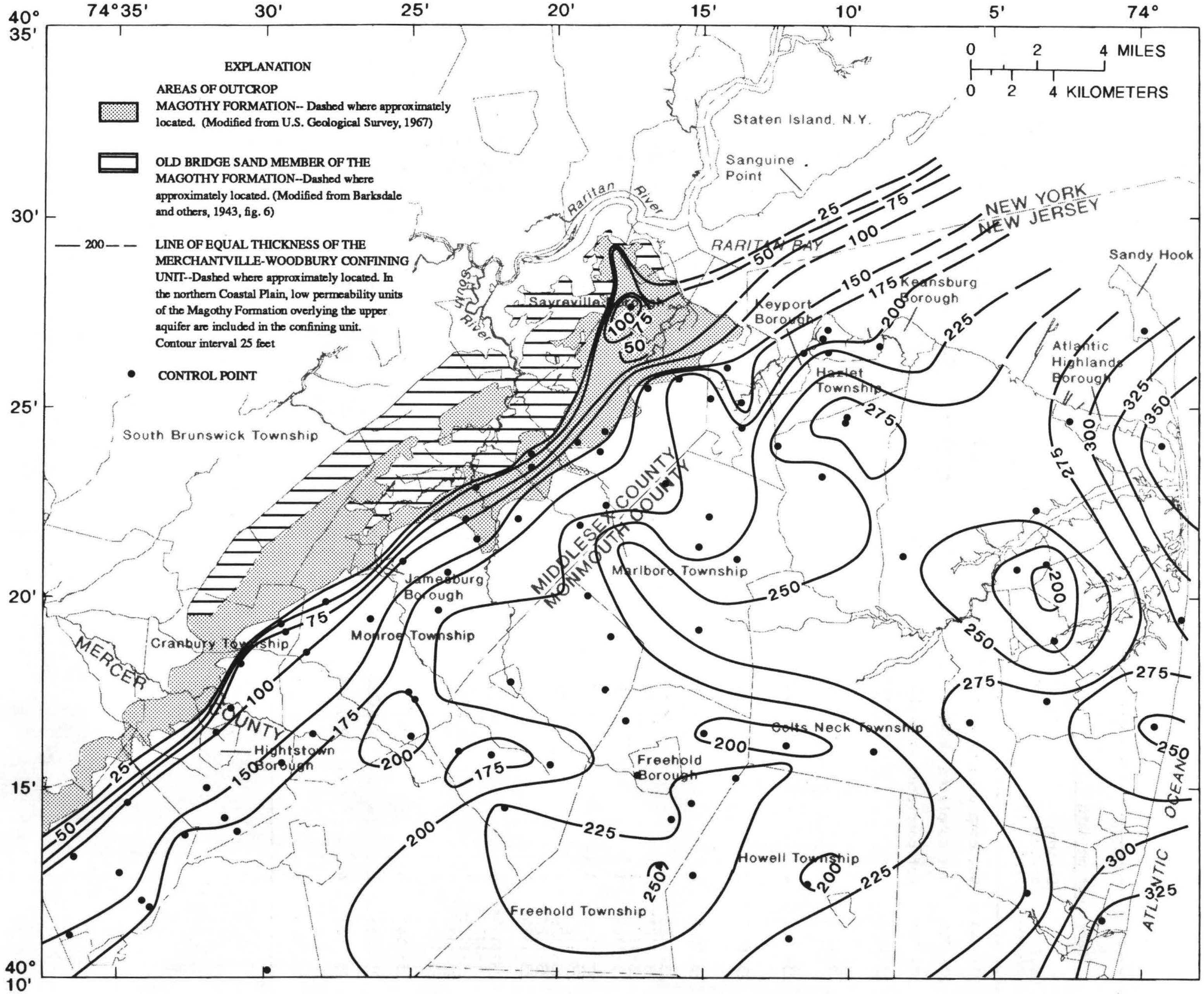


Figure 3.--Thickness of the Merchantville-Woodbury confining unit. (Modified from Gronberg and others, 1991, pl. 8)

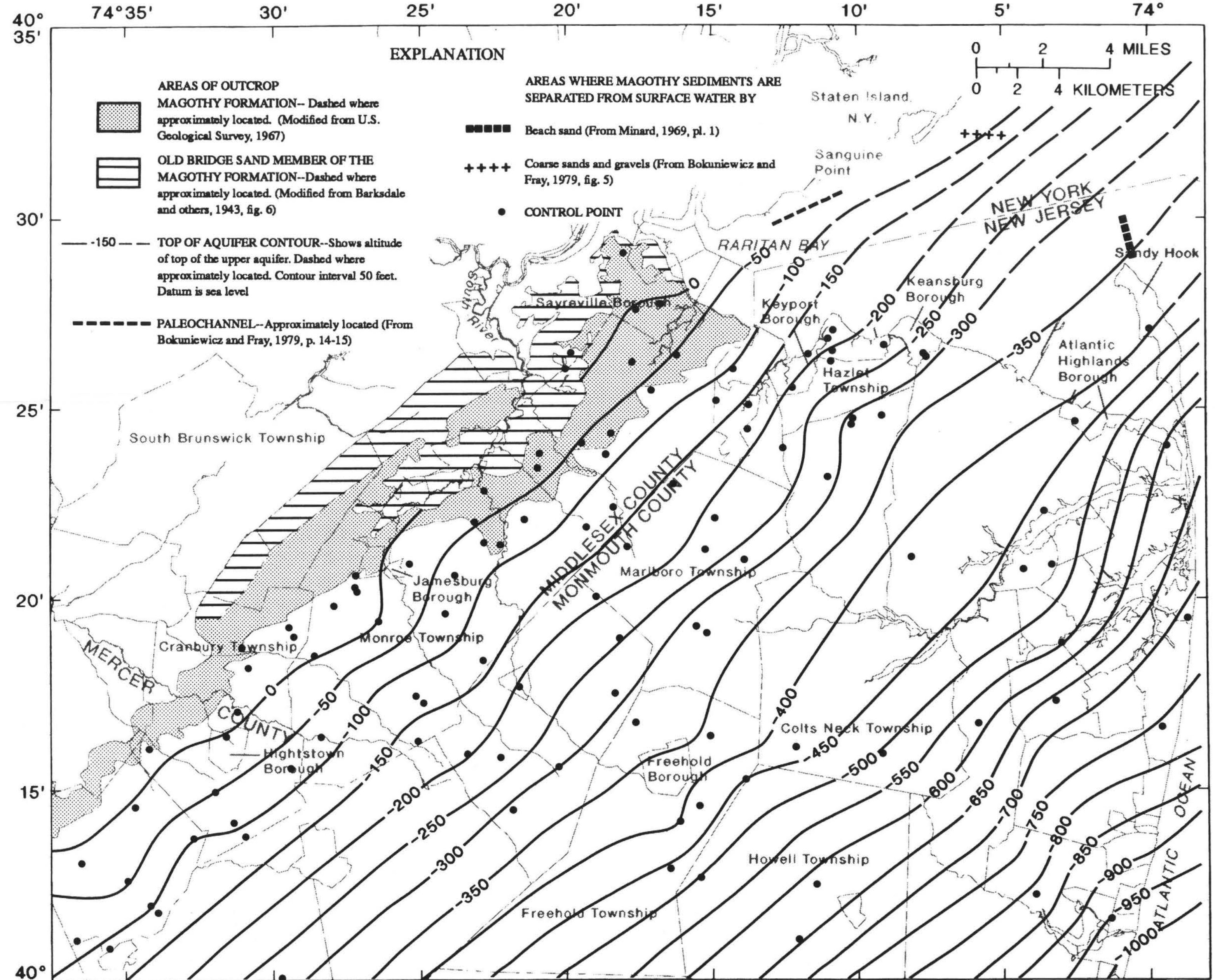


Figure 4.--Structure contours of the top of the upper aquifer. (Modified from Gronberg and others, 1991, pl. 6)

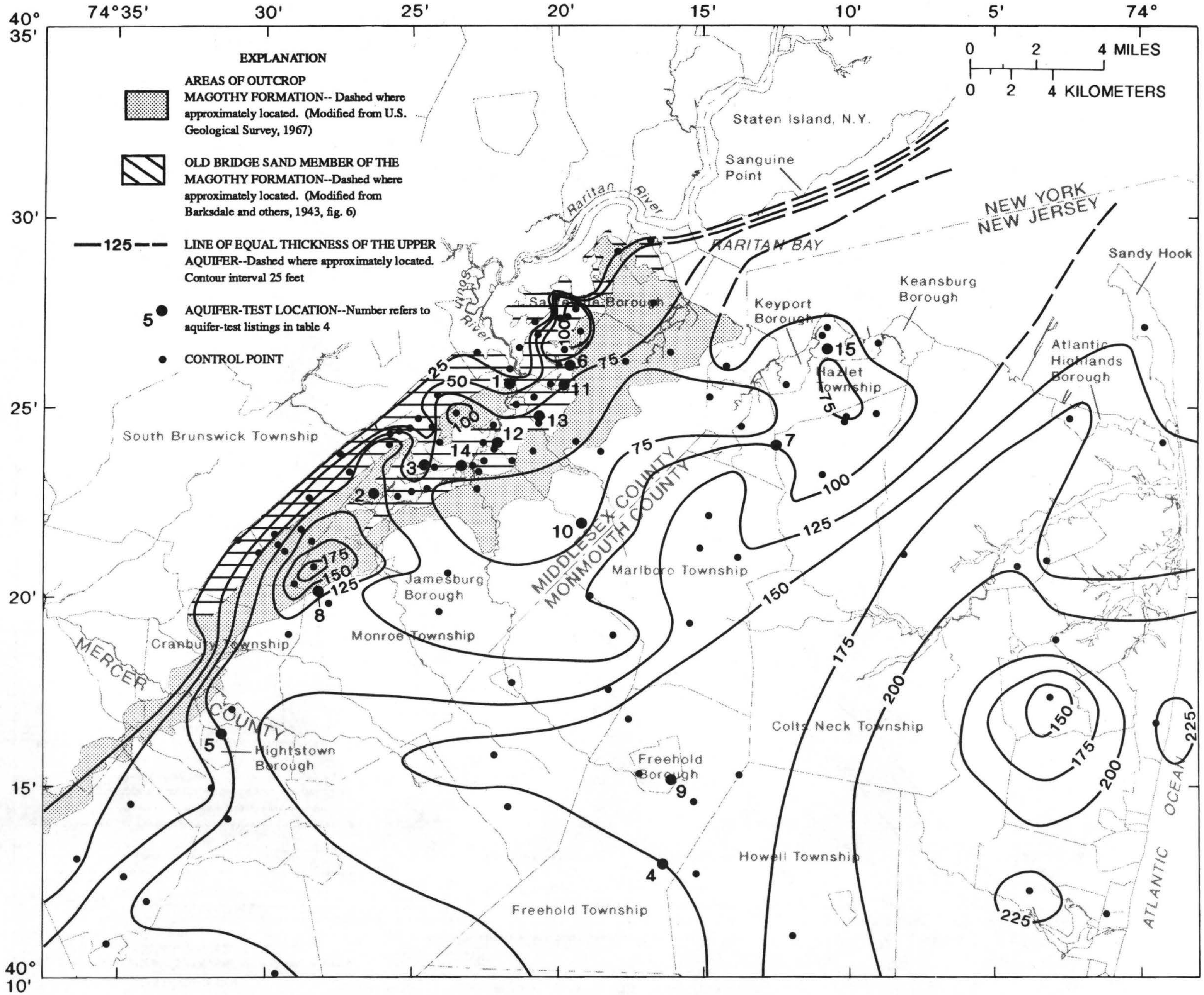


Figure 5.--Thickness of the upper aquifer. (Modified from Gronberg and others, 1991, pl. 7)

Table 4.--Summary of reported range of values for hydraulic properties of the upper aquifer

[All aquifer-test results reported by Pucci and others (1989); location of aquifer tests shown in figure 5; WD, Water Department; MUA, Municipal Utility Authority; Leakance represents the combined leakance of overlying and middle confining units except where * or ** are noted; *, Leakance of overlying confining unit; **, Leakance of middle confining unit; --, data missing or not applicable.]

Location number from figure 8	Aquifer test identifier and location	Aquifer-test date	Aquifer description	Transmissivity (feet squared per day)	Hydraulic conductivity (feet per day)	Storage coefficient (dimensionless)	Leakance (feet per day) per day
1	East Brunswick WD Phase I aquifer test East Brunswick Township	9/12/78-9/15/78	Unconfined	5,000	250	1.0×10^{-2}	--
2	East Brunswick WD Phase II (test well 6) aquifer test East Brunswick Township	10/30/78-11/6/78	Semiconfined	5,600	108	1.4×10^{-1}	--
3	East Brunswick Phase II (test well 8) aquifer test East Brunswick Township	1/24/79-2/1/79	Semiconfined	4,010	81	1.8×10^{-3}	--
4	Freehold Township aquifer test Freehold Township	5/14/84-5/17/84	Confined	7,500 - 8,420	50 - 56	3.3×10^{-4}	--
5	Hightstown WD aquifer test Hightstown Borough	3/10/77-3/23/77	Leaky confined	6,900	77	1.2×10^{-4}	3.0×10^{-4}
6	Madison Industries aquifer test Old Bridge Township	3/4/82	Unconfined	5,130 - 5,820	86 - 97	5.7×10^{-2}	--
7	Levitt and Sons aquifer test Aberdeen Township	1/23/62-1/26/82	Leaky confined	5,600	67	2.6×10^{-4}	1.5×10^{-5} 1.6×10^{-5}
8	Monroe MUA aquifer test Monroe Township	8/21/80-8/24/80	Leaky confined	15,450	150	1.0×10^{-5}	*2.5×10^{-2} **2.5×10^{-2}
9	Nestle aquifer test Freehold Borough	6/22/70-6/25/70	Confined	8,060	87	3.1×10^{-4}	--
10	Olympia & York aquifer test Old Bridge Township	7/8/81-7/10/81	Confined	5,400	84	1.9×10^{-4}	--
11	Perth Amboy WD aquifer test Old Bridge Township	3/73	Unconfined	1,760 - 2,850	26 - 41	4.0×10^{-5}	--
12	Parlin aquifer test Old Bridge Township	5/31/39-6/6/39	Unconfined	11,500 - 19,400	195 - 329	3.7×10^{-3} - 1.4×10^{-4}	--
13	Perth Amboy WD aquifer test Runyon	6/20/85-6/22/85	Unconfined	9,500	146	--	--
14	Spotswood WD aquifer test Spotswood Borough	3/18/58	Semiconfined	9,750	--	7.0×10^{-4}	--
15	Union Beach aquifer test Union Beach Borough	4/21/86-4/28/86	Leaky confined	8,400	120	4.2×10^{-4}	6.5×10^{-5}
--	RASA Model results [a] New Jersey Coastal Plain	--	--	3,000 - 11,000	--	1.0×10^{-4}- 8.0×10^{-4}	[a] 1.0×10^{-8} 5.0×10^{-4}

[a] Martin (1990, fig. 56)

The range of storage coefficients, derived from eight of the nine aquifer tests (tests 3, 4, 5, 7, 8, 9, 10, and 15, table 4), in the confined, semiconfined, and leaky confined areas of the upper aquifer range from 1.0 x 10^{-5} to 1.8 x 10^{-3}. The storage coefficient derived from test 2 (table 4) was 1.4 x 10^{-1}, which is more typical of an unconfined system than of a confined system. Interpretation of lithologic logs at this site and proximity to the general outcrop area of the aquifer indicate that the system is semiconfined at the site of test 2 (Pucci and others, 1989, p. 25).

Analysis of drawdown data from three of five aquifer tests in the unconfined area of the aquifer (tests 1, 6, and 12) yielded storage coefficients representative of unconfined aquifers, ranging from 3.7 x 10^{-3} to 5.7 x 10^{-2}. A storage coefficient below this range, 4.0 x 10^{-5}, was calculated for test 11, in which the well screen penetrated only 11 percent of the aquifer thickness. When the screened interval is a small fraction of the aquifer thickness, clay layers within the aquifer can limit the migration of water to the screen, and can result in a low estimate of the storage coefficient (Pucci and others, 1989). Although test 14 was done near the edge of the unconfined area of the upper aquifer, it resulted in a low storage coefficient (7.0 x 10^{-4}), which could indicate the presence of confining units at the site.

Pucci and others (1989) reported that leakage into the upper aquifer through the overlying and (or) underlying confining units was observed from the stresses caused by withdrawals at four locations (sites of aquifer tests 5, 7, 8, and 15) in the confined area (table 4; fig. 4). Leakage during test 8, in the shallow part of the aquifer, probably was derived from both confining units. Aquifer tests 4, 7, 9, 10, and 15 (table 4; fig. 4) were done in the central part of the study area, and leakage was observed at two locations (sites of tests 7 and 15). Results of test 25 (table 5), which was done in the middle aquifer near the site of test 8, also indicate that the confining unit between the middle and upper aquifers is leaky in this part of the study area. As discussed earlier, lithologic data confirm that the confining unit overlying the middle aquifer is thin or sandy--and probably is leaky--in the southwestern part of the study area; in parts of Jamesburg Borough, South Brunswick Township, and Cranbury Township; and in the northwestern part of the Hightstown Borough area (Gronberg and others, 1991).

Lithologic and geophysical logs of sediments at the site of test 5 indicate that the underlying confining unit is continuous. Pucci and others (1989) reported that most of the leakage calculated from results of test 5 probably is through the Merchantville-Woodbury confining unit. Results of test 22 (table 5), done in the middle aquifer near the location of aquifer test 5, show that the confining unit between the middle and upper aquifers is virtually impermeable.

The hydraulic properties of the sediments that fill the ancient Raritan River channel in Raritan Bay are not well known because no laboratory or field hydraulic tests or accurate mapping has been done. The paleochannel south of Staten Island was eroded into the upper aquifer and Merchantville-Woodbury confining unit and was filled with sediments of varying permeability.

Table 5.--Summary of reported range of values for hydraulic properties of the middle aquifer

[All aquifer-test results reported by Pucci and others (1989); location of aquifer tests shown in figure 15; WD, Water Department; MUA, Municipal Utility Authority; * Leakance of the confining unit overlying middle aquifer; **, vertical hydraulic conductivity of the confining unit overlying middle aquifer, ft/d; --, data missing or not applicable.]

Location number from figure 15	Aquifer test identifier and location	Aquifer test Date	Aquifer description	Transmissivity (feet squared per day)	Hydraulic conductivity (feet/day)	Storage coefficient (dimensionless)	Leakance (feet/day) /feet
16	Dupont aquifer test Sayreville Borough	6/16/44	Confined	7,750	91	4.8×10^{-5}	--
17	East Brunswick #4 aquifer test East Brunswick Township	7/8/75-7/10/75	Confined	9,800 - 10,400	140 - 148	1.4×10^{-4}	--
18	East Brunswick #5 aquifer test East Brunswick Township	7/7/75-7/9/75	Confined	10,200 - 13,180	111 - 143	3.4×10^{-3}	--
19	East Brunswick #6 aquifer test East Brunswick Township	9/29/75-9/30/75	Confined	9,630 - 10,600	116 - 128	8.0×10^{-5}	--
20	East Brunswick #7 aquifer test East Brunswick Township	10/16/75-10/17/75	Confined	9,400	171	4.2×10^{-5}	--
21	Hercules aquifer test Sayreville Borough	6/16/44	Confined	7,420	114	1.6×10^{-3}	--
22	Hightstown aquifer test Hightstown Borough	3/10/77-3/23/77	Confined	11,500	100	5.0×10^{-5}	--
23	Marlboro MUA aquifer test Marlboro Township	4/3/72	Leaky confined	9,800	100	1.0×10^{-4}	$*7.0 \times 10^{-4}$
24	Runyon, Old Deep aquifer test Old Bridge Township	8/41	Confined	6,250	76	3.0×10^{-4}	--
25	South Brunswick aquifer test South Brunswick Township	5/21/56-5/29/56	Leaky confined	11,800	200	3.5×10^{-4}	$*1.1 \times 10^{-3}$
26	Spotswood 1976 aquifer test Old Bridge Township	4/21/76-4/27/76	Confined	13,800	153	2.2×10^{-4}	--
27	Woodbridge aquifer test Woodbridge Township	3/25/57-3/28/57	Confined	2,140 - 2,145	36	2.6×10^{-5} - $2.3. \times 10^{-4}$	2.3×10^{-3}
--	Model results [a] Middlesex, Monmouth, Southeastern Mercer and northern Ocean Counties	--	--	42 - 16,800	105	1.6×10^{-4}	3.6×10^{-2} - 8.6×10^{-6}
--	Model results [b] New Jersey Coastal Plain	--	--	4,000 - 22,000	--	1.0×10^{-4} - 8.0×10^{-4}	$*5.0 \times 10^{-7}$ - $*1.0 \times 10^{-4}$

[a] From Farlekas (1979, p. 32 and 51)
[b] From Martin (1990, figs. 56 and 66)

Ground-water withdrawals

Reported withdrawals from the upper aquifer within the study area began at the Perth Amboy Water Works in 1902 (Barksdale and others, 1943, p. 72). The largest volume of the water withdrawn during the early development of the aquifer was from or near the outcrop area of the Old Bridge Sand Member of the Magothy Formation, in the unconfined part of the upper aquifer. Since the early 1900's, the distribution of withdrawal centers has changed with growth in population and expansion of population and commercial and industrial development to the south and east into confined parts of the aquifer in both Middlesex and Monmouth Counties. Horn and Bratton (1991) reported that, for the period 1981-85, the upper aquifer provided about 57 percent of ground water used for public, industrial, and commercial supply in Middlesex and Monmouth Counties. The locations of the major water users within the modeled area described in this report (fig. 25) and a graphical representation of their 1985 withdrawals are shown in figure 6.

Table 6 is a summary of rates of ground-water withdrawal from the upper aquifer by major ground-water purveyors. Withdrawal rates are reported as averages in million gallons per day for pumping periods, or stress periods, from 1896 through 1985. These pumping periods were used for numerical analysis of ground-water flow. In 1985, the largest users of ground water in Middlesex County were Duhernal Water Company, Perth Amboy Water Works, Anheuser-Busch, Inc.[1], Sayreville Water Department, Monroe Township Municipal Utility Authority (MUA), Old Bridge MUA, and P.J. Schweitzer, Inc.; in Monmouth County the largest users were Monmouth Consolidated Water Company (WC) (outside modeled area, and not in table 6), Gordons Corner WC, Shoreline WC, Keansburg MUA, Freehold Township Water Department, and Aberdeen Township MUA.

Annual withdrawal rates for the upper aquifer in all of Middlesex and Monmouth Counties for the period 1900-85 are shown in figure 7. Except for a period of decline in production from the upper aquifer in the 1920's, withdrawal rates in the upper aquifer increased fairly steadily until about 1970. The decline in total annual withdrawals since 1971 has resulted principally from reductions in withdrawal rates by Duhernal WC and Perth Amboy Water Works (table 6) and from the shutdown of wells in Keyport and Union Beach Borough municipal well fields because of the saltwater intrusion (Schaefer and Walker, 1981). For 1985, withdrawals from the upper aquifer were about 43 Mgal/d (fig. 7).

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[1] The use of firm names in this report is for identification or location purposes only and does not impute responsibility for any present or potential effects on water resources in the study area.

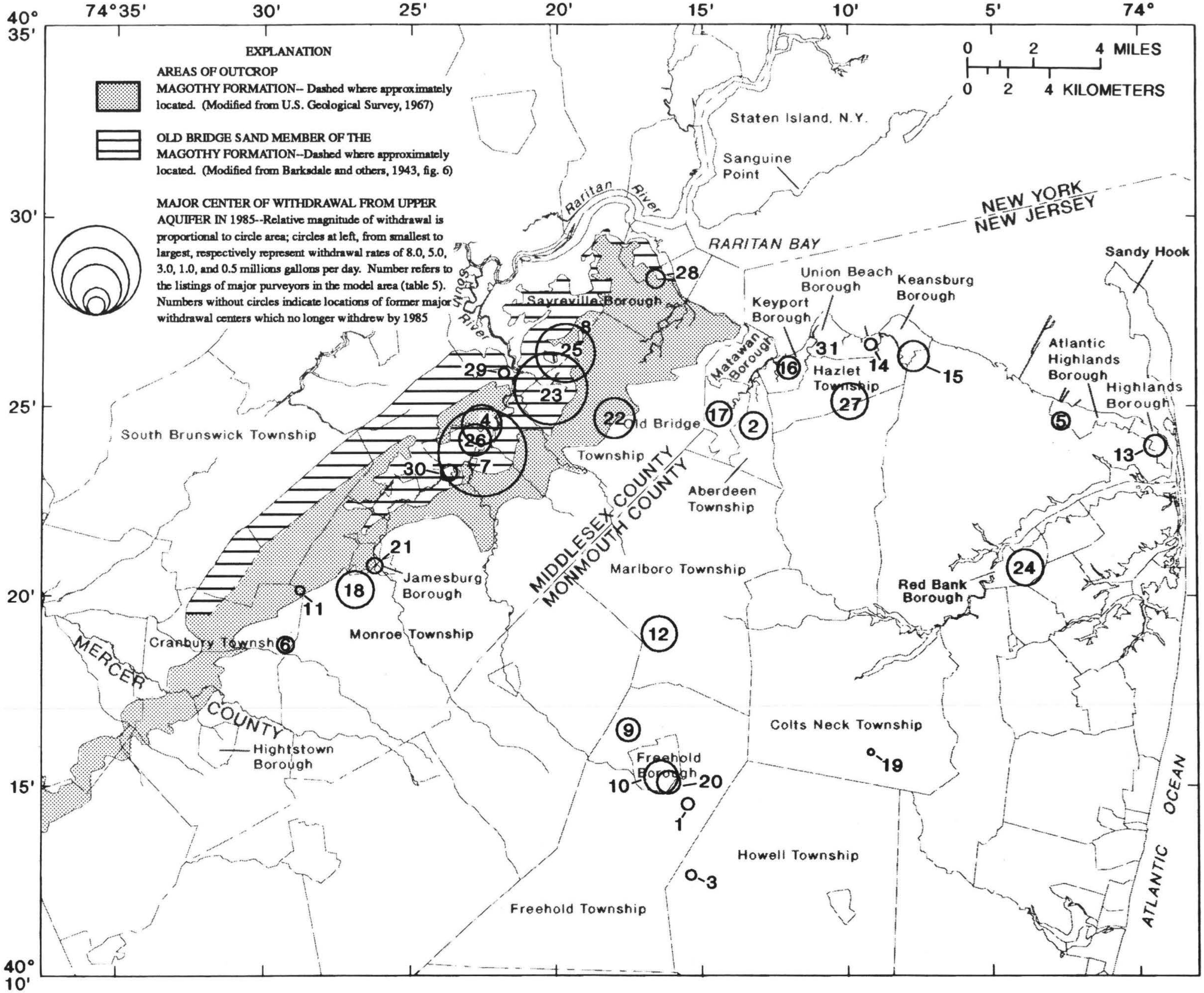


Figure 6.--Locations of major withdrawal centers in the upper aquifer, 1985.

Potentiometric surface

The predevelopment potentiometric surface of the upper aquifer shown in figure 8 was constructed from water levels measured before 1900 or from water levels measured in wells after 1900 that were in areas considered to be unaffected by withdrawals. A ground-water high in Cranbury and Monroe Townships in southwestern Middlesex County corresponds to a topographic high and a regional recharge area for the upper aquifer. Ground-water flow is toward low-lying streams in the north and toward discharge regions in Raritan Bay and the Atlantic Ocean.

The potentiometric surfaces in the upper aquifer in 1959 and 1983 are shown in figures 9 and 10, respectively. By 1959, heads in the upper aquifer had declined as much as 40 ft, and a cone of depression had developed in the northern part of the study area near Keyport and Keanesburg Boroughs and Hazlet Township (Farlekas, 1979). By 1983, increased withdrawals had lowered heads to as much as 90 ft below predevelopment heads and had created new cones of depression in parts of Freehold, Marlboro, Colts Neck, and Howell Townships in Monmouth County. The lowering of the potentiometric surface has caused the direction of ground-water flow in eastern Monmouth County to reverse from the predevelopment flow direction.

Maps of more recent potentiometric surfaces were prepared from two synoptic measurements of water levels in wells in November 1984 and in early spring 1986. Heads calculated from these synoptic water-level measurements represent the potentiometric surface that has resulted from current and historical withdrawal patterns. Measurements in production wells were made about 1 hour after pumping was stopped, if possible. Pumps on nearby production wells were not shut off before water levels in observation wells were measured; therefore, these synoptic measurements reflect water levels under stress conditions. For the 1983 synoptic measurements, pumps on most production wells were shut off the day before water-level measurements were made in production wells.

The 1984 and 1986 synoptic measurements were timed to observe the seasonal high and low water levels. In general, heavy withdrawals during summer lower the water level to a minimum from late summer through fall. Water levels recover through winter and reach an annual high in late winter or early spring. The first synoptic measurement was completed in early November 1984, when the water levels had recovered partially from the maximum seasonal drawdowns. The second synoptic measurements were completed in late March and early April 1986, when water levels presumably had recovered from the previous drawdowns.

The potentiometric surface in the upper aquifer determined from water levels in 94 wells during the fall 1984 synoptic measurements is shown in plate 1a (data are listed in appendix B, at end of report). The most significant features of the potentiometric surface of the upper aquifer in 1984 are the generally lowered heads (from 60 to 80 ft below predevelopment levels in Monmouth County) and large cones of depression, which are 30 ft below sea level in northern Holmdel Township, southern Marlboro and northern Freehold Townships, and Neptune Township, all in Monmouth County. Heads at the centers of the cones of depression in fall 1984 were 38 ft below sea level (well 25-85) in Marlboro Township, 42 ft below sea level (well 25-154) in Holmdel Township, and 46 ft below sea level (well 25-333) in Neptune Township. Small cones of depression also are noted in Highlands Borough and near Red Bank in Monmouth County.

The potentiometric surface based on water levels measured in 101 wells during spring 1986 is shown in plate 1b. The broad cone of depression throughout Monmouth County is the most significant feature of the 1986 potentiometric surface of the upper aquifer. The contour line for 30 ft below sea level is centered on cones of depression in southern Marlboro Township and Howell and Freehold Townships, all in Monmouth County. Heads in the centers of the cones of depression in spring 1986 were 39 ft below sea level (well 25-251) in Marlboro Township and 36 ft below sea level (well 25-174) in Howell Township.

Confining Unit Overlying the Middle Aquifer

Farlekas (1979, p. 16) reported that the confining unit between the middle and upper aquifers consists mainly of the Woodbridge Clay Member of the Raritan Formation. Locally, the confining unit can also include the clayey lithofacies of the overlying South Amboy Fire Clay Member of the Raritan Formation and the Sayreville Sand Member. This confining unit is a thick, continuous unit of clay and silt whose general outcrop area is delineated by Gronberg and others (1991) as the area southeast of the unconfined area of the middle aquifer of the Potomac-Raritan-Magothy aquifer system, or the outcrop of the Farrington Sand Member of the Raritan Formation, and the area northwest of the unconfined area of the upper aquifer of the Potomac-Raritan-Magothy aquifer system, or the outcrop of the Old Bridge Sand Member of the Magothy Formation. Southeast of the outcrop area, the confining unit generally is greater than 100 ft thick (fig. 11). In the northeastern part of the study area, in Holmdel Township, this unit is as much as 241 ft thick (Gronberg and others, 1991).

In the southwestern part of the study area, the confining unit contains a high proportion of sand, and its thickness generally is less than 100 ft (fig. 11) (Gronberg and others, 1991). The confining unit thins to 39 ft in Monroe Township and to 26 ft in Cranbury Township (Gronberg and others, 1991). Further to the southwest, near the Middlesex-Mercer County line, geophysical logs and surface geophysical data show that the confining unit is sandy (Gronberg and others, 1989) and may be discontinuous (S.K. Sandberg and others, New Jersey Geological Survey, written commun., 1989).

The variation in the thickness and lithology of the confining unit probably is the result of one or more of a number of depositional and post-depostional factors. One possible reason for the change in lithology is the influence of the basement structure on the deposition of the sediments. Proximity to a junction of the basement tectonic features could have caused a thinning or change in the lithology of the sediments (Owens and Sohl, 1969, p. 237; Owens and Gohn, 1985, p. 26). The absence of the Woodbridge Clay Member could also be the result of post-depositional erosion and reworking of the sediments by the flow of the ancestral Hudson River or one of its tributaries (Owens and Minard, 1979, p. D19).

Table 6.--Withdrawal rates of major ground-water purveyors, by pumping period, upper aquifer, 1896-1985

[Withdrawal rates, in million gallons per day, are averages reported for pumping periods that correspond to simulation periods discussed in this report; --, no data reported and no withdrawals used for that simulation period; MUA, Municipal Utilities Authority; WD, Water Department; Twp, Township; Boro, Borough; Co., Company; Corp., Corporation; Inc., Incorporated]

Location number from figure 6	Owner	Municipality	Withdrawal rate by pumping period					
			1 (1896-1920)	2 (1921-1945)	3 (1946-1952)	4 (1953-1957)	5 (1958-1964)	6 (1965-1967)
1	3M Co.	Freehold Twp	--	--	--	0.036	0.259	0.363
2	Aberdeen Twp MUA	Aberdeen Twp	0.023	0.128	0.088	.247	.162	.784
3	Adelphia Water Co.	Howell Twp	--	--	--	--	--	--
4	Anheuser-Busch Corp.	E. Brunswick Twp	--	.195	.552	.870	.803	.493
5	Atlantic Highland WD	Atlantic Highlands Boro	--	.055	.319	.394	.508	.285
6	Carter Wallace Corp.	Cranbury Twp	--	--	.005	.036	.280	.323
7	Duhernal Water Co.	Old Bridge Twp	--	2.578	12.956	14.476	13.419	13.847
8	E. I. Dupont Corp.	Sayreville Boro	--	.246	.157	.015	--	--
9	Freehold Borough WD	Freehold Twp	.042	.463	.670	.640	.820	.966
10	Freehold Twp WD	Freehold Twp	--	--	--	--	.032	.301
11	General Foods, Inc.	Cranbury Twp	--	--	--	.027	.078	.079
12	Gordons Corner Water Co.	Marlboro Twp	--	--	--	--	.027	.106
13	Highlands WD	Highlands Boro	.113	.277	.357	.342	.356	.417
14	Int Flavor Frag, Inc.	Union Beach Boro	--	--	.008	.051	.113	.218
15	Keansburg MUA	Keansburg Boro	.066	.526	1.007	1.255	1.379	1.480
16	Keyport Borough WD	Keyport Boro	.036	.462	.754	.958	1.116	1.115
17	Matawan Borough WD	Matawan Boro	--	.016	.258	.441	.543	.792
18	Monroe Twp MUA	Monroe Twp	--	--	.008	.061	.051	.041
19	NAD EARLE	Colts Neck Twp	--	.006	.104	.138	.139	.139
20	Nestle Co.	Freehold Boro	--	--	.113	.317	.411	.532
21	N.J. Water Co.	Jamesburg Boro	.011	.058	.111	.166	.242	.331
22	Old Bridge MUA	Old Bridge Twp	--	--	.096	.227	.569	.947
23	Perth Amboy WD	Old Bridge Twp	1.136	4.556	4.710	7.429	7.724	7.130
24	Red Bank WD	Red Bank Boro	--	--	.164	.456	.684	.861
25	Sayreville WD	Sayreville Boro	--	--	--	--	1.304	2.484
26	P.J. Schweitzer, Inc.	Spotswood Boro	--	.006	.476	1.198	2.618	2.921
27	Shoreline Water Co.	Hazlet Twp	--	--	--	--	.795	1.326
28	South Amboy WD	Sayreville Boro	--	.832	.730	.749	.568	.299
29	South River WD	South River Boro	.051	.165	.222	.203	.240	.345
30	Spotswood WD	Spotswood Boro	--	--	--	.030	.299	.400
31	Union Beach WD	Union Beach Boro	--	.080	.252	.415	.475	.485

Table 6.--Withdrawal rates of major ground-water purveyors, by pumping period, upper aquifer, 1896-1985--Continued

Location number from figure 6	Withdrawal rate by pumping period						Number of wells in service during 1896-1985
	7 (1968-1972)	8 (1973-1977)	9 (1978-1980)	10 (1981-1983)	11 (1/1/84-12/31/84)	12 (1/1/85-12/31/85)	
1	0.363	0.296	0.182	0.264	0.273	0.234	1
2	1.035	1.088	1.046	.914	.727	.999	6
3	.016	.096	.105	.128	.138	.167	2
4	.565	1.169	1.266	1.551	1.956	1.958	7
5	.449	.505	.528	.481	.473	.468	4
6	.334	.391	.448	.358	.468	.424	5
7	13.508	11.062	11.301	9.148	7.796	7.920	26
8	--	--	--	--	--	--	1
9	1.159	1.578	1.611	1.101	1.061	.761	6
10	.510	1.117	1.371	1.550	1.714	1.446	5
11	.148	.121	.088	.084	.136	.140	2
12	.363	.887	.813	1.008	1.222	1.581	5
13	.541	.613	.505	.573	.663	.672	5
14	.308	.440	.368	.351	.334	.231	5
15	1.461	1.410	1.499	1.310	1.270	1.240	8
16	.931	.875	.833	.824	.663	.727	7
17	.939	1.412	1.015	.896	.855	.871	4
18	.174	.412	.606	.910	1.284	1.735	7
19	.133	.114	.111	.113	.077	.077	2
20	1.104	1.536	1.634	1.144	.861	.743	3
21	.397	.415	.407	.459	.386	.377	3
22	1.052	1.273	2.027	2.176	2.364	1.990	6
23	7.719	5.063	4.979	4.738	5.514	5.578	14
24	1.008	1.332	1.643	1.675	1.735	1.686	2
25	2.168	2.015	1.864	2.718	3.367	3.425	15
26	3.104	2.532	2.073	1.673	1.381	1.317	10
27	1.927	2.059	1.989	1.908	1.766	1.671	3
28	.623	.393	.080	.148	.550	.512	5
29	.296	.307	.318	.193	.247	.178	1
30	.569	.598	.418	.411	.387	.419	4
31	.593	.843	--	--	--	--	4

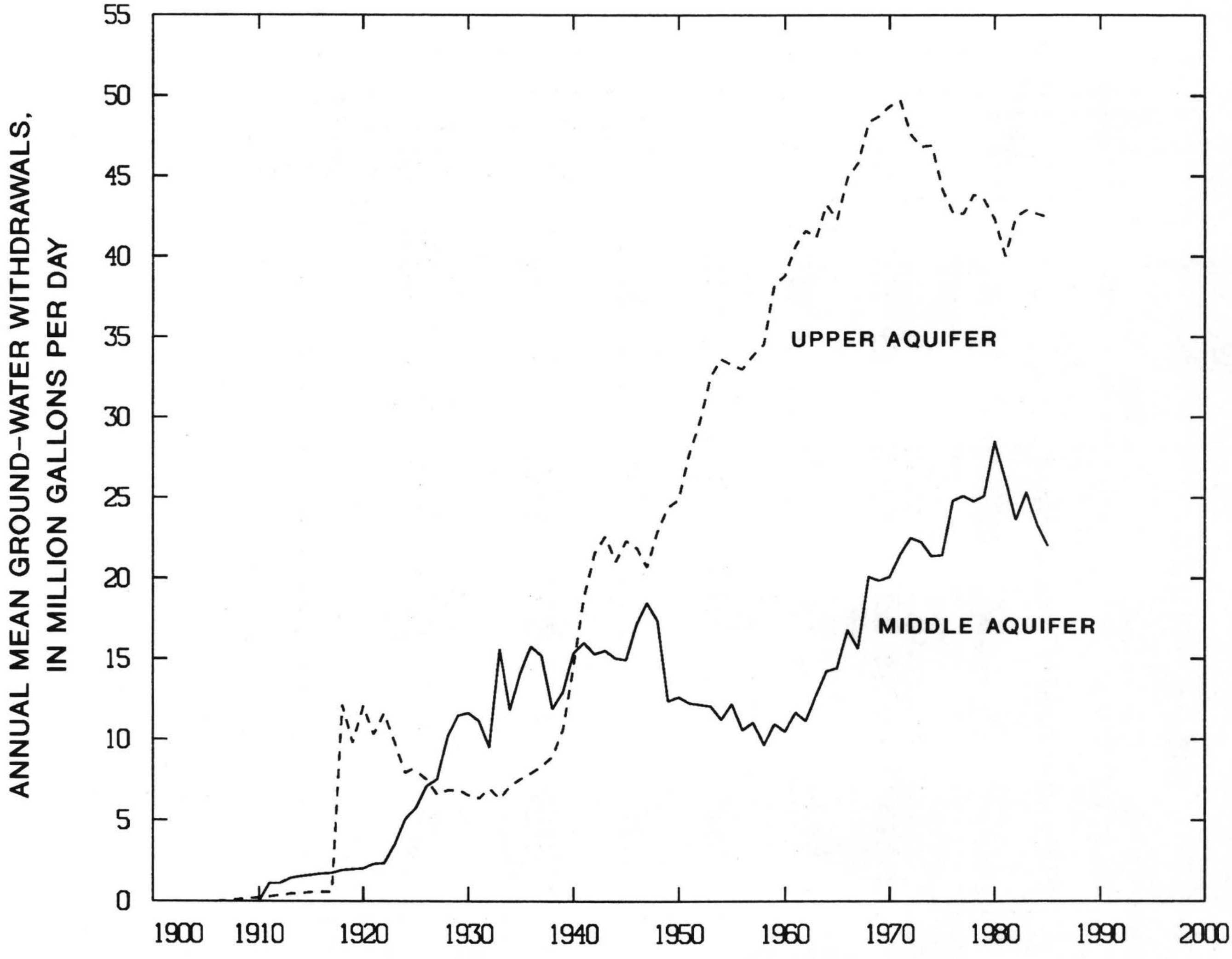


Figure 7.--Rates of withdrawal from the upper and middle aquifers in Middlesex and Monmouth Counties.

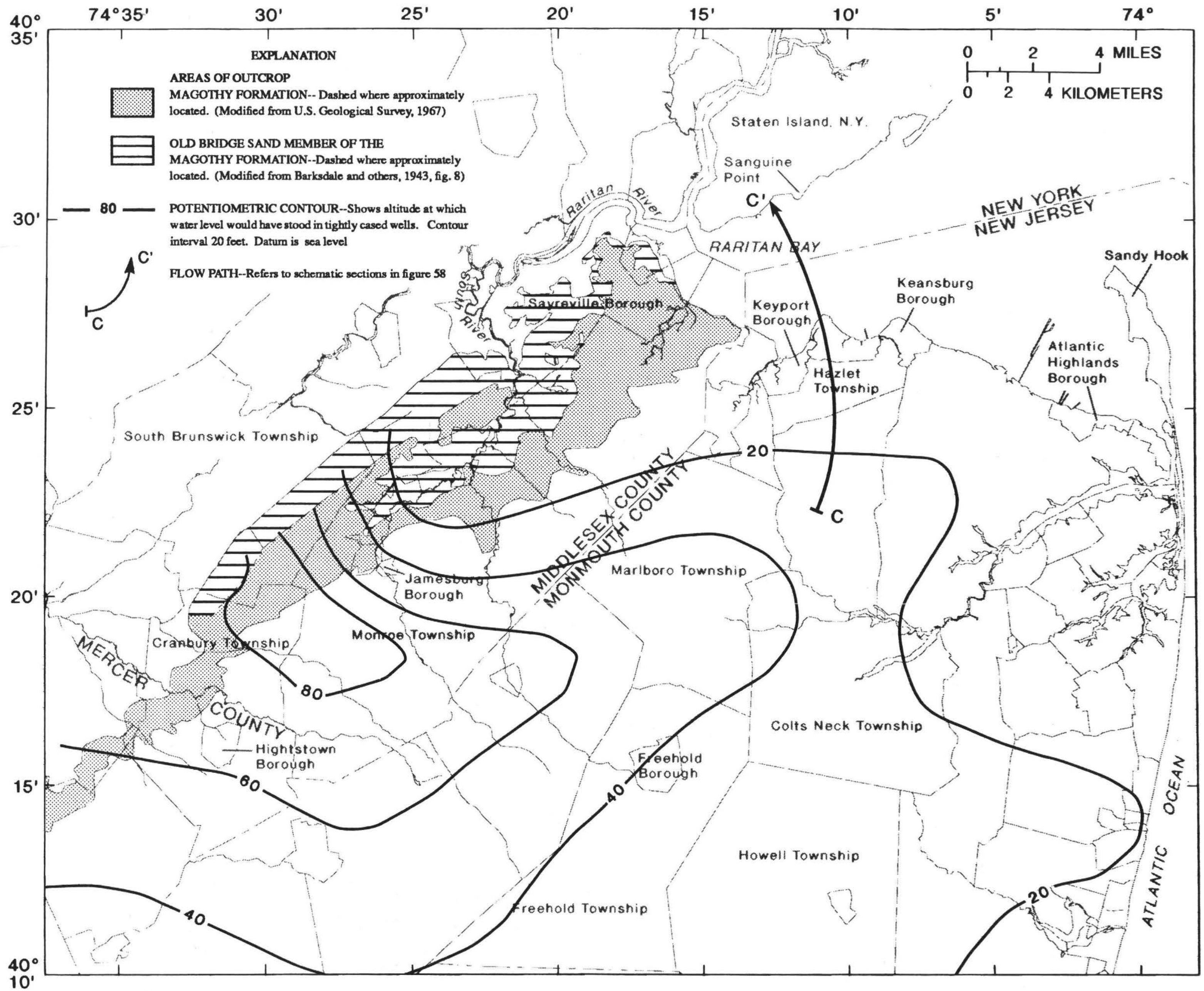


Figure 8.--Predevelopment potentiometric surface in the upper aquifer. (Modified from Zapecza and others, 1987, fig. 4)

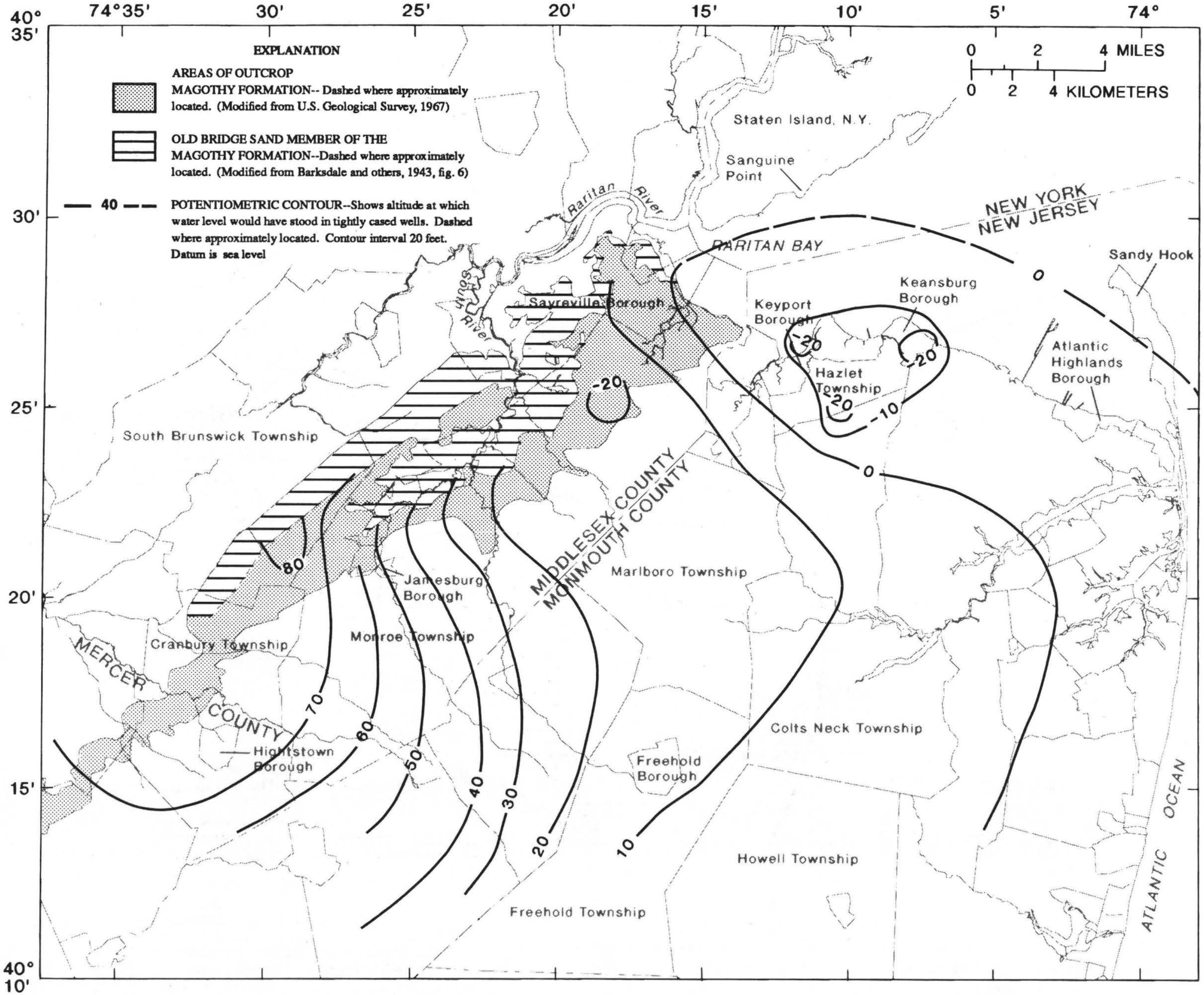


Figure 9.--Potentiometric surface in the upper aquifer, 1959. (From Farlekas, 1979, fig. 10)

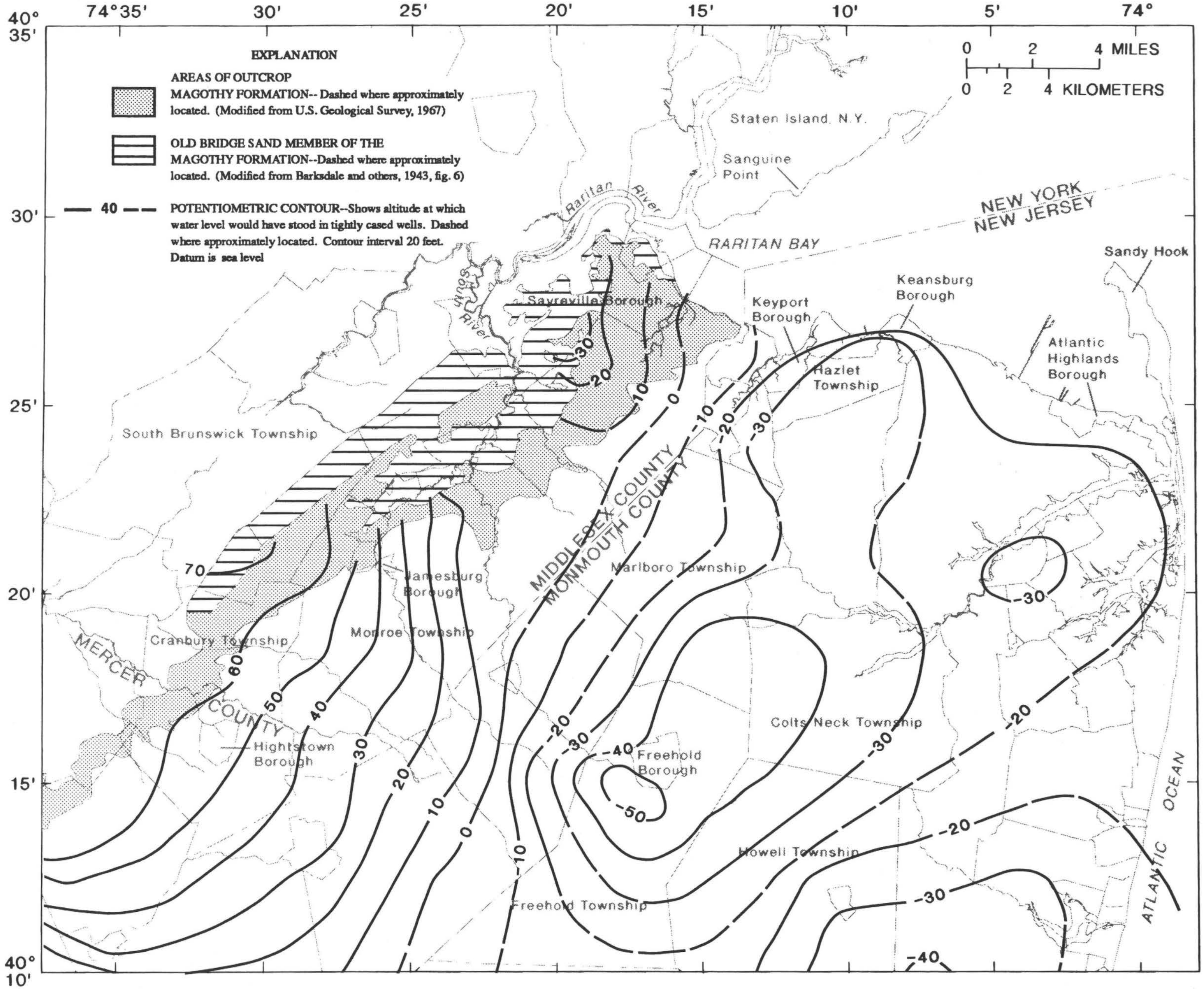


Figure 10.--Potentiometric surface in the upper aquifer, 1983. (Modified from Eckel and Walker, 1986, pl. 3)

The lithology and decreased thickness of the confining unit in the southwestern part of the study area results in a significant hydraulic connection between the upper and middle aquifers. This hydraulic connection causes the aquifers to respond similarly, rather than independently, to hydraulic stresses. Hydrographs of two pairs of nested wells near the area in which the confining unit between the middle and upper aquifers is thin and sandy (wells 23-228 and 23-229 in Monroe Township; wells 23-291 and 23-292 in South Brunswick Township; see fig. 11) demonstrate that the aquifers tend to respond similarly to hydraulic stresses. Each pair of nested wells is screened separately in the upper aquifer and in the middle aquifer. Water-level records from the early 1960's show that water-level trends in both aquifers are similar through time, although the water levels in wells in the upper aquifer generally are 4 to 6 ft higher (figs. 12 and 13).

Middle Aquifer

The middle aquifer is composed of the Farrington Sand Member of the Raritan Formation in most of the northern Coastal Plain of New Jersey. It also includes younger surficial sand and gravel at or near the outcrop area (Farlekas, 1979, p. 8). The middle aquifer is characterized by fine to coarse sand containing minor amounts of lignite and pyrite (Farlekas, 1979, p. 8). Locally, it also contains clay beds (Barksdale and others, 1943, p. 104-105) and, in Monmouth County, it can include the uppermost sands of the Potomac Group (Farlekas, 1979, p. 9).

The middle aquifer is usually identified as the sand unit beneath a thick and continuous confining unit. In areas where the overlying confining unit becomes sandy or contains many sandy layers, identification of the top of the aquifer is difficult (Gronberg and others, 1991). The base of the aquifer is marked by the presence of the Raritan fire clay, pre-Cretaceous bedrock, and saprolitic clay in the Mercer and Middlesex Counties part of the study area. Southeast of the Middlesex-Monmouth County line, the base of the aquifer is considered to be the first layer of clay beneath the middle aquifer that is more than 20 ft thick (Farlekas, 1979, p. 7).

The altitude of the top the middle aquifer is shown in figure 14. In general, the aquifer strikes northeast-southwest and dips to the southeast at approximately 60 ft/mi (Gronberg and others, 1991). In the downdip areas of Monmouth County, the great variation of lithologic material makes it difficult to distinguish the middle aquifer from other beds within the Potomac Group and Raritan Formation (Zapecza, 1989, p. B11). The log of well 25-566 (Gronberg and others, 1989, p. 133), the Oak Rise Drive test borehole in Freehold Township, New Jersey (table 3; fig. 2), shows the great thickness of undifferentiated sediment.

The thickness of the middle aquifer is shown in figure 15. Thickness contours generally are parallel to the strike. The aquifer thickness generally ranges from about 75 to 150 ft and is greatest near East Windsor, where the maximum measured thickness is 168 ft. Along the shore of Raritan Bay the middle aquifer ranges in thickness from 33 ft (in Aberdeen Township) to 81 ft (in Union Beach Borough) (Gronberg and others, 1991).

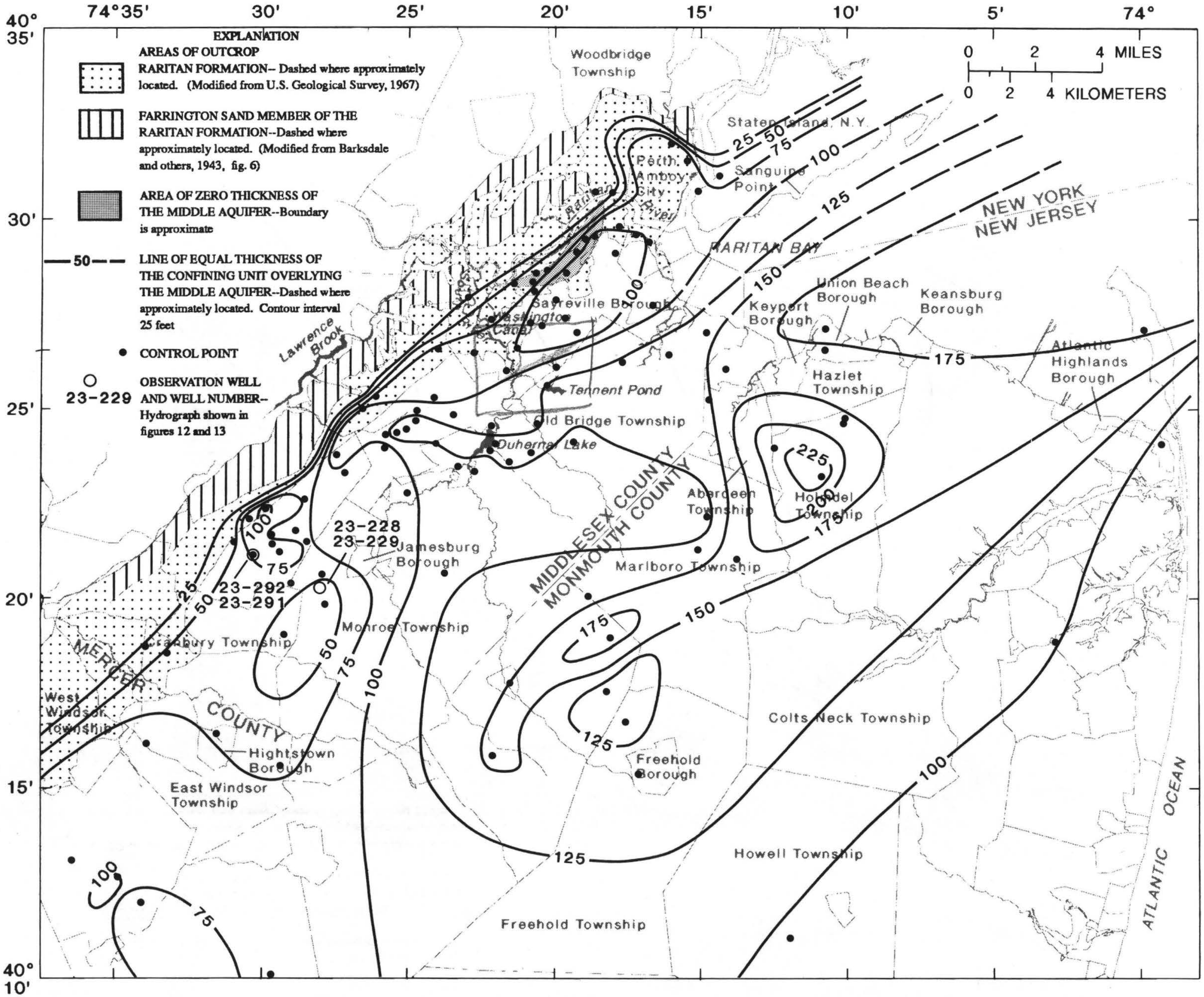


Figure 11.--Thickness of the confining unit overlying the middle aquifer. (Modified from Gronberg and others, 1991, pl.5)

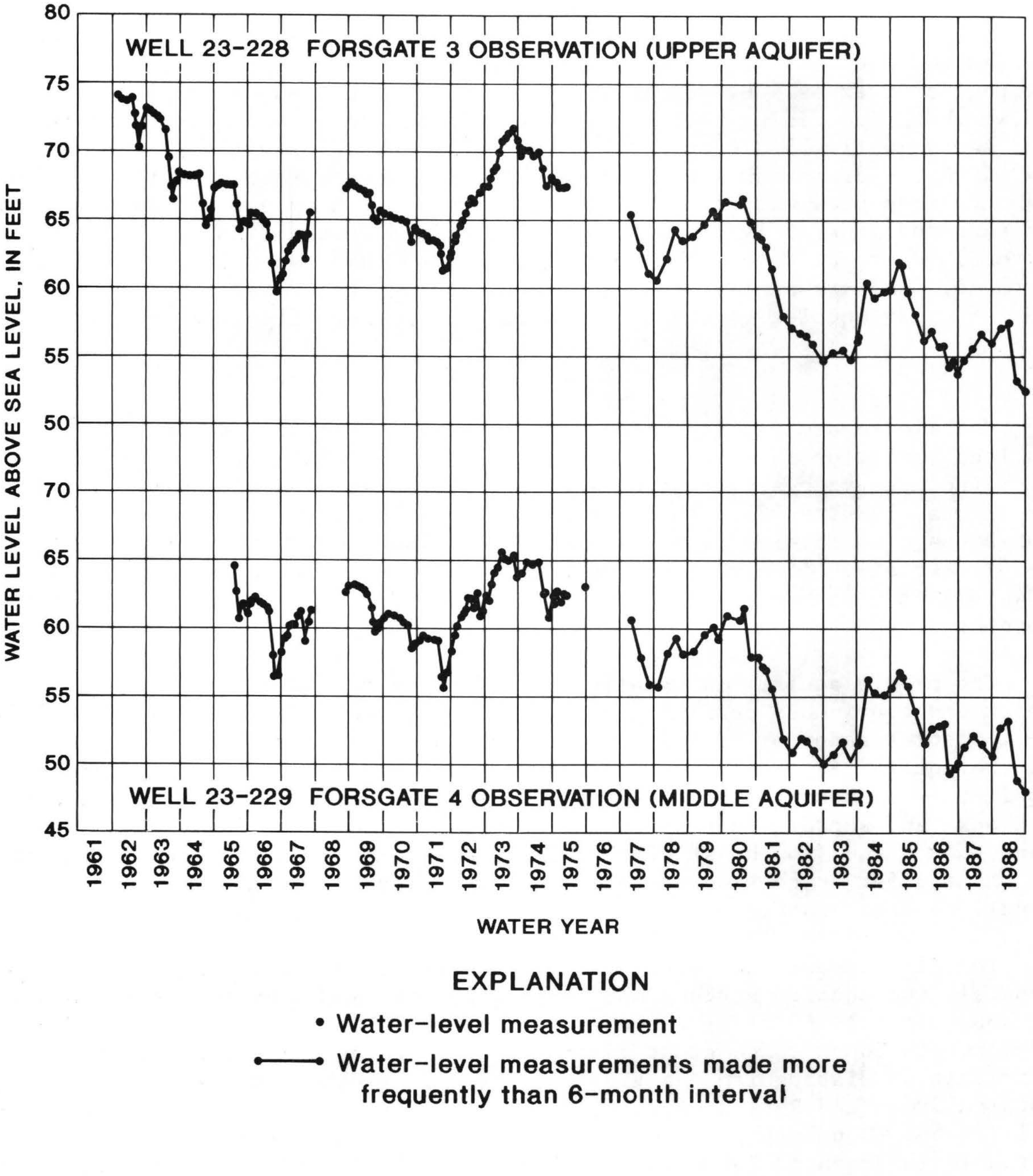


Figure 12.--Water levels in nested observation wells 23-228 and 23-229, screened in the upper and middle aquifers. (Locations of wells shown in fig. 11)

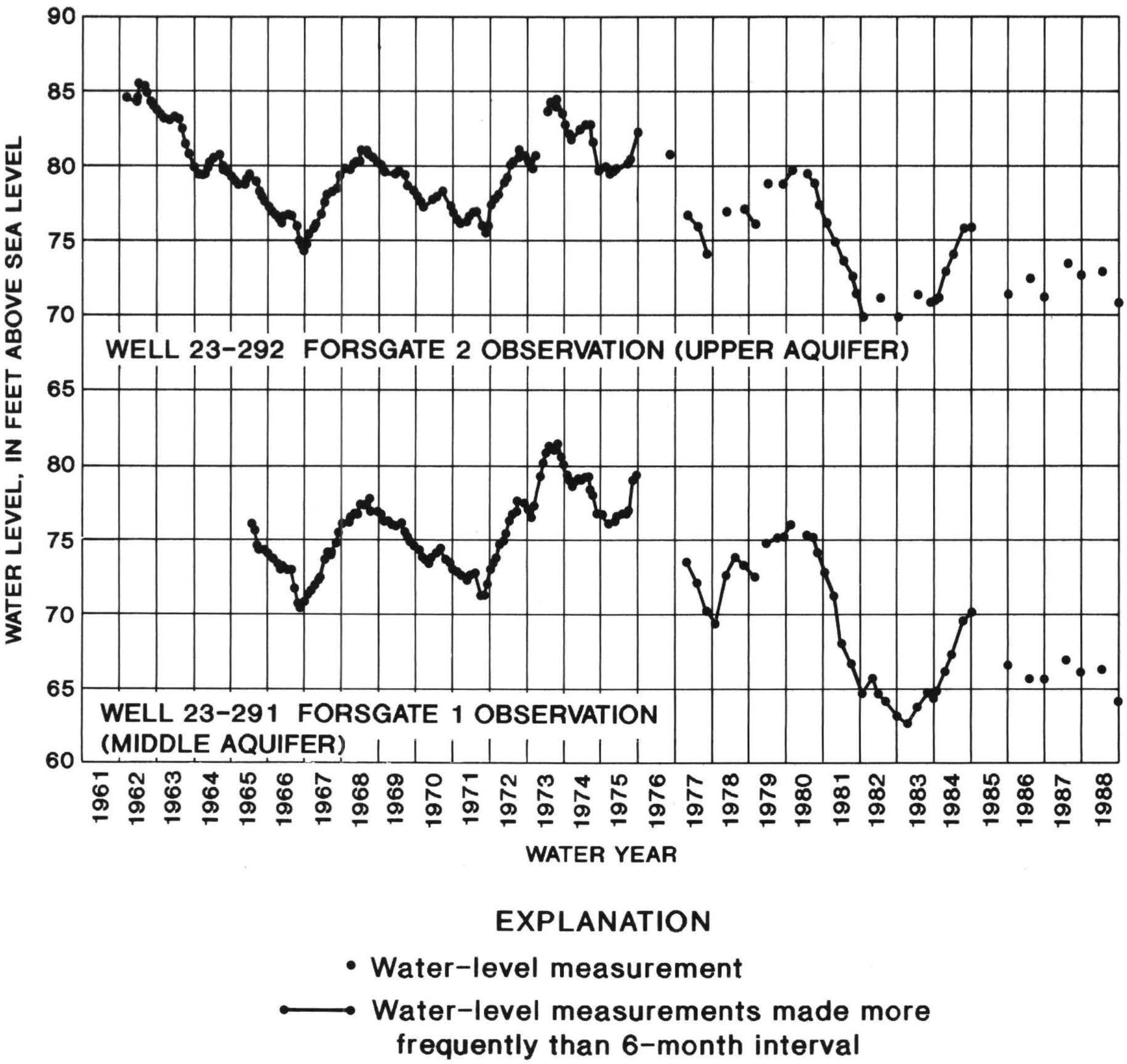


Figure 13.--Water levels in nested observation wells 23-291 and 23-292, screened in the upper and middle aquifers. (Locations of wells shown in fig. 11)

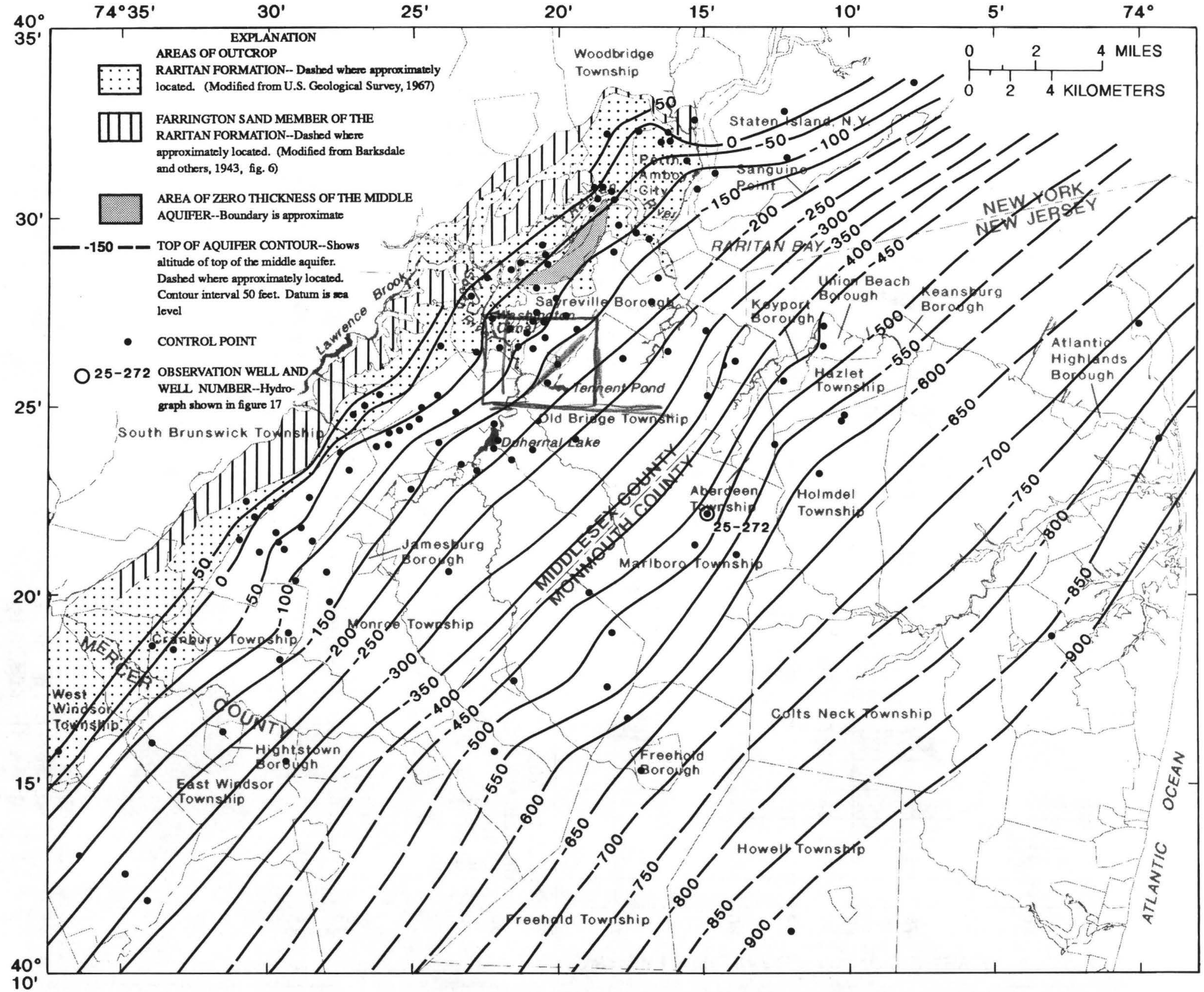


Figure 14.--Structure contours of the top of the middle aquifer. (Modified from Gronberg and others, 1991, pl.3)

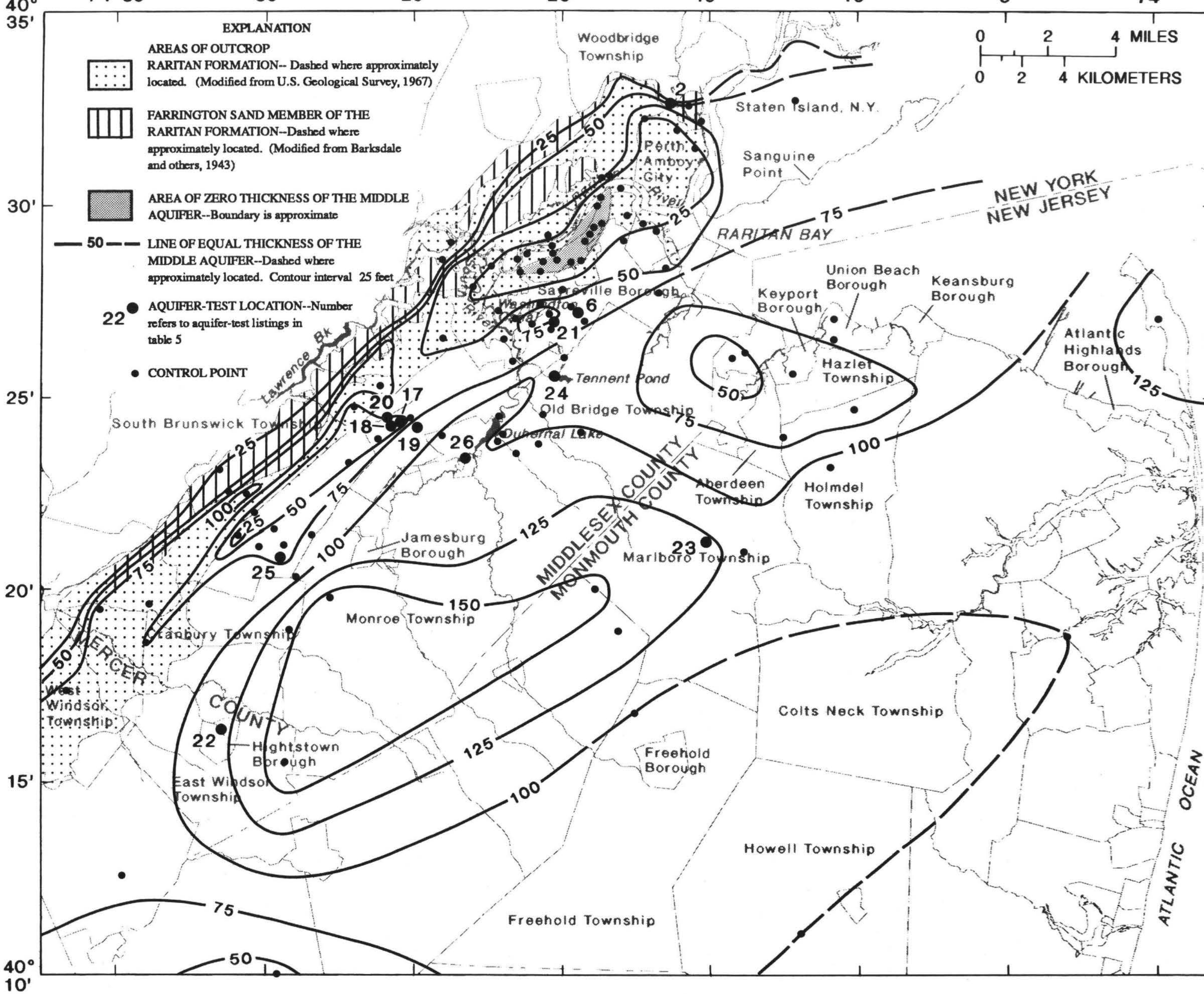


Figure 15.--Thickness of the middle aquifer. (Modified from Gronberg and others, 1991, pl.4)

As shown in figure 15, the middle aquifer is thin or absent south of the Raritan River in Sayreville Borough and neighboring townships (Gronberg and others, 1991, pl. 2), probably as a result of postdepositional erosion (S.K. Sandberg and others, New Jersey Geological Survey, written commun., 1989). Sea level was 300 ft lower during Pleistocene time, and the ancient Raritan River cut a channel to, or almost to, bedrock, from the mouth of Lawrence Brook to Perth Amboy. Sediments filled the channel as sea level rose. These sediments consisted mainly of poorly permeable river silts and clays and some sand and gravel. Where these fine sediments are present, the hydraulic connection between the part of the aquifer north of the Raritan River and the part south of the river is minimal (Barksdale, 1937, p. 5-7; Farlekas, 1979, p. 8). Alternatively, the absence of middle aquifer could be the result of the presence of the Palisades diabase sill, which formed a ridge of bedrock that prevented deposition of the Farrington Sand Member (Barksdale, 1937, p. 6-7).

The construction of the Washington Canal in Sayreville Borough was accomplished by removal of confining-unit material that separated the middle aquifer from the brackish estuarine water at the surface. Dredging in 1929 removed additional alluvium and exposed the middle aquifer to the brackish surface water (Barksdale, 1937, p. 9; Appel, 1962, p. 12). In other areas, such as the southwestern part of the outcrop near West Windsor and Plainsboro, the overlying confining unit thins, is absent, or becomes sandy, and the aquifer is exposed to or connected with overlying sediments.

Hydraulic properties

A summary of hydraulic properties of the middle aquifer is listed in table 5. The table includes results of aquifer-test analyses (aquifer-test locations are shown in figure 15) and calibrated model results. The discussion in this section summarizes results from aquifer and well-acceptance tests (Pucci and others, 1989, tables 4 and 6). Discussion of calibrated model results are included later in the report.

The transmissivity of the middle aquifer, determined from the 12 aquifer tests done in the study area, ranges from 2,140 to 13,800 ft^2/d. Transmissivities at the low end of this range in the northern half of the study area, in Sayreville Borough (test 16 and 21), Old Bridge Township (test 24), and Woodbridge Township (test 27) (Hardt and Jablonski, 1959), are attributed to the thinness of the aquifer in these areas (Pucci and others, 1989). Removal of these four aquifer tests from consideration results in a range in transmissivity from 9,400 to 13,800 ft^2/d.

The horizontal hydraulic conductivity of the middle aquifer, determined from aquifer-test and well-acceptance-test data, ranges from 17 to 385 ft/d (Pucci and others, 1989, tables 4 and 6). Hydraulic conductivities less than or equal to 100 ft/d were found in isolated locations throughout the study area; however, areas in which hydraulic conductivities are greater than 100 ft/d were concentrated near the outcrop area of the Farrington Sand Member of the Raritan Formation (Pucci and others, 1989).

Storage coefficients derived from aquifer-test analyses of the middle aquifer range from 2.6×10^{-5} to 3.4×10^{-3} (table 5). As previously mentioned, errors in the storage coefficient can result if the screened interval of the pumped well is small compared to the aquifer thickness and if the aquifer contains semipermeable units that retard the vertical flow of water. For these reasons, the most accurate estimates of the storage coefficient were derived from six aquifer tests (tests 16, 17, 20, 23, 24, and 26; table 5) in which the well screen in the pumped well extends through a large part of the aquifer (Pucci and others, 1989). The storage coefficient for these six tests ranges from 4.2×10^{-5} to 3.0×10^{-4}.

Results of the aquifer tests in the middle aquifer indicate that the overlying confining unit in most of the study area is relatively impermeable; however, leakage from the confining unit was observed at three test locations (tests 23, 25, and 27; table 5). Leakage from the underlying basal fire clay (tables 1 and 2) and bedrock is assumed to be negligible in this analysis; leakage into the middle aquifer is more likely to be from the overlying confining unit. The results of tests 23, 25, and 27 indicate a range of leakance from 7.0×10^{-4} (ft/d)/ft to 1.1×10^{-3} (ft/d)/ft for this unit.

Ground-water withdrawals

The first recorded withdrawals from the middle aquifer in the study area were at the Perth Amboy Water Works in 1897. Industrial development in Perth Amboy, South Amboy, and Sayreville during World War I resulted in a sudden increase in the use of water from the aquifer (Barksdale and others, 1943, p. 107). Barksdale and others (1943, p. 107-109) and Farlekas (1979, p. 16) documented the early development of water from this aquifer. Horn and Bratton (1991) reported that, for the period 1981-85, the middle aquifer provided 33 percent of ground-water for public, industrial, and commercial supply in Middlesex and Monmouth Counties. The distribution of withdrawal centers has changed with the growth of population and the expansion of commercial and industrial development to the south and east into confined parts of the aquifer in Middlesex and Monmouth Counties. The locations of the major water users within the area of the ground-water flow model and a graphical representation of their 1985 withdrawals are shown in figure 16.

Ground-water withdrawals from the middle aquifer by major ground-water purveyors are summarized in table 7. Withdrawal rates are reported as averages for time periods from 1896 through 1985, which correspond to pumping periods used for numerical analysis of ground-water flow. For modeling reasons, the pumping periods begin in 1886. Actual withdrawal rates tend to vary seasonally, with maximum withdrawals during summer and minimum withdrawals during winter. Seasonal withdrawals are reflected in regular annual variations in water levels, as seen in the hydrograph of well 25-272 (fig. 17), which is screened in the middle aquifer in Marlboro Township, Monmouth County (fig. 14). In 1985, the largest users of ground water in Middlesex County were Old Bridge MUA; P.J. Schweitzer, Inc.; East Brunswick Township WD; Anheuser-Busch Corporation; South Brunswick MUA; and South River WD. In Monmouth County the largest users were Marlboro Township MUA, Shoreline Water Company, Gordons Corner Water Company, Aberdeen Township MUA, and Union Beach Water Department.

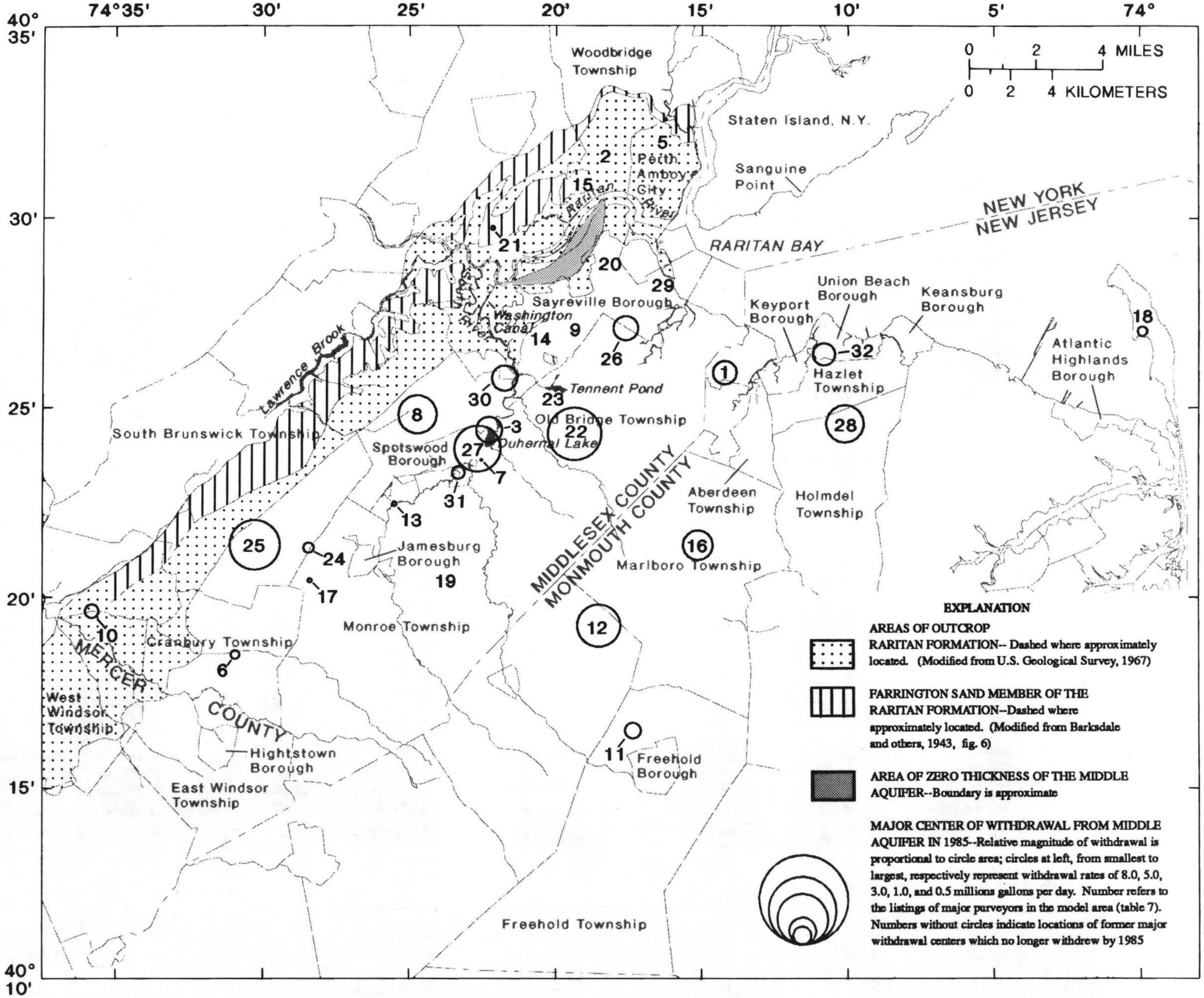


Figure 16.--Locations of major withdrawal centers in the middle aquifer, 1985.

Annual rates of withdrawal from the middle aquifer in Middlesex and Monmouth Counties generally increased from 1900 through 1985 (fig. 7). Several of the large users in the early period of development reduced withdrawals during the 1940's and early 1950's because of the migration of saltwater into the middle aquifer (Barksdale, 1943, p. 118). These users include Duhernal Water Company, Hercules Corporation, Perth Amboy Water Department, NUODEX Incorporated, and E.I. duPont Corporation (table 7). Because of saltwater intrusion into its wells in the upper aquifer (Schaefer and Walker, 1981, p. 12), Union Beach Water Department began withdrawing water from the middle aquifer in the late 1970's. In 1985, withdrawals from the middle aquifer totaled about 23 Mgal/d (fig. 7).

Potentiometric surface

Because only three water-level measurements in the middle aquifer prior to development are available, a predevelopment potentiometric-surface map could not be constructed. Because no withdrawals from either the upper or middle aquifer took place during predevelopment, the water levels in the middle aquifer can be assumed to have been about the same as those in the upper aquifer. Comparison of the available predevelopment measurements in the middle aquifer with the predevelopment surface of the upper aquifer shows that heads in the middle aquifer were within about 5 ft of those in the upper aquifer (Zapecza and others, 1987, fig. 4); therefore, the predevelopment potentiometric surface of the upper aquifer approximates the regional head distribution in the middle aquifer (fig. 8).

The potentiometric surface in the middle aquifer in 1959 (fig. 18) was prepared from water-level data collected from 1958 through 1960 (Farlekas, 1979, p. 13). The map shows the regional cone of depression centered in Sayreville and Old Bridge Townships, Middlesex County. This cone results from withdrawals in South Amboy City and near Tennent Pond and Duhernal Lake (fig. 16). The potentiometric surface in the middle aquifer in 1983 (fig. 19) was delineated after large-capacity wells within 1 mi of the measured well had been shut off for at least 1 hour (Eckel and Walker, 1986, pl. 5). In 1983, the areal extent of the regional cone of depression was larger and heads were lower than in the potentiometric surface in 1959 and in 1973 (Farlekas, 1979, fig. 6) over much of the area. The center of the cone shifted eastward between 1959 and 1983, toward Keyport Borough and Aberdeen Township in Monmouth County, where the heads decreased by 70 to 90 ft from 1959 levels. In the rest of Monmouth County, 1983 heads generally were 20 to 40 ft below 1959 heads. Heads in the Sayreville area declined about 20 to 30 ft from 1959 heads. Heads in southern Middlesex County declined about 20 ft.

Water levels in the middle aquifer were measured in 1984 and 1986 by use of the same procedure described previously for the upper aquifer. The effect of the pinchout of the middle aquifer in Sayreville Borough was considered in the mapping of the 1984 and 1986 potentiometric surfaces; however, the potentiometric-surface maps of previous investigators for this area were not changed. The potentiometric surface of the middle aquifer produced from measurements made in 95 wells in early November 1984 is shown in plate 1c. Heads had decreased at least 20 ft below those in the predevelopment potentiometric surface everywhere except at or near the outcrop area. The largest declines were at the two cones of depression

Table 7.--Withdrawal rates of major ground-water purveyors, by pumping period, middle aquifer, 1896-1985

[Withdrawal rates in million gallons per day are averages reported for pumping periods that correspond to simulation periods discussed in this report; --, no data are reported and no withdrawals used for that simulation period; MUA, Municipal Utilities Authority; WD, Water Department; Twp, Township; Boro, Borough; Co., Company; Corp., Corporation; Inc., Incorporated]

Location number from figure 20	Owner	Municipality	Withdrawal rate by pumping period					
			1 (1896-1920)	2 (1921-1945)	3 (1946-1952)	4 (1953-1957)	5 (1958-1964)	6 (1965-1967)
1	Aberdeen Twp MUA	Aberdeen Twp	--	--	--	--	0.391	0.551
2	American Cyanamid Corp.	Woodbridge Twp	.438	1.534	1.213	.565	.150	.135
3	Anheuser-Busch Corp.	E. Brunswick Twp	--	.195	.220	.185	.371	.932
4	BASF-Wyandotte Corp.	S. Brunswick Twp	--	--	--	--	--	.011
5	Chevron Oil Co.	Perth Amboy City	--	--	.096	.284	.262	.452
6	Cranbury Twp WD	Cranbury Twp	.004	.018	.030	.036	.077	.124
7	Duhernal Water Co.	Old Bridge Twp	--	.030	3.831	3.514	1.009	.717
8	E. Brunswick Twp WD	E. Brunswick Twp	--	--	.043	.593	1.181	1.607
9	E.I. DuPont Corp.	Sayreville Boro	--	2.015	.736	.149	.053	.038
10	Elizabethtown Water Co.	S. Plnsboro Boro	--	--	--	--	--	--
11	Freehold Borough Water Dept.	Freehold Twp	--	--	--	--	--	--
12	Gordons Corner Water Co.	Manalapan Twp	--	--	--	--	.002	.248
13	Helmetta Water Co.	Helmetta Boro	--	--	--	--	.005	.010
14	Hercules Corp.	Sayreville Boro	--	1.868	.708	.166	--	--
15	Heyden Chemical Co.	Woodbridge Twp	--	.720	.364	--	--	--
16	Marlboro Twp MUA	Marlboro Twp	--	--	--	--	--	--
17	Monroe Twp MUA	Monroe Twp	--	--	--	--	.050	.178
18	National Park Service	Middletown Twp	--	--	--	--	--	.165
19	NJ Home For Boys	Monroe Twp	.016	.146	.205	.159	.160	.124
20	NL Industries Inc.	Sayreville Boro	--	.512	.526	.130	.100	.094
21	NUODEX Inc.	Edison Twp	.167	.691	.487	.355	.345	.345
22	Old Bridge MUA	Old Bridge Twp	--	--	--	--	.440	.871
23	Perth Amboy WD	Old Bridge Twp	--	2.111	2.028	2.091	2.324	2.658
24	Phelps Dodge Co.	S. Brunswick Twp	--	--	--	.055	.584	.835
25	S. Brunswick MUA	S. Brunswick Twp	--	--	--	.001	.049	.509
26	Sayreville, WD	Sayreville Boro	--	--	--	--	--	--
27	P.J. Schweitzer, Inc.	Spotswood Boro	--	.001	.606	1.856	2.087	2.214
28	Shoreline Water Co.	Hazlet Twp	--	--	--	--	--	--
29	South Amboy WD	Sayreville Boro	--	--	.382	.318	.355	.499
30	South River WD	South River Boro	.016	.154	.242	.492	.648	.799
31	Spotswood WD	Spotswood Boro	--	--	--	--	--	--
32	Union Beach WD	Union Beach Boro	--	--	--	--	--	--

Table 7.--Withdrawal rates of major ground-water purveyors, by pumping period, middle aquifer, 1896-1985--Continued

Location number from figure 20	Withdrawal rate by pumping period						Number of wells in service during 1896-1985
	7 (1968-1972)	8 (1973-1977)	9 (1978-1980)	10 (1981-1983)	11 (1/1/84-12/31/84)	12 (1/1/85-12/31/85)	
1	0.735	0.896	0.922	0.874	0.812	0.780	3
2	.132	.091	.083	.062	.010	.011	3
3	.904	.979	.970	.964	.952	.938	3
4	.178	.295	.553	.514	.352	.181	2
5	.318	.338	.370	.215	--	--	3
6	.130	.130	.129	.136	.147	.138	3
7	.329	.136	.913	1.244	.021	.010	2
8	2.192	2.164	2.373	1.617	2.408	1.852	2
9	.067	.022	.050	.051	--	--	4
10	--	--	--	.274	.343	.299	2
11	--	--	--	.292	.562	.388	1
12	1.317	1.524	1.793	2.259	2.002	2.164	6
13	.012	.017	.040	.041	.045	.046	1
14	--	--	--	--	--	--	6
15	--	--	--	--	--	--	2
16	--	.216	.562	1.525	1.037	1.186	4
17	.285	.443	.442	.394	.370	.037	2
18	.254	.231	.182	.190	.164	.164	1
19	.130	.168	.152	.055	--	--	4
20	.141	.093	.012	.008	.158	--	4
21	.345	.316	.288	.288	.062	.033	3
22	1.899	2.933	2.882	3.064	2.355	3.213	7
23	2.957	1.872	1.337	.501	--	--	4
24	.941	.172	--	--	--	--	3
25	.983	1.857	2.222	2.929	3.707	2.904	5
26	.985	1.649	3.115	1.435	1.219	1.267	3
27	2.621	2.471	2.314	1.795	2.688	2.541	4
28	.216	1.236	1.180	1.392	1.660	1.783	3
29	.447	.544	.080	.184	--	--	1
30	.975	1.143	1.137	1.144	.988	.892	6
31	--	.038	.243	.253	.266	.265	1
32	--	--	.900	.668	.696	.701	1

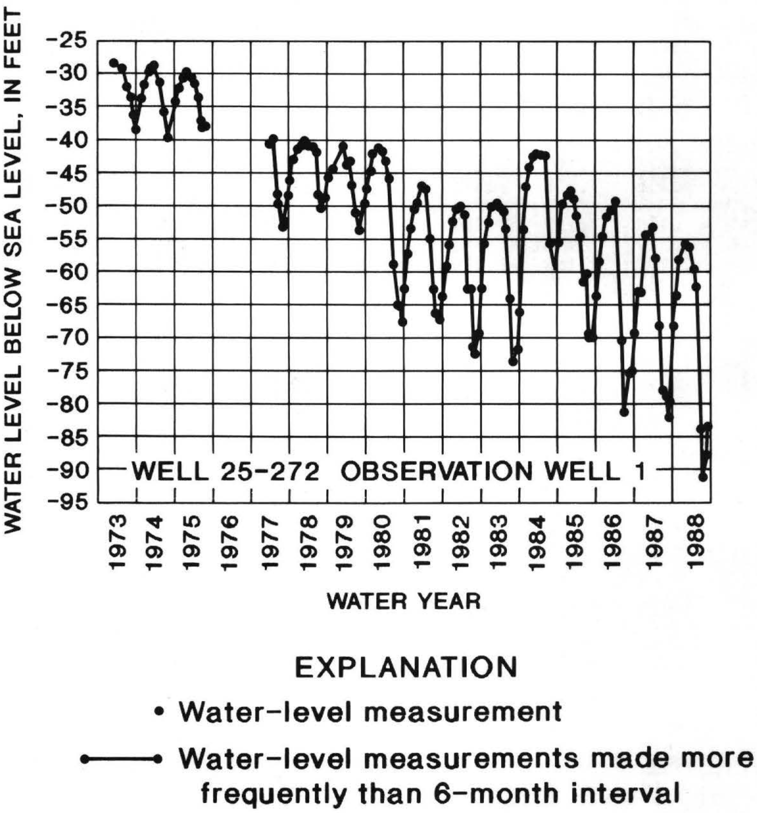


Figure 17.--Water level in observation well 25-272, screened in the middle aquifer.
(Location of well shown in fig. 14)

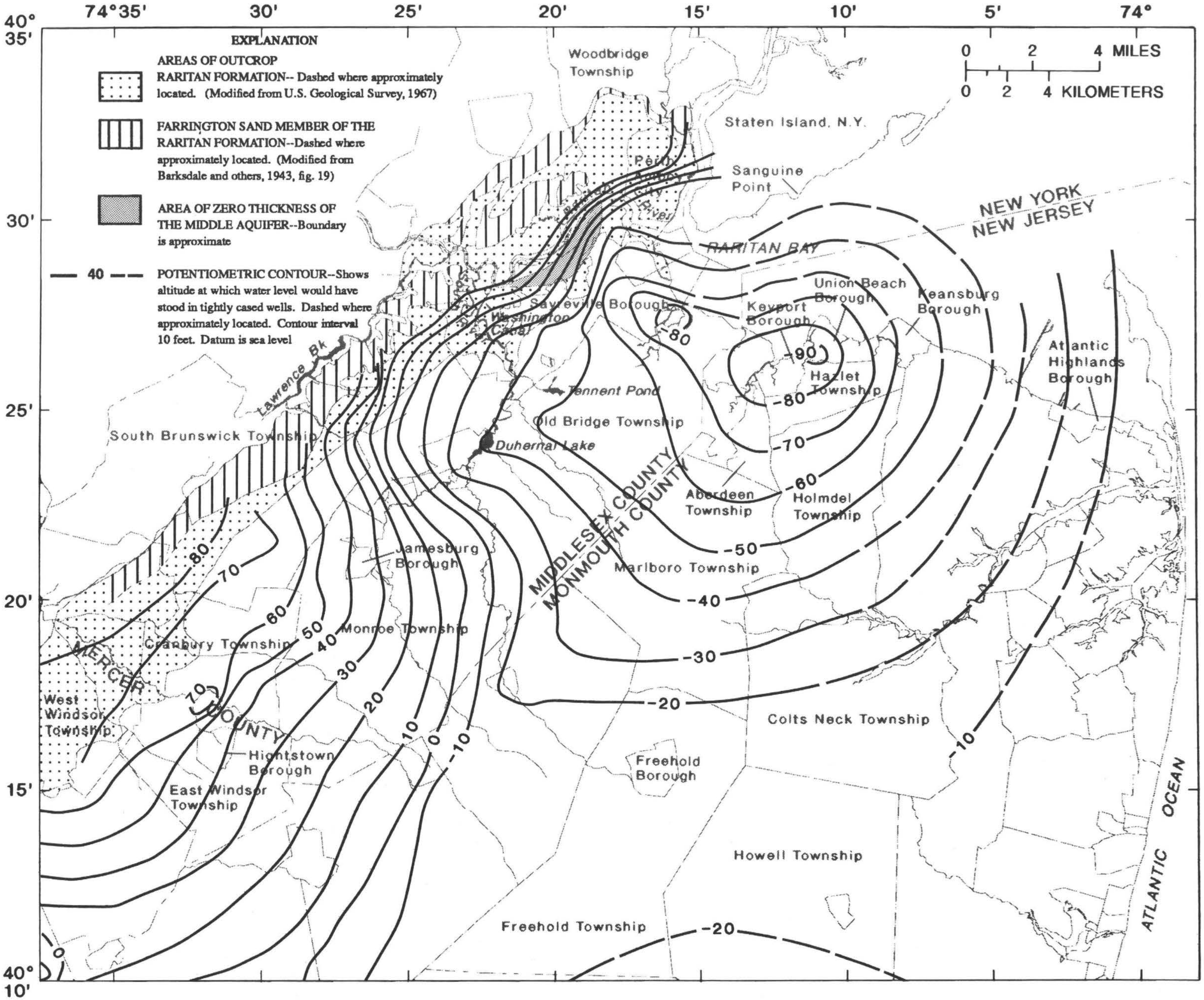


Figure 18.--Potentiometric surface in the middle aquifer, 1959. (From Farlekas, 1979)

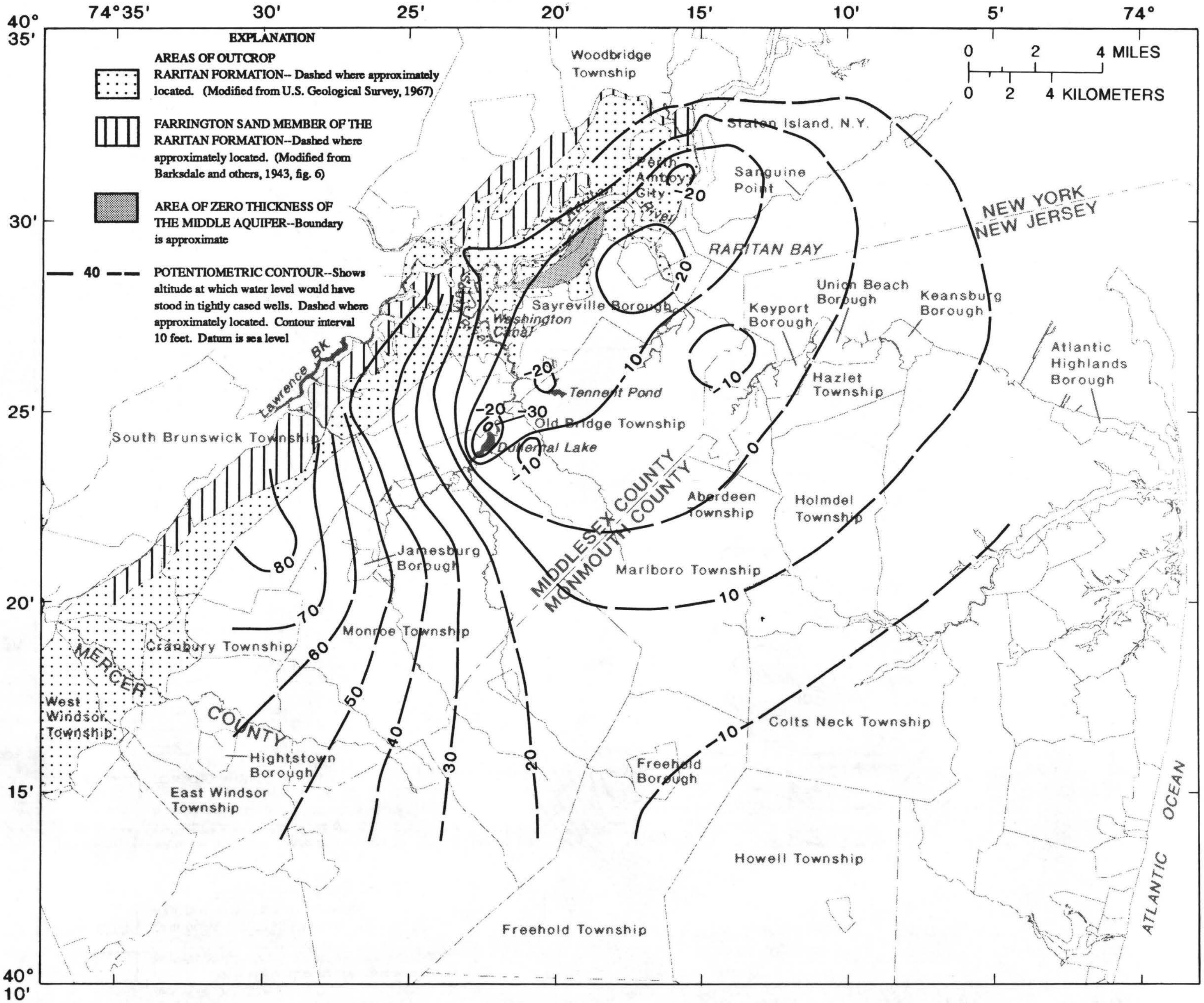


Figure 19.--Potentiometric surface in the middle aquifer, 1983.
(From Eckel and Walker, 1986)

centered in Spotswood Borough, Middlesex County, and Hazlet and Holmdel Townships, Monmouth County, where 1984 heads were more than 100 ft below predevelopment heads. Heads in the centers of these cones of depression in fall 1984 were 67 ft below sea level (well 23-456) in Spotswood Borough, and 89 ft below sea level (well 25-153) in Holmdel Township. In surrounding areas in northwestern Monmouth County and northeastern Middlesex County, heads declined 80 ft from predevelopment heads. Compared to the 1983 potentiometric surface, heads generally rose about 5 ft.

The potentiometric surface delineated from measurements made in 96 wells in spring 1986 is shown on plate 1d (data are listed in appendix B). Heads generally were the same or slightly higher than in fall 1984. The only major changes were increases of about 20 ft near South Amboy and increases of 5 to 15 ft south of Spotswood. Heads in the centers of these cones of depression in spring 1986 were 77 ft below sea level (well 23-456) in Spotswood Borough and 93 ft below sea level (well 25-153) in Holmdel Township.

Lower Confining Units

In updip parts of the study area, the confining unit underlying the middle aquifer consists of either the Raritan fire clay member of the Raritan Formation, pre-Cretaceous bedrock, or saprolitic clay. Southeast of the Middlesex-Monmouth County line, the lower confining unit can be considered to be the first layer of clay more than 20 ft thick below the middle aquifer. Further downdip, the confining unit underlying the middle aquifer also can consist of fine-grained sediments of the Potomac Group (Gronberg and others, 1991).

Precipitation and Evapotranspiration

Recharge to the ground-water system is primarily from precipitation. Mean annual precipitation, based on data from the U.S. Weather Service Stations at New Brunswick, Freehold, and Hightstown, New Jersey (National Climatic Data Center, Asheville, North Carolina), is about 45 in. Snowfall averages 26 in/yr, which is equivalent to about 2.5 in. of rain. Mean annual precipitation for the period 1951-80 at these stations is given in table 8, below:

Table 8.--Mean annual precipitation at selected U.S. Weather Service stations in New Jersey, 1951-80

[Locations of stations shown in figure 20]

Station	Mean annual precipitation (inches)
New Brunswick	45.50
Freehold	45.89
Hightstown	44.39

Evapotranspiration (ET) is the sum of the losses of water by evaporation from the streams, lakes, and ground-water system and by transpiration from plants to the atmosphere. Barksdale (1937, p. 15) estimated ET in the study area to be 20 in/yr. Forman (1979, p. 157) estimated the ET south of the study area, in the New Jersey Pine Barrens, to be 22.5 in/yr. Vowinkel and Foster (1981, p. 18-19) estimated the average annual water loss, primarily as a result of ET, in selected drainage basins in the Middlesex and Monmouth County areas to be 25.9, 24.3, and 25.5 in/yr, respectively.

Potential ET for the study area was calculated to be 27.5 in/yr by use of Thornthwaite's method (Thornthwaite, 1948). On the basis of the Thornthwaite ET, about 81 percent of the annual potential ET occurs from May through September. Because this method incorporates the monthly mean temperatures and is based on the assumption that moisture is always available, potential ET estimates of 27.5 in/yr are higher than actual ET.

Surface-Water System

Raritan Bay, which is part of the Lower Bay of New York Harbor, covers approximately 20 percent of the study area. Raritan Bay is salty, typically shallow (1-10 ft deep), and rarely exceeds 20 ft in depth. The natural bathymetry of the bay has been altered by the dredging of channels for shipping, by the mining of sand and gravel, and by landfilling and development at the shore (Kastens and others, 1978, p. 7).

The Raritan River (fig. 20), which drains the Piedmont physiographic province, flows southeast and east into the study area. Woodbridge Creek, which is north of the Raritan River, flows southeast to Arthur Kill. Both rivers are bordered by tidal marsh and ultimately empty into Raritan Bay. Additional major streams south of the Raritan River are Lawrence Brook, South River, Millstone River, and Cheesequake Creek (fig. 20). These streams flow northward and empty into either the Raritan River or Raritan Bay. They are tranquil streams characterized by moderate rises in stage after heavy rains and slowly diminishing base flows during extended dry periods.

Lawrence Brook was dammed in East Brunswick Township to form Farrington Lake and Weston's Mill Pond; about three-quarters of Lawrence Brook traverses the outcrop of the Potomac-Raritan-Magothy aquifer system (Barksdale, 1937; p. 17). Beaverdam Brook and Ireland Brook are the principal tributaries to Lawrence Brook. The South River is formed where Manalapan and Matchaponix Brooks unite in Spotswood; its principal tributaries include Iresick Brook, Deep Run, and Tennent Brook. Duhernal Lake was formed in 1939 by the construction of a dam and recharge pond near the confluence of the South River and Iresick Brook. Tennent Pond was formed by the construction of a dam on Tennent Brook. A similar surface-water impoundment is under construction (1989) on Deep Run.

Streams in the upstream part of the Millstone River basin, in southwestern Middlesex County, western Monmouth County, and northeastern Mercer County, flow to the northwest. The major tributaries to the Millstone River are Big Bear Brook, Devils Brook, and Cranbury Brook. The Millstone River flows out of the study area to the northwest and eventually enters the Raritan River.

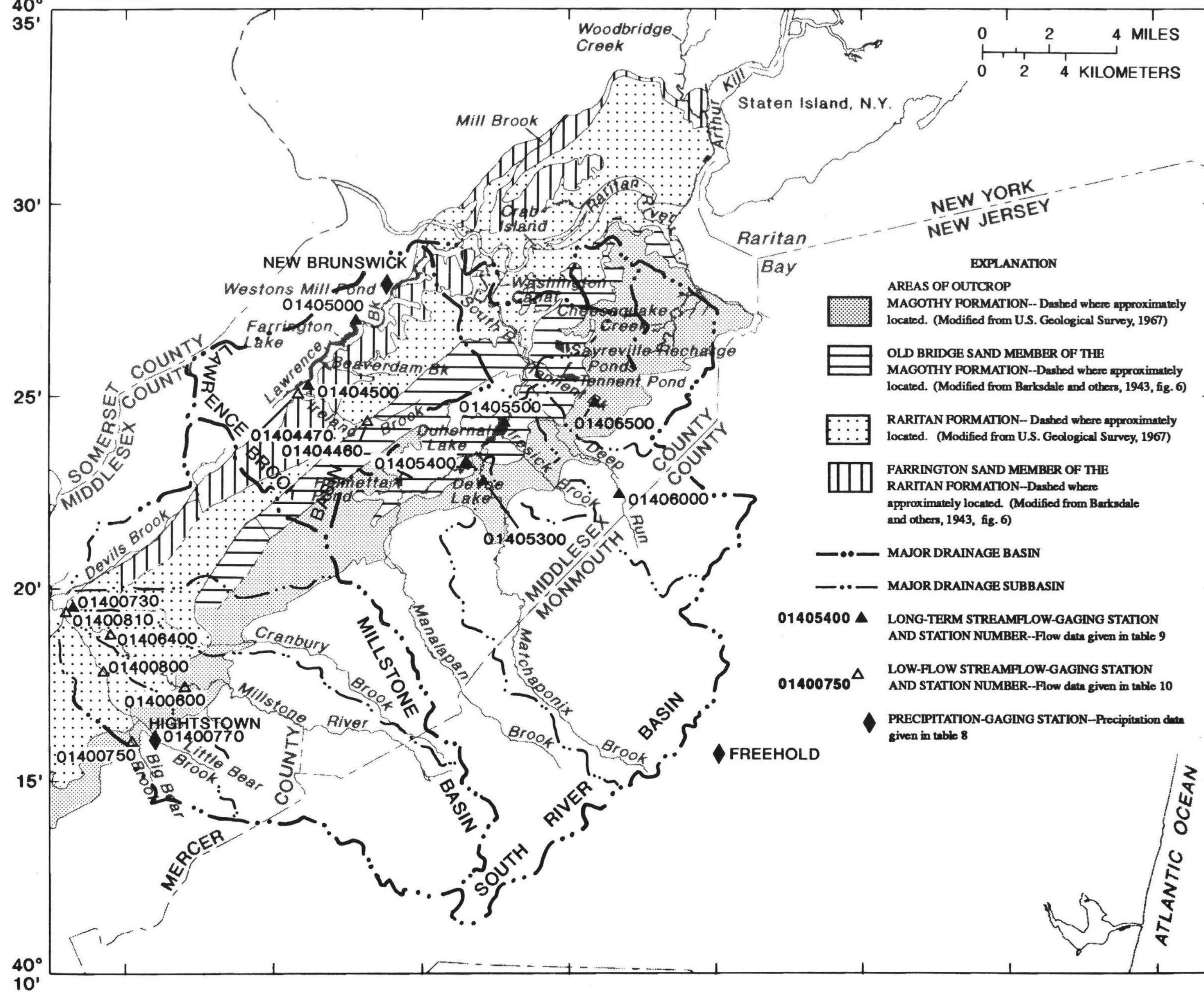


Figure 20.--Major surface-water bodies and drainage basins within the outcrop area of the Potomac-Raritan-Magothy aquifer system in the study area.

Streamflow

Daily streamflow data were collected at eight stations in the study area (fig. 20). Some of these streamflow-gaging stations are on sections of streams where the flow is partially controlled by dams. Data for the eight stations and their basins are summarized in table 9.

Base Flow

The mean annual discharge of a stream can be separated into two flow components--direct runoff and base flow. Base flow is the component of streamflow that is derived from ground-water discharge. Base-flow separations for each streamflow-gaging station listed in table 9 were computed by use of a hydrograph-separation program (Pettyjohn and Henning, 1979) for the periods for which data are available. This program incorporates three different methods of hydrograph separation to separate base flow from direct runoff; the program then averages the results. Base flow at these stations ranged from 51 to 65 percent of total flow and averaged 59 percent. The highest percentage of base flow was at station 01405400 (Manalapan Brook at Spotswood); the lowest was at station 01406500 (Tennent Brook at Browntown). The low percentage of streamflow derived from base flow at the latter station is attributed to the effects of long-term ground-water withdrawals in the area (Parker and others, 1964, p. 112 and 138).

Interactions of Ground Water and Surface Water

Under predevelopment conditions, the hydraulics of the unconfined ground-water system included recharge from precipitation, lateral flow of water through the aquifer, and discharge to streams, rivers, or the bay. The streams are connected hydraulically to the water-table system and derive about 59 percent of their flow from ground-water discharge, as discussed previously. Movement of water between aquifers and streams depends on the hydraulic stage of the stream, the water level in the aquifer, and the hydraulic properties of the ground-water and surface-water systems. Most of the time, the streams are shallow drains from the unconfined aquifers. Some streams are intermittent--that is, they stop flowing during dry periods.

The major drainage basins in the unconfined, or water-table, areas of the middle and upper aquifers of the Potomac-Raritan-Magothy aquifer system are the South River, Millstone River, and Lawrence Brook (fig. 20). Surface-water subbasins within the major drainage basins also are shown in figure 20. Other minor drainage basins in parts of the recharge area of the upper aquifer, or north of the Raritan River for the middle aquifer, are not discussed here. Water is more easily exchanged directly between surface water and ground water in areas where the aquifer is unconfined and is hydraulically well connected to the confined aquifer than in the outcrop area of the confining units (fig. 20). In addition, because of the reversal of flow directions caused by large ground-water withdrawals in the region, Raritan Bay has become an area of recharge of saltwater to the upper aquifer where it is hydraulically well connected to Raritan Bay.

Table 9.--Characteristics of regional drainage basins and their tributaries at long-term streamflow-gaging stations within the outcrop area of the Potomac-Raritan-Magothy aquifer system

[Gaging-station locations shown in fig. 20; in/year, inches per year]

Station number	Station name	Period of record	Drainage area (square miles)	Mean annual (cubic feet per second)	Discharge (in/year)	Estimated base flow	
						(in/year)	(percent)
0140550	South River at Old Bridge[1]	1939-1987	94.6	143	20.3	12.4	61
01405400	Manalapan Brook at Spotswood[2]	1957-1987	40.7	65.6	21.4	13.9	65
01405300	Matchaponix Brook at Spotswood[2]	1958-1967	43.9	62.5	19.2	11.4	59
01406000	Deep Run near Browntown[2]	1933-1940	8.07	14.0	23.4	14.8	63
01406500	Tennent Brook at Browntown[2]	1932-1941	5.2	4.6	11.7	5.9	51
01400730	Millstone River at Plainsboro[1]	1965-1975	65.8	99.2	20.45	12.2	60
01404500	Lawrence Brook at Patrick Corner[1]	1922-1927	29.0	26.9	13.4	7.5	56
01405000	Lawrence Brook at Farrington Dam[1]	1927-1987	34.2	39.0	15.2	8.4	55

[1] Regional drainage basin
[2] Tributary drainage basin

Estimated Ground-Water Recharge

Several estimates of recharge to the unconfined-aquifer areas have been reported in the literature (Vowinkel and Foster, 1981, p. 19). Recharge is precipitation that has percolated through the unsaturated zone to the water table. This water ultimately discharges to the surface-water system as base flow or recharges the deeper, confined system. Barksdale (1937, p. 16) reported that 20 in/yr of recharge to the middle aquifer is likely. Barksdale and others (1943, p. 84-87) estimated that the recharge to the upper aquifer probably is similar to the recharge to the middle aquifer (20 in/yr).

Wilson and others (1972, p. 57) estimated the net recharge to the Coastal Plain unconfined-aquifer areas in the Millstone River basin in the southwestern part of the study area, based on streamflow analysis, to be 0.61 ft/yr (7 in/yr) for the 1969 water year. They also stated that this estimate could vary from year to year and from one area within the basin to another. Geraghty and Miller, Inc. (1976, table 6), estimated total net recharge (recharge minus ET) to the Coastal Plain unconfined-aquifer area in Middlesex County to be 15 in/yr, of which 13 in/yr discharges to streams. On the basis of calibration of a ground-water flow model, Farlekas (1979, p. 36) estimated the amount of recharge to the confined area of the aquifer system from the recharge area of the middle aquifer to be 5.2 in/yr.

The hydrologic budget is an accounting of all water entering and leaving a basin area. The flow of water within a basin is influenced by precipitation, ET, hydrogeology, and other natural and human factors. Over extended periods of time, streamflow varies in response to these factors to maintain hydraulic equilibrium within the basin. Nevertheless, the hydrologic budget within a surface-water basin area can be estimated by use of long-term average flow values. The water budget can be described by the relation

$$P + Q_{in} + Q_{gw} = ET + Q_{out} + Q_{well} \pm \Delta S.$$

Water enters each basin as precipitation (P) and through streams that flow into the area (Q_{in}). Water is lost from the drainage basin through evapotranspiration (ET), streamflow out of the basin (Q_{out}), net ground-water discharge to surface water (Q_{gw}), and net ground-water withdrawals (Q_{well}). A necessary assumption when estimating Q_{gw} by means of surface-water hydrologic budgets is that the areas of the surface-water drainage basin and ground-water drainage basin are equal. In reality, these areas do not necessarily coincide. The area that contributes surface-water drainage to the stream is determined by use of a planimeter on a topographic map, whereas the ground-water contributing area is determined from water-table-contour maps that can be used to infer ground-water flow directions during base flow. Some of the ground water withdrawn (Q_{well}) could be discharged to the ground-water system within the basin or discharge to streamflow within the stream basin. Diversions and withdrawals of surface water and ground water, which are not accounted for, also introduce errors into the budget. Some of the precipitation flows directly into the stream as overland flow or as interflow; this water is included in Q_{out} term. Change in storage (ΔS) includes surface-water and ground-water storage.

The Q_{in} and Q_{out} terms in the surface-water hydrologic budget are calculated from estimates of mean annual discharge determined at low-flow streamflow-gaging stations on a stream (Gillespie and Schopp, 1982, p. 10-11). This method is most useful over short reaches of streams, where streamflow measurements are made at both ends of the reach and where the effects of ground-water withdrawals and surface-water diversions are minimal.

Hydrologic budgets were calculated for selected stream reaches from discharge records from nine available low-flow partial-record stations in the study area (fig. 20). Average annual discharge data (Q_{in} and Q_{out}) at these partial-record stations were estimated and normalized to data from nearby continuous-record stations (index stations) by use of least-squares regression equations (Gillespie and Schopp, 1982, p. 15-19). Data from each low-flow partial-record station were correlated with data from three to five nearby index stations, and a mean annual discharge for the available period of record was computed. Instead of separate terms for ET and P, an estimated net recharge to the basin (P - ET) of 20 in/yr was used in this calculation.

Change in ground-water storage is reflected as a change in ground-water level. For these water-budget estimates, changes in storage are assumed to be zero. Where this assumption is invalid (where water levels in the water-table aquifer have declined), a hydrologic budget tends to yield estimates of ground-water discharge to streamflow (Q_{gw}) that are greater than actual values for the budget area. Changes in the amount of water stored in surface-water bodies are negligible and are assumed to be zero for these budgets.

Hydrologic-budget calculations for stream subreaches in four drainage basins in the recharge areas of the aquifers showed that the exchange of water between the streams and the unconfined-aquifer areas is variable (table 10). Hydrologic budgets were computed for one subreach in the Ireland Brook basin, one in the Millstone River basin, and two in the Bear Brook basin where satisfactory measurement sites were available. Subreaches of Ireland Brook (between stations 01404460 and 01404470), the Millstone River (between stations 01400600 and 01400640), and Bear Brook between Hickory Corner and Grover Mills (between stations 01400770 and 01400750 and station 01400800), were gaining subreaches in which the estimated mean annual streamflow at the upstream partial-record station was less than the estimated mean annual streamflow at the downstream partial-record station ($Q_{in} < Q_{out}$). Between Grover Mills and Princeton Junction on Bear Brook (between stations 01400800 and 01400810), the stream subreach was losing, and the estimated mean annual streamflow at the upstream partial-record station was greater than the estimated mean annual runoff at the downstream partial-record station ($Q_{in} > Q_{out}$).

Estimates of net recharge to the ground-water system within the four stream subreaches ranged from -11.9 to 26.8 in/yr. These estimates were based on the assumption that the contribution from well discharge or recharge in the drainage area (Q_{well}) affecting the stream reach is negligible. For the reach along the Millstone River, the stream was discharging to the aquifer (Q_{gw} was negative). Estimates for the reach of

Table 10.--Estimated ground-water recharge between low-flow partial-record stations

[Assumed net recharge from precipitation and evapotranspiration is 20 inches per year; partial-record-station locations shown in fig. 20.]

Station number	Station name	Period of low-flow measurements (number of measurements)	Calculated mean annual runoff: cubic feet per second	Calculated mean annual runoff: inches per year	Calculated mean annual runoff: million gallons per year	Station drainage area (square miles)	Net drainage area between inflow and outflow stations (square miles)
+01404460	Ireland Brook near French Pond	1947 - 1949 (8 measurements)	1.99	7.8	469	3.47	
*01404470	Ireland Brook near Patrick Corner	1973 - 1977 (10 measurements)	6.36	13.2	1,500	6.52	3.05
+01400770	Little Bear Brook near Hickory Corner and	1960 - 1964 (11 measurements)	1.5	4.7	354	1.88	
+01400750	Bear Brook near Hickory Corner	1960 - 1965 (14 measurements)	5.2	16.9	1,227	3.46	5.34
*01400800	Bear Brook near Grover Mills	1959 - 1964 (11 measurements)	9.4	13.4	2,217	9.52	4.18
+01400800	Bear Brook near Grover Mills	1959 - 1964 (11 measurements)	9.4	13.4	2,217	9.52	
*01400810	Bear Brook at Prince-ton Junction	1962 - 1971 (16 measurements)	7.95	8.7	1,875	12.4	2.88
+01400600	Millstone River near Locust Corner	1959 -1971 (16 measurements)	55.0	19.9	12,974	37.5	
*01400640	Millstone River near Grover Mills	1959 - 1971 (18 measurements)	67.0	21.3	15,805	42.6	5.1

+ Subreach inflow, Q. in
* Subreach outflow, Q. out

Table 10.--Estimated ground-water recharge between low-flow partial-record stations--Continued

Station number	Net precipitation and evapotranspir-ation in area (million gallons per year)	Estimated ground-water recharge (million gallons per year)	(inches per year)
+01404460			
*01404470	1,060	29.0	0.6
+01400770			
+01400750			
*01400800	1,450	817	11.2
+01400800			
*01400810	1,000	1,340	26.8
+01400600			
*01400640	1,770	-1,060	-11.9

Ireland Brook and both reaches of Bear Brook showed that ground water was discharging to streamflow (Q_{gw} was positive). Low-flow measurements also have shown that the upper Millstone River and Matchaponix Brook sometimes lose water along some reaches, possibly as a result of surface-water diversion for irrigation or ground-water withdrawals from the basins (R.D. Schopp, U.S. Geological Survey, oral commun., 1987).

Hydrogeologic factors that control flow within each ground-water basin and the effects of ground-water withdrawals most likely affect the calculations within the boundaries of the surface-water basins; however, the range of estimates of net recharge to the ground-water system indicates that the hydrologic equilibrium between aquifer and streams varies between subreaches of the same stream and between basins.

A long-term decline in water levels in the unconfined-aquifer area was observed in some wells. An example is shown for well 23-151 for the period 1938-67 (fig. 21), for which the water-level trend is downward. These declines probably are caused by surface-water diversions in combination with ground-water withdrawals. At other wells in the area, such as well 23-292 (fig. 13), water-level variations in the unconfined-aquifer area are caused by variations in precipitation (Barksdale and others, 1943, p. 36). Declines in water level followed by a trend of recovery for well 23-292 reflect variations in annual precipitation. Years of drought or significantly reduced rainfall during 1964-66, 1977, 1981-83, and 1985-86 were followed by years of high or average rainfall (National Climatic Data Center, Asheville, North Carolina). Areas in which water levels in wells in the unconfined-aquifer area are constant indicate that water movement within the unconfined-aquifer area has not been affected by ground-water withdrawals or by a surface-water recharge source, as for well 23-181 (fig. 21). Effects of withdrawals and recharge on water levels in wells in an unconfined aquifer are discussed in detail in the next section.

Artificial Recharge

A goal of managing the aquifers in the Coastal Plain is to determine an appropriate withdrawal rate that will satisfy the demand for water in the area without exceeding the recharge rate. Years ago, consumptive use of water was minimal and, therefore, water demands were easily satisfied. Ground-water demand has grown with the development of the area, however, and the need to increase recharge to the ground-water system has been considered for several reasons. Increased ground-water recharge would (1) increase the available yield of ground-water withdrawals, (2) facilitate the treatment of ground water, (3) prevent the loss of recharge to the aquifer system through increased runoff caused by development, and (4) mitigate the encroachment of saltwater. Water-management regulations promulgated by the New Jersey Department of Environmental Protection and Energy for the control of ground-water diversions have encouraged the enhancement of artificial-recharge capacity in the study area (Gaston, 1985).

The potential for artificial recharge of ground water in the study area to increase the available yield has been discussed by Barksdale and others (1943, p. 87-90, p. 110), Barksdale and DeBuchananne (1946, p. 726-731), and Appel (1962, p. 30-33) for the study area and by May (1985, p. 12) for the Atlantic City area in the New Jersey Coastal Plain. More recently, May

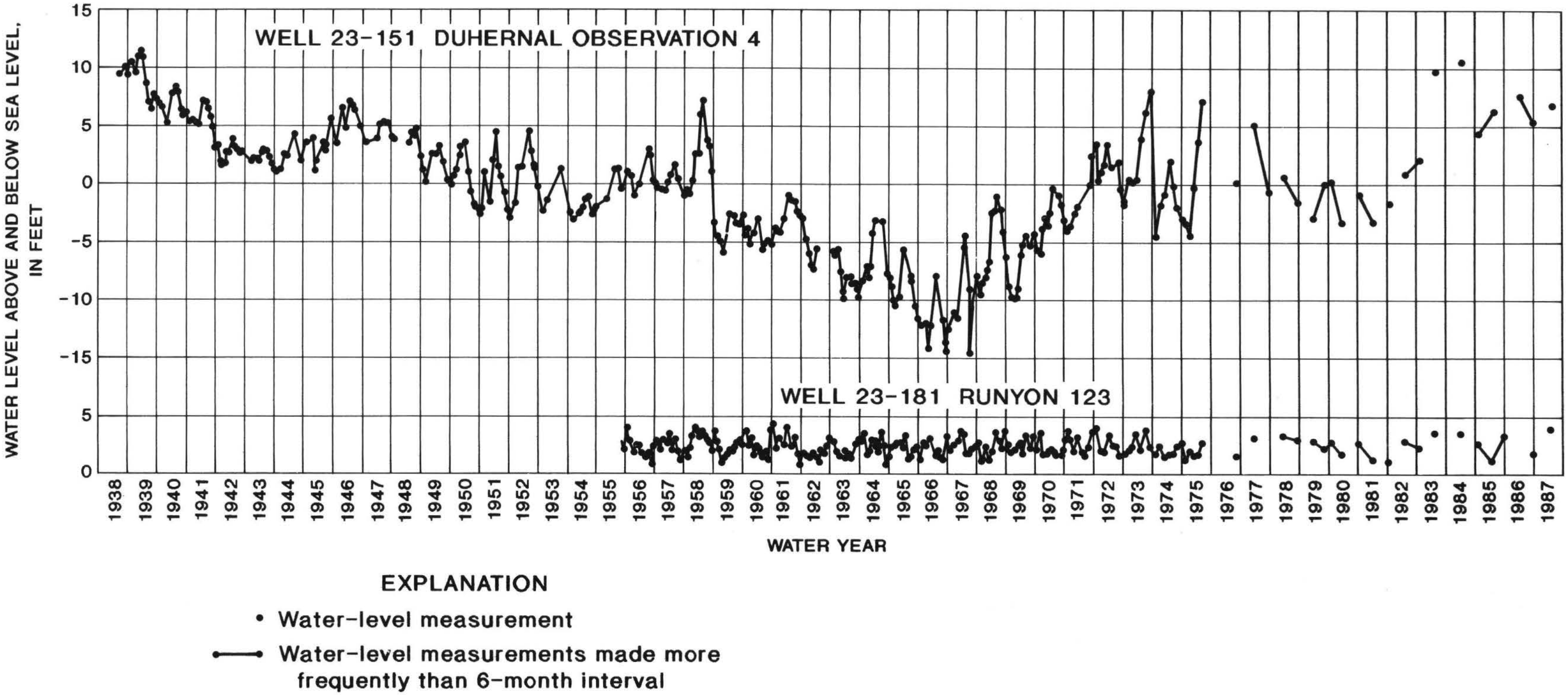


Figure 21.--Water levels in observation wells 23-151 and 23-181, screened in the upper aquifer. (Locations of wells shown in fig. 22)

(1985) reported on the feasibility of artificial recharge in an area to the south of the study area but within the New Jersey Coastal Plain. Barksdale and DeBuchananne (1946, p. 727) reported that successful methods of artificial recharge had been practiced in the study area for 30 to 40 years. Artificial recharge has been limited to areas near well fields pumping from the unconfined-aquifer areas or from areas near the main recharge areas for the upper aquifer. Various methods of surface-water spreading in the vicinity of wells have been used, such as damming streams, digging recharge canals, and diverting surface water to recharge lagoons. In the unconfined areas of the upper aquifer in the study area, these techniques have been used at Duhernal Lake, Tennent Pond, and Sayreville recharge lagoons in Middlesex County (fig. 22). In 1985, facilities at those sites withdrew ground water at a rate of 16.9 Mgal/d--about 40 percent of the total withdrawals from the upper aquifer in the entire study area. Reinjection of ground water has also been used to enhance production for the Gordons Corners Water Company in Manalapan and Marlboro Townships, Monmouth County.

The earliest application of artificial recharge was at the Tennent Pond well field of the Perth Amboy Water Works (fig. 22) (Barksdale and others, 1943, p. 33). The importance of Tennant Pond as a source of water to wells through which water is withdrawn from the upper aquifer was recognized when the first wells were drilled at the Perth Amboy Water Works in Old Bridge Township about 1902. Later, recharge canals were dug to enhance the recharge of the ground water into the upper aquifer (Barksdale and DeBuchananne, 1946, p. 727). The pond has an area of 63 acres, and the maximum recharge rate is estimated to be 125,000 gallons per acre per day (Barksdale and DeBuchananne, 1946, p. 729); therefore, the maximum effective recharge rate of the pond is about 7.8 Mgal/d. Geraghty & Miller, Inc. (1976), reported a lower estimate of potential recharge for the pond (5.0 Mgal/d). In 1988, the Perth Amboy Water Department began to enlarge its production capacity near Deep Run, south of Tennant Pond. At this site, water for a recharge pond will be supplied by diverting streamflow from the Deep Run. Water will be captured from the recharge pond by pumping radial collector wells in the upper aquifer. This project initially will produce 8.0 Mgal/d of water.

The artificial-recharge facility with the largest capacity in the outcrop area of the Potomac-Raritan-Magothy aquifer system in the study area is Duhernal Lake, built by Duhernal Water Company by dam construction on the South River. Barksdale (1943, p. 89) estimated the recharge rate for Duhernal Lake to be 4.0 to 5.0 Mgal/d; a maximum possible rate of 8.0 Mgal/d has been calculated (Barksdale and DeBuchananne, 1946, p. 730). A potential recharge rate of 15.3 Mgal/d also has been reported (Geraghty & Miller, Inc., 1976, p. 15). Wells owned by P.J. Schweitzer, Inc., and Anheuser-Busch Corporation on the northern side of the lake also derive a substantial proportion of their withdrawals from ground-water recharge from Duhernal Lake (Barksdale and DeBuchananne, 1946, p. 729).

The effects of surface-water recharge ponds on water levels in wells in the unconfined-aquifer area are seen in hydrographs of wells 23-151 and 23-181 (fig. 21). Well 23-151 is about 400 ft from the south shore of Duhernal Lake, and well 23-181 is about 0.5 mi northeast of the lake (fig. 22). Water levels in well 23-151, excluding short-term variations, decreased from 1938 to about 1966 as ground-water withdrawals by Duhernal Water Company increased (table 6); from 1959 to 1971, water levels were below sea level. As water levels declined, the gradient between the lake and the aquifer increased, and more water from the lake entered the aquifer. Duhernal Water Company reduced withdrawals from the unconfined-aquifer area near Duhernal Lake beginning in 1967. Reduced withdrawals have resulted in an increase in water levels near Duhernal Lake, a reduction in the gradient between the lake and the aquifer, and a reduction in recharge from Duhernal Lake.

Water levels in well 23-181 (fig. 21) indicate that the well is outside the area of influence of ground-water withdrawals around Duhernal Lake. Water levels in the well show neither seasonal variations nor trends that correspond to the variation in water levels measured in well 23-151. The range in water-level altitudes in well 23-181 (about 1 to 4 ft above sea level) is relatively small and is similar to the magnitude of tidal variation in nearby South River. Barksdale and others (1943, p. 81-84) reported that water levels in most observation wells near Duhernal Lake are not affected by ground-water withdrawal wells near the lake shore.

Sayreville Water Department excavated two recharge lagoons at its well field north of Tennent Pond (fig. 22). These recharge lagoons, which have a total surface area of 66 acres, were constructed from 1970 through 1971 by clearing woodland and then excavating the lagoons. Recharge water for the lagoons is diverted by a pipeline from South River at the foot of the dam on Duhernal Lake. Diversions began in January 1973, although the lagoons began to fill immediately after excavation with captured rainwater and surface runoff. The potential recharge rate of these lagoons was estimated to be 4.0 Mgal/d (Geraghty & Miller, Inc., 1976, table 4).

Hydrographs of wells 23-344 and 23-351 (fig. 23) show the effect of artificial recharge at the Sayreville Water Department recharge lagoons. Well 23-351 is approximately 0.25 mi west of the lagoon; well 23-344 is approximately 300 ft south of the lagoons (fig. 22). Both wells are screened in the unconfined area of the upper aquifer. The hydrographs indicate an increase in the altitude of the water table in the upper aquifer soon after excavation of the lagoons during 1970-71 and the introduction of the recharge water. The effect of the recharge lagoons is to maintain the water table at a higher level than before recharge began, despite the large withdrawals that began near the recharge lagoon in January 1973.

The successful use of injection wells for ground-water recharge was demonstrated by Gordons Corner Water Company in Marlboro and Manalapan Townships in Monmouth County (fig. 22). The injection wells are located in the deeper, confined area downdip from the unconfined main recharge areas of the aquifers. For one injection well in each township, Gordons Corner Water Company uses a ground-water management technique called aquifer storage recovery by which water is stored seasonally in an aquifer when the capacity of water-supply facilities exceeds system demand. The objective of this artificial-recharge technique is to maximize the water company's water-treatment capacity during periods of low demand, typically from October through April. During these months, about 0.7 Mgal/d of water is withdrawn from two upper-aquifer wells in Marlboro Township and from five middle-aquifer wells in Manalapan Township. The water is then treated and injected

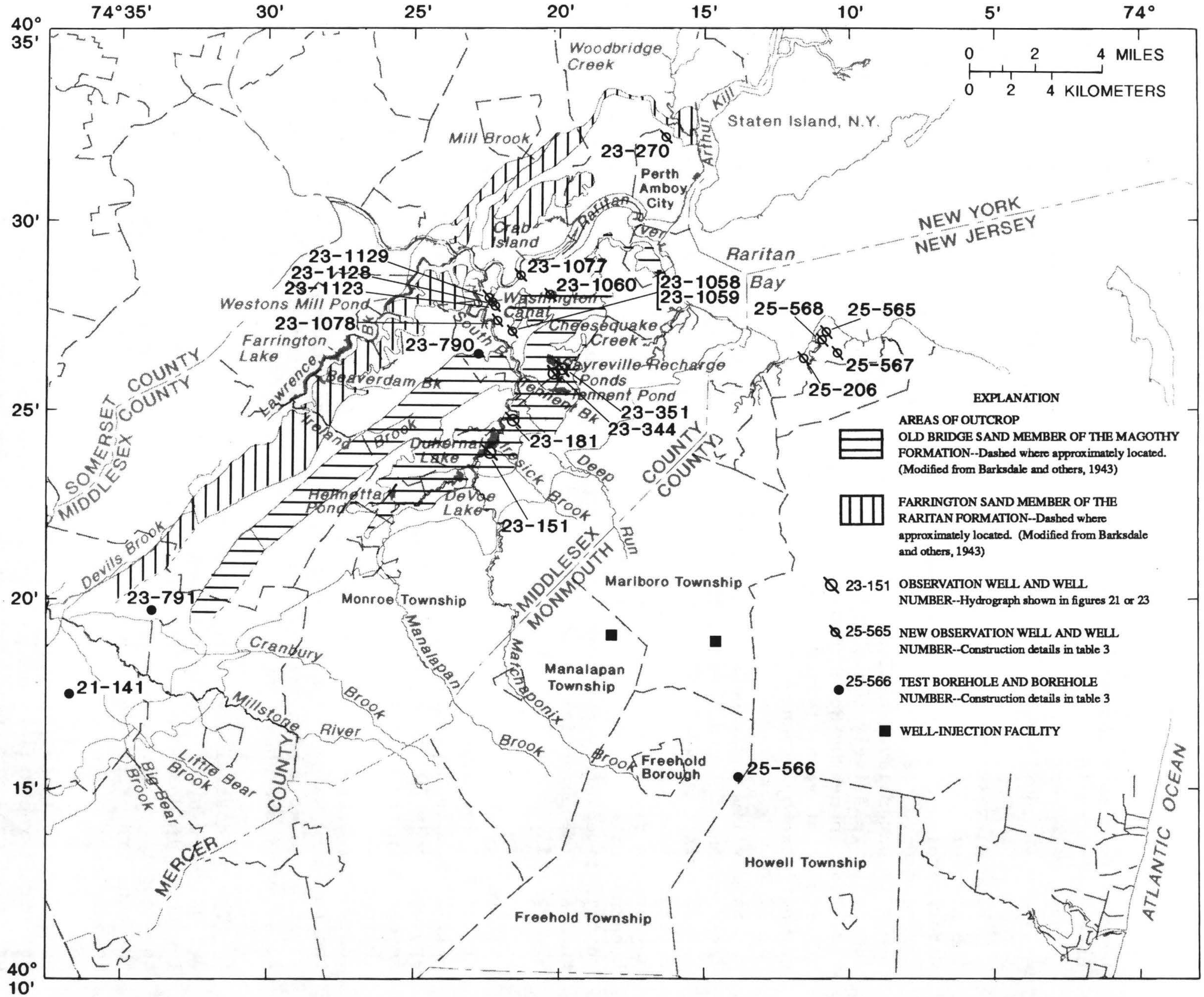


Figure 22.--Locations of selected observation wells, test boreholes, and artificial-recharge ponds, and location of injection-well facility, Potomac-Raritan-Magothy aquifer system.

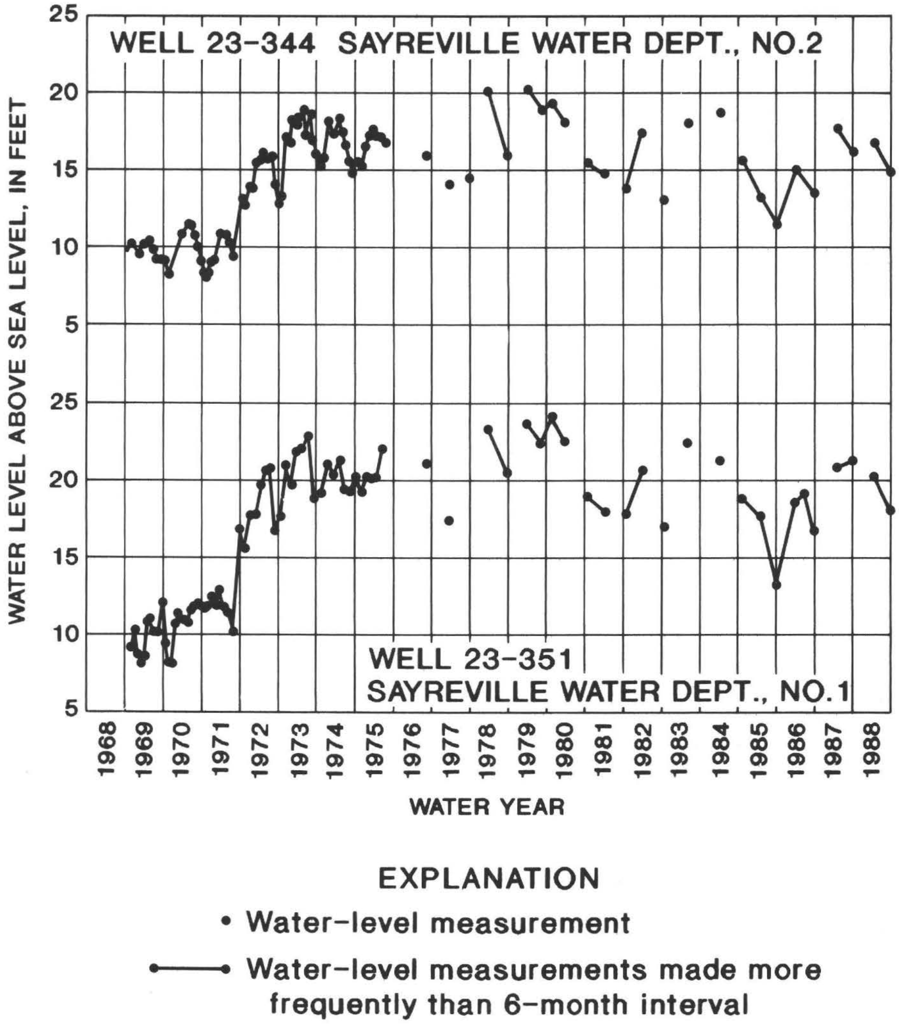


Figure 23.--Water levels in observation wells 23-344 and 23-351, screened in the upper aquifer. (Locations of wells shown in fig. 22)

at a distance from the production wells into the same aquifer. From June through September, the pretreated water is withdrawn again from the aquifer at a rate of about 1.4 Mgal/d (Art Ford, Gordons Corner Water Company, oral commun., 1989).

Construction of storm drains and storm-runoff detention basins to capture storm runoff for ground-water recharge is used in Middlesex County. This method compensates for decreased previous land area and decreased recharge to the aquifer system resulting from construction of housing and industrial developments (Middlesex County Planning Board, 1981, p. 31). The effect of this and other ground-water recharge methods to preserve the availability of ground water is under consideration by the Middlesex County Planning Board and the New Jersey Department of Environmental Protection and Energy as part of a cooperative project on protection of aquifer-recharge areas (Lawrence Shrager, Middlesex County Planning Board, oral commun., 1989).

A tidal dam on the South River, which would create a freshwater-recharge lake and a hydraulic barrier to saltwater intrusion, also has been proposed by Barksdale and others (1943). By raising the freshwater hydraulic head above sea level, the dam would effectively prevent the landward migration of seawater. Appel (1962, p. 27) reported on a proposal to build a tidal dam on the South River between Sayreville Borough and South River Borough. The purpose of the proposed dam and subsequent planned lake was to increase recharge of freshwater and to prevent the infiltration of salty tidal water into the recharge area of the upper aquifer. Irwin Remson and A.A. Fungaroli (U.S. Geological Survey, written commun., 1969) considered the effects of a tidal dam on the Raritan River near Crab Island in Sayreville (fig. 22). This dam would have formed a reservoir over parts of the recharge areas of the middle aquifer and upper aquifer. Neither plan was adopted.

SIMULATION OF REGIONAL GROUND-WATER FLOW

Ground-water-flow conditions, including heads, directions of flow, and flow velocities, have changed significantly as a result of increased use of ground water. The ground-water flow model described herein was used as a tool to evaluate the aquifer system and to estimate its response to future withdrawals.

Development of a quantitative ground-water flow model requires certain assumptions and simplifications of hydrogeologic conditions to allow a mathematical representation of the system. In this study, emphasis was placed on the regional flow system in the confined areas of the upper and middle aquifers. Some mathematical simplifications were based on current knowledge of the aquifer system; others were necessary to accommodate model-area boundaries, the scale of the investigation, and the availability of data. Even if the mathematical model is calibrated to the data for the ground-water system, the limited availability of data would result in a model that only approximates the true flow system. Calibration of such a model could be improved with the availability of additional data and the development of new methods of analysis.

The major model assumptions are listed below.

- The hydraulic properties of the ground-water system are heterogeneous between model grid blocks but homogeneous within each block. Aquifer properties are isotropic, and flow within the aquifers is parallel to the plane of the aquifer. Flow through the confining units is vertical.

- Ground water is withdrawn at constant rates during specified periods through pumped wells. All wells are screened through the full thickness of the aquifer and are 100-percent efficient.

- Long-term net ground-water recharge from net precipitation and evapotranspiration fluxes to the unconfined-aquifer areas of the Potomac-Raritan-Magothy aquifer system is constant, both areally and through time.

- Surface water-bodies in the unconfined aquifer areas act as areas of recharge to or discharge from the ground-water system.

- In areas where the confining unit crops out, water-table altitudes are constant, there is no horizontal flow, and recharge to the confined ground-water system is from head-dependent flow.

- In unconfined-aquifer areas, changes in the saturated thickness are negligible and transmissivity and storage coefficient are areally and temporally constant. In confined areas, tranmissivity and storage coefficient also are constant.

The conceptual hydrogeologic-framework model on which the quantitative model was based is shown in figure 24. The lithology and water-bearing properties of the sediments are summarized in table 1.

Approach

The ground-water-flow system was simulated by use of a three-dimensional finite-difference ground-water flow model (McDonald and Harbaugh, 1988). The model is a numerical finite-difference approximation of the partial-differential equation for three-dimensional ground-water flow. A quasi-three-dimensional approach is used to simulate aquifers as layers in which heads are simulated and flow is horizontal. Confining-unit heads and storage are not simulated directly; flow through the confining units is completely vertical and is represented by vertical leakage. Water released from aquifer storage is simulated to represent water released from aquifer storage and confining-unit storage. Other features of the numerical code that are used to represent hydrologic features such as streams, lakes, and recharge conditions are described in McDonald and Harbaugh (1988).

The model simulates hydraulic heads in four aquifers and vertical flow through three confining units; the middle and upper aquifers are the bottom two aquifer layers, and the Englishtown aquifer system and Wenonah-Mount Laurel aquifer are the two overlying aquifer layers (table 1). The two aquifers overlying the upper aquifer were modeled by use of the same hydraulic-property data that were used in the New Jersey Regional Aquifer System Analysis (RASA) ground-water model of the New Jersey Coastal Plain (Martin, 1990) for the period 1896-1980. The withdrawal data for the

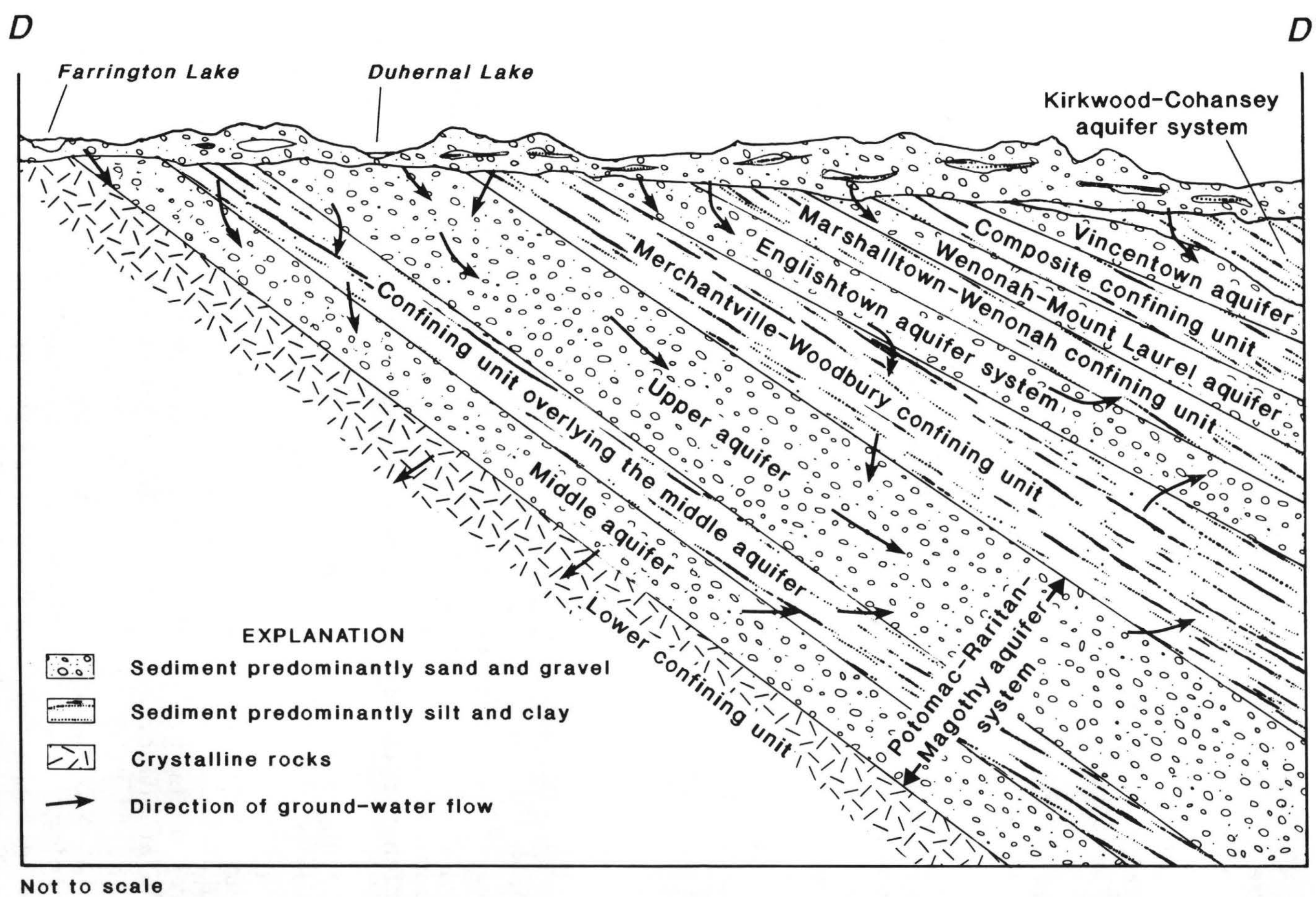


Figure 24.--Diagrammatic section D-D' through the hydrogeologic units in the simulated area. (Location of section shown in fig. 25)

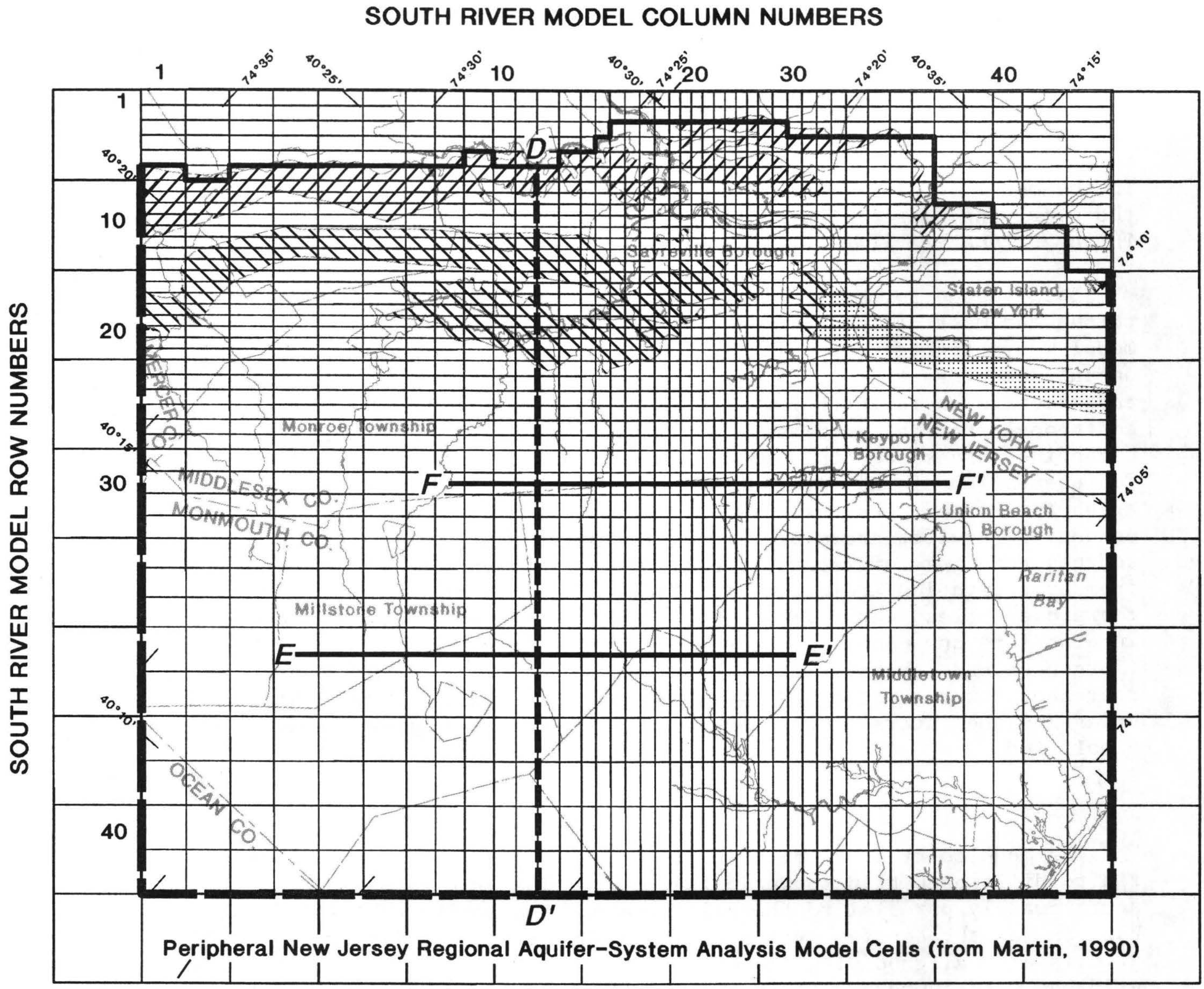
aquifers were the same as those used by Zapecza and others (1987, p. 7) for the period 1896-1980 and by Battaglin and Hill (1989) for the period 1980-83. Withdrawal data for the study area for the period 1984-85 were added to extend simulations to the end of 1985. These overlying layers were included in the model to allow simulation of leakage between the upper aquifer and the overlying Coastal Plain sediments in response to ground-water stresses in the Potomac-Raritan-Magothy aquifer system and overlying aquifers.

Because the Potomac-Raritan-Magothy aquifer system is confined throughout most of the study area and is modeled on a regional scale, the model was designed to predict the volume of water contributed from the unconfined areas to the regional confined areas; the model is less effective and accurate in representing the unconfined areas. Because of these and additional factors, such as data limitations, complexity of processes in the unconfined areas, and the emphasis on regional simulation, the representation of the interaction among the processes in the unconfined areas is limited. For example, many finite-difference cells in the unconfined-aquifer areas of the model simultaneously represent several sources and sinks of water; streams, recharge ponds, wells, and net recharge from precipitation are examples. These processes all interact and, therefore, affect water levels nonlinearly. The model simulates the interactions and computes the resulting hydraulic head within each cell (Jorgensen and others, 1989). Finite-difference cells in the confined areas represent fewer sources and sinks of water than cells in the unconfined areas and the interactions among these processes in the confined areas are simplified.

Grid Design

The modeled area was discretized areally by use of the variably spaced finite-difference grid shown in figure 25. The grid is aligned approximately parallel to the Fall Line and the strike of the Potomac-Raritan-Magothy aquifer system in the study area. The finite-difference grid is also aligned with the New Jersey RASA model grid (fig. 25). The grid has 42 columns and 41 rows. The finite-difference cells are block-centered, and the nodes are at the center of each cell.

Ground-water-flow direction in areas of saltwater migration was examined by letting the smallest finite-difference grid cells be in the model cells that represent the area near Sayreville Borough, Middlesex County, and the area of Keyport and Union Beach Boroughs. In these areas, the cells measure 1,320 ft by 1,320 ft (0.0625 mi^2). Similarly, small grid cells in the updip areas were selected to represent hydrologic controls and processes of local significance, such as stream-aquifer interactions, small cones of depression, and recharge from ponds and lakes in the unconfined-aquifer areas. Cells near the southern and eastern lateral boundaries of the model are largest--6,600 ft by 6,600 ft (1.56 mi^2). Discretization is coarsest in the southern periphery of the modeled area, where the fewest data were available for model calibration. The grid for the South River model fits into the northern part of the New Jersey RASA model grid, in which the spacing is a constant 13,200 ft by 13,200 ft (6.25 mi^2).



EXPLANATION

AREAS OF OUTCROP
OLD BRIDGE SAND MEMBER OF THE MAGOTHY FORMATION--Dashed where approximately located. (Modified from Barksdale and others, 1943, fig. 6)

FARRINGTON SAND MEMBER OF THE RARITAN FORMATION--Dashed where approximately located. (Modified from Barksdale and others, 1943, fig. 6)

AREA WHERE UPPER AQUIFER IS SUBMERGED BENEATH RARITAN BAY--Simulated location

MODEL BOUNDARIES--Lateral flux from New Jersey Regional Aquifer System Analysis model (Martin, 1987)

NO-FLOW BOUNDARY

E —— E' MODEL SECTIONS--Location refers to sensitivity analyses in figures 43-46

D ▬ ▬ D' Location of generalized section in figure 24

0 2 4 MILES
0 2 4 KILOMETERS

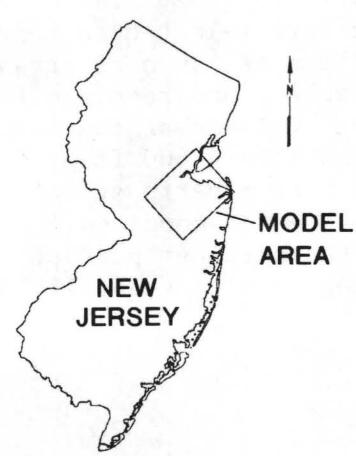


Figure 25.--Finite-difference grid and lateral model boundaries.

Model Boundaries

Wherever possible, model boundaries were selected to coincide with natural no-flow, recharge, and constant-head conditions in the ground-water system or places where lateral fluxes are minimal. Natural boundary conditions for the modeled area include the updip no-flow boundary of the aquifers to the northwest along the Fall Line, the underlying no-flow boundary beneath the lower aquifer, a constant-head boundary along Raritan Bay in the north, recharge boundaries in unconfined areas of the aquifer system, and head-dependent flow boundaries representing streams in the unconfined areas of the aquifers.

The New Jersey RASA model (Martin, 1990) was used to formulate flow boundaries because of the absence of natural boundaries to the south, northeast, and east of the study area (fig. 25). The boundary conditions were chosen as flux boundaries rather than constant-head boundaries to improve the accuracy of the simulated hydraulic-head distribution and the simulated water budget (Franke and Reilly, 1987). These specified lateral fluxes for the South River model-area cells were computed for each stress period as a part of the flux from the appropriate New Jersey RASA model cell (table 11). A section of the northeastern boundary coincides with a column of four boundary cells of the New Jersey RASA model (Martin, 1990), shown adjacent to the heavy dashed lines in figure 25. Boundary fluxes used in the New Jersey RASA model along this boundary were divided into the appropriate number of South River model cells to represent the specified-flux boundary in this area. The southwestern boundary of the model approximately follows a streamline for the predevelopment and transient periods, so flow across this boundary is minimal. The southeastern boundary is located approximately along a flow divide between two large cones of depression as determined for the 1983 potentiometric surface of the upper aquifer (Eckel and Walker, 1986, pl. 3).

A schematic vertical section through the aquifers and confining units in the model (fig. 26) shows how boundary conditions are represented. The upper boundary of the confined part of the top model layer is a time-dependent, specified-flux boundary or a head-dependent-flux boundary in the outcrop areas. Flows across this upper model boundary were calculated from simulated flows between the Vincentown aquifer and the confined area of the Wenonah-Mount Laurel aquifer in the New Jersey RASA model. The specified fluxes were applied as wells in the Wenonah-Mount Laurel aquifer, the uppermost of the four simulated layers (table 11). The outcrop areas of the Englishtown aquifer system and Wenonah-Mount Laurel aquifer received a constant recharge of 20 in/yr and also had overlying constant-head nodes representing long-term, areally averaged stream elevation (fig. 26). The initial values for ground-water withdrawals and hydraulic properties for these overlying layers were unchanged from the final values used in the RASA model (Martin, 1990) and were not changed during calibration of this model.

Table 11.--Ground-water withdrawals and boundary fluxes for each pumping period

[In million gallons per day; positive fluxes are flows out of the modeled area; negative fluxes are flows into the model area]

		Middle aquifer		Upper aquifer		Overlying aquifers		
Pumping period	End date	Withdrawals	Lateral fluxes	Withdrawals	Lateral fluxes	Withdrawals[1]	Lateral fluxes [1]	Top fluxes[2]
Predevelopment	1/01/1896	0	-2.2	0	-2.2	0	-1.2	1.7
1	12/31/1920	.6	-2.3	1.4	-2.9	.4	-1.9	2.0
2	12/31/1945	11.1	-1.7	10.7	-2.4	.7	-2.1	2.5
3	12/31/1952	14.6	-1.4	24.3	-2.0	.3	-2.5	3.1
4	12/31/1957	11.4	-1.7	31.4	-2.2	.9	-2.9	3.6
5	12/31/1964	11.5	-2.3	36.5	-2.7	2.7	-3.2	4.2
6	12/31/1967	15.5	-2.1	40.6	-2.2	4.0	-3.9	4.7
7	12/31/1972	20.6	-1.6	44.7	-1.4	4.4	-4.7	5.8
8	12/31/1977	22.8	-1.1	43.4	.5	4.0	-4.8	6.2
9	12/31/1980	25.9	-1.2	41.9	.2	4.4	-5.0	6.0
10	12/31/1983	24.6	-.7	39.5	-.3	1.2	-5.0	5.6
11	12/31/1984	22.9	[3] -.7	40.0	[3] -.3	.7	[3] -5.0	[3] 5.6
12	12/31/1985	21.6	[3] -.7	39.9	[3] -.3	1.3	[3] -5.0	[3] 5.6

[1] Englishtown aquifer system and Wenonah-Mount Laurel aquifer.

[2] Wenonah-Mount Laurel aquifer.

[3] Same as fluxes from stress period 10.

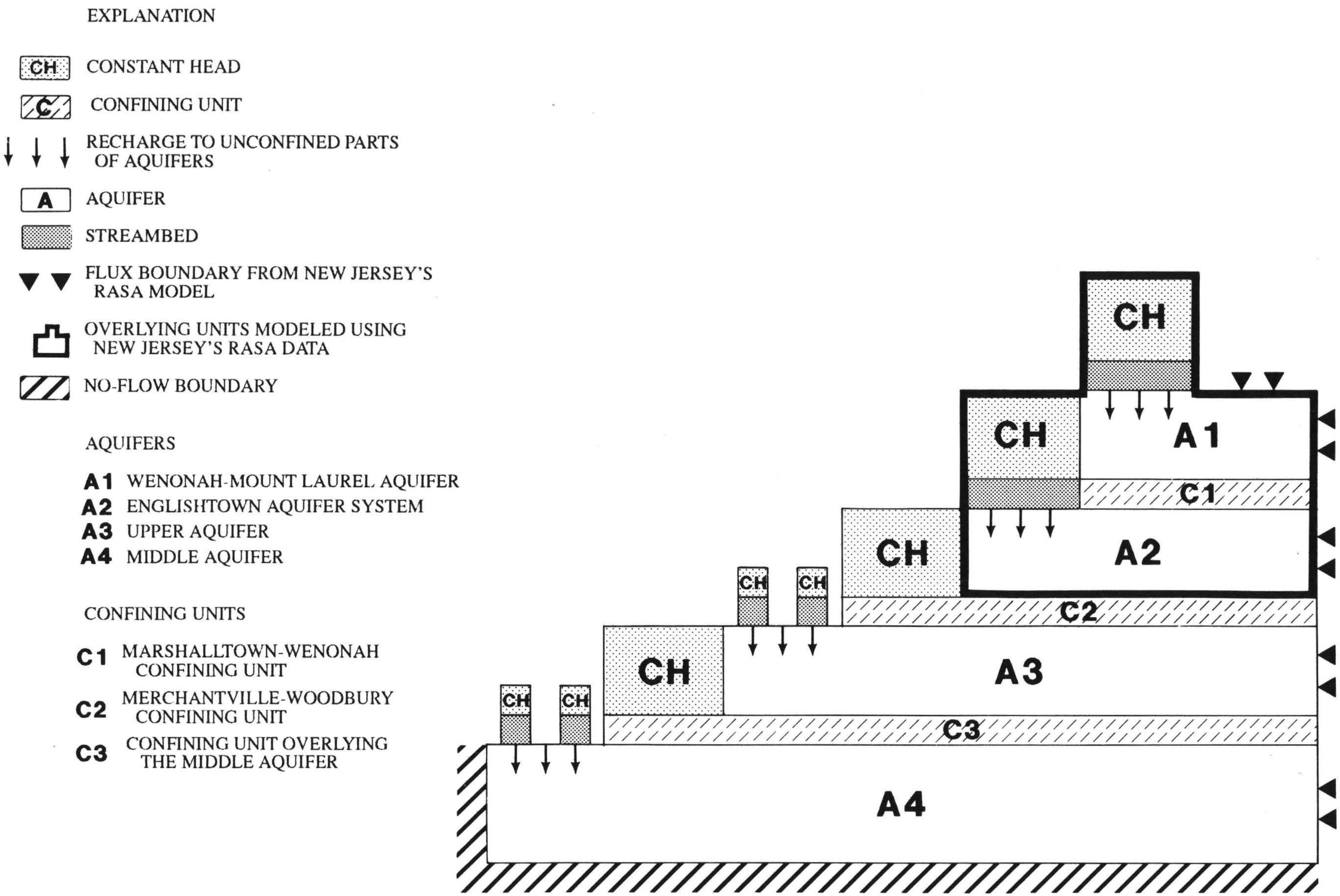


Figure 26.--Schematic diagram of aquifers, confining units, and boundary conditions used in the model.

The outcrop areas of the Merchantville-Woodbury confining unit, the upper aquifer, the confining unit overlying the middle aquifer, and the middle aquifer were discretized by use of the model grid. Recharge was applied to all aquifer-outcrop cells at a rate of 15 in/yr, a value that resulted from the model calibration. The actual aquifer-outcrop areas, the discretized-model outcrop areas, actual stream locations, model stream cells, and water levels in the outcrop areas are shown in figure 27.

The outcrop areas of the confining units are represented as constant-head boundaries because of limited available hydrogeologic data and the model's regional emphasis. Resistance to flow through these confining units is simulated as leakance. The constant-head water table in the outcrop areas of the confining units was included in the model because (1) Pleistocene and Miocene sediments overlie these areas, and (2) without this constant-head source of ground-water recharge, ground-water discharge to stream cells ceased in many areas, even in the simulation of the unstressed, predevelopment system. In these areas, the estimated constant-head values (fig. 27) are a simplified representation of the water-table system, which responds to stresses only by vertical flow to or from the underlying confined system.

Constant-head cells are used to simulate the location where the upper aquifer is estimated to be well-connected to Raritan Bay, just offshore from Staten Island, New York, as shown in figure 27. The pathways for hydraulic connection of the upper aquifer to Raritan Bay were discussed earlier. The constant-head value for cells representing the submerged area is the equivalent freshwater head, hf, in the bay, which was calculated from estimates of the depth of Raritan Bay and corrected for the density of seawater, 1.025 g/mL. Because the aquifer is assumed to contain saltwater where it crops out in Raritan Bay, the equivalent freshwater head is computed at the middle elevation of each cell. The equivalent freshwater head, hf, is the sum contributed from the depth of the bay plus the saltwater in the submerged outcrop:

$$hf = (\text{water depth} + (\text{aquifer thickness} / 2)) * 0.025.$$

For the confining unit overlying the upper aquifer in the bay, constant heads were simulated in an overlying layer (fig. 27). Because water within the outcrop of the upper confining clay is assumed to be fresh, the equivalent freshwater head is calculated from the water depth and the density of seawater:

$$hf = \text{water depth} * 0.025.$$

The lower boundary of the model is a no-flow boundary representing the top of the bedrock surface, or the top of the lower confining unit. In most of the modeled area, the lower aquifer of the Potomac-Raritan-Magothy aquifer system is absent, and the middle aquifer lies directly on bedrock. In the small area downdip where the lower aquifer could be present, it is simulated as part of the middle aquifer.

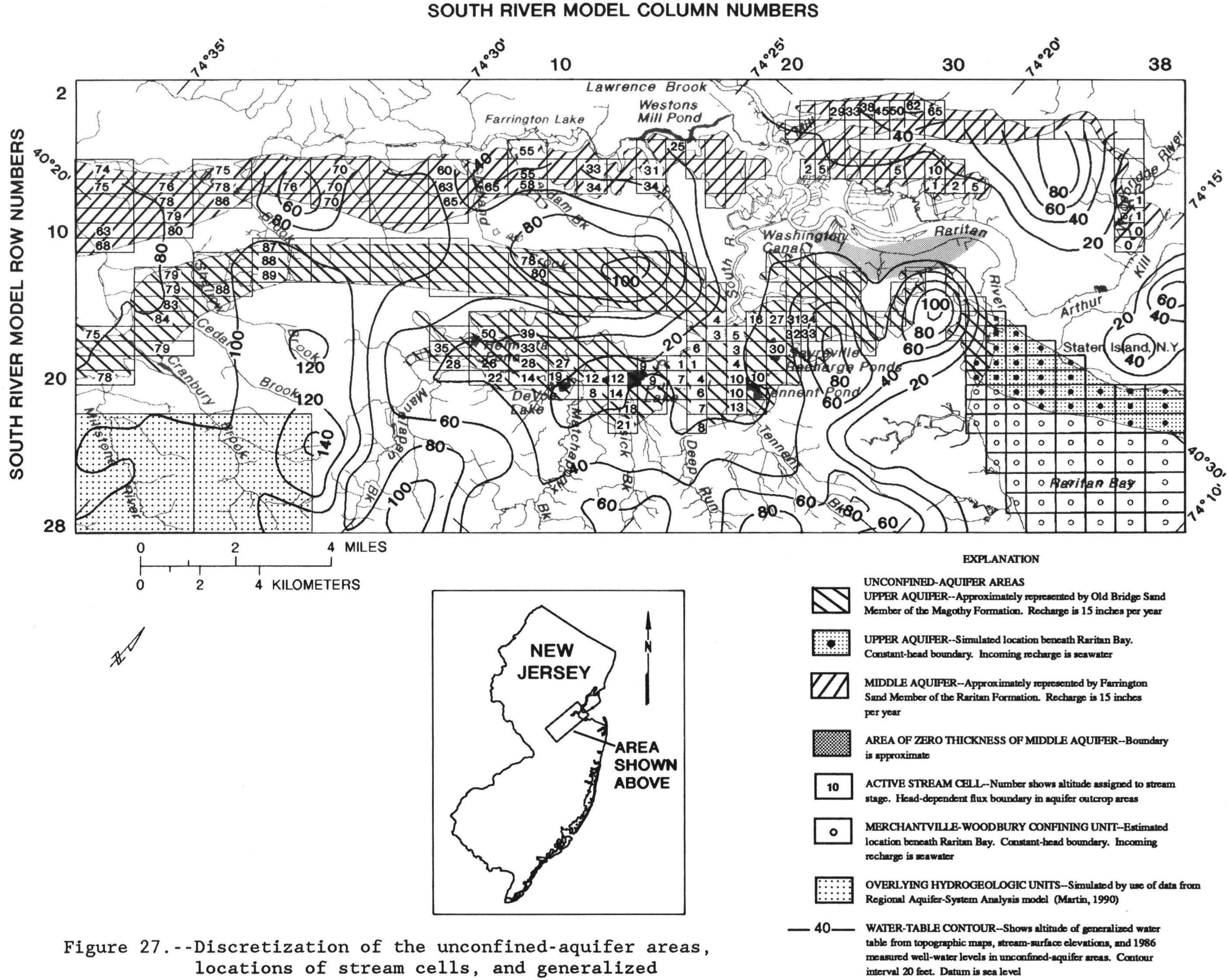


Figure 27.--Discretization of the unconfined-aquifer areas, locations of stream cells, and generalized water-table altitude in outcrop areas.

Temporal Conditions

The model simulates ground-water flow for predevelopment conditions (steady-state flow) and for stressed conditions (transient flow). The transient model simulates ground-water withdrawals beginning with the first ground-water withdrawals in the study area in 1896 and ending in 1985. The transient-simulation period was divided into 12 pumping periods ranging in duration from from 1 to 25 years. The same pumping periods were used in the New Jersey RASA model (Martin, 1990), which was used to compute the transient lateral- and vertical-flux boundary conditions for the South River model. Withdrawals for the first 10 stress periods coincide with stress periods previously used for the New Jersey RASA model (Martin, 1990; Battaglin and Hill, 1989, p. 16) and end in 1983. Data on major users of ground water from the upper and middle aquifers, and the duration of the stress periods and ground-water withdrawal rates for simulations are listed in tables 6 and 7. Ground-water withdrawal data for the upper and middle aquifers used in the transient model were derived from the data base of annual withdrawal rates discussed previously.

Lateral boundary flows for each stress period were applied along the model boundary on the basis of the results of the last time step of each stress period from the New Jersey RASA model. Lateral- and top-boundary fluxes for stress period 10 (table 11) were also used to simulate stress periods 11 and 12 (1984 and 1985) because withdrawal data for the New Jersey RASA model during these years were unavailable. Lateral-boundary flows between the New Jersey RASA model and the South River study-area model for the upper and middle aquifers and the total combined lateral- and top-boundary fluxes for overlying aquifers (Englishtown aquifer system and Wenonah-Mount Laurel aquifer) are listed in table 11.

Data Input and Output

Most of the hydrogeologic data used to construct and calibrate the model were derived from aquifer tests, well-acceptance tests, or well logs, as described earlier in this report. Most of these data are from the shallow, updip parts of the aquifer system where well construction is less expensive than for deeper zones or where the aquifer is most productive.

Although hydrogeologic properties can be similar over large areas, local variations also are evident in the observed data. Therefore, the danger exists of overcalibrating the model by regarding variability in the data as information needed to be incorporated into the model. An objective of the model calibration is to predict the distribution of the average, or trend, of these properties over large areas and to minimize sensitivity to randomness or uncertainty in these data. Therefore, values representing some hydrogeologic properties, such as horizontal and vertical hydraulic conductivity, are input as average values over zones rather than as individual hydrogeologic-property values assigned node by node.

Geostatistical and exploratory data analysis of trends in regional properties (Pucci and Murashige, 1987) was considered in the formulation of zones and sensitivity analysis and calibration. Estimates of hydrogeologic-unit surface and hydrogeologic properties, such as aquifer hydraulic conductivity, are less reliable for the shallow, unconfined areas of the aquifer system than for the deep, confined areas of the system because variability in these properties is greatest in the shallow areas (Pucci and Murashige, 1987; Pucci and others, 1989). To compensate for this variability, model formulation included more hydraulic-property zones in and near the unconfined areas than elsewhere; however, because the difficulty of predicting any hydrogeologic property with the ground-water model is proportionate to the spatial variability and irregularity of the data, the correlation of these hydraulic-property zones with the real system is the least reliable in and near the shallow, unconfined areas.

Hydrogeologic parameters used in the New Jersey RASA model generally were used as initial model input data; these data were modified later during calibration. In the early stages of calibration, the effect of discretization was examined for the same model area but with additional nodes. The observed effect was considered significant in most of the model area. All hydrogeologic data used to model the Wenonah-Mount Laurel aquifer and the Englishtown aquifer system are from the New Jersey Coastal Plain RASA model (Martin, 1990) and were not changed during calibration.

Aquifer transmissivity for each cell for the upper and middle aquifers was determined by multiplying the aquifer-thickness value (figs. 5 and 15) by the estimated horizontal hydraulic conductivity of the aquifer. Horizontal hydraulic conductivities were estimated for areas, or zones, within each aquifer. Hydraulic-conductivity zones were created by use of estimates of hydraulic conductivity from the RASA model (Martin, 1990) and hydraulic-conductivity data from aquifer and well-acceptance tests (Pucci and others, 1989). For the final calibrated model, which is described in detail later, the upper aquifer was divided into 16 horizontal-hydraulic-conductivity zones; the middle aquifer was divided into 23 zones.

Vertical hydraulic conductivities were estimated from RASA model data (Martin, 1990) and aquifer-test results (tables 4 and 5). Representative vertical hydraulic conductivities were assigned to areas, or zones, within each confining unit. These zones were distinct from horizontal-hydraulic-conductivity zones. In the final calibrated model, which is described in detail later, the upper aquifer includes 17 vertical-hydraulic-conductivity zones; the middle aquifer includes 26 vertical-hydraulic-conductivity zones.

The storage coefficients used in the model are those used in the New Jersey RASA model. A uniform value of 1.0×10^{-4} was used for the confined areas of the aquifers. A specific-yield value of 0.15 was used in unconfined areas. These coefficients are average values for the aquifers and were not changed during model calibration.

Stream locations in the outcrops of the upper and middle aquifers were assigned to the grid cells on the basis of 1:24,000-scale topographic maps and verification by field reconnaisance (fig. 28). Estimates of the elevation of stream surface were taken from flood-insurance studies and from elevations on the topographic maps. Contour intervals on the topographic maps were 10 or 20 ft; therefore, estimates of the elevation of the stream surface were accurate to within 10 ft. These estimates are assumed to represent a long-term average elevation of the stream surface and an areal average within each cell.

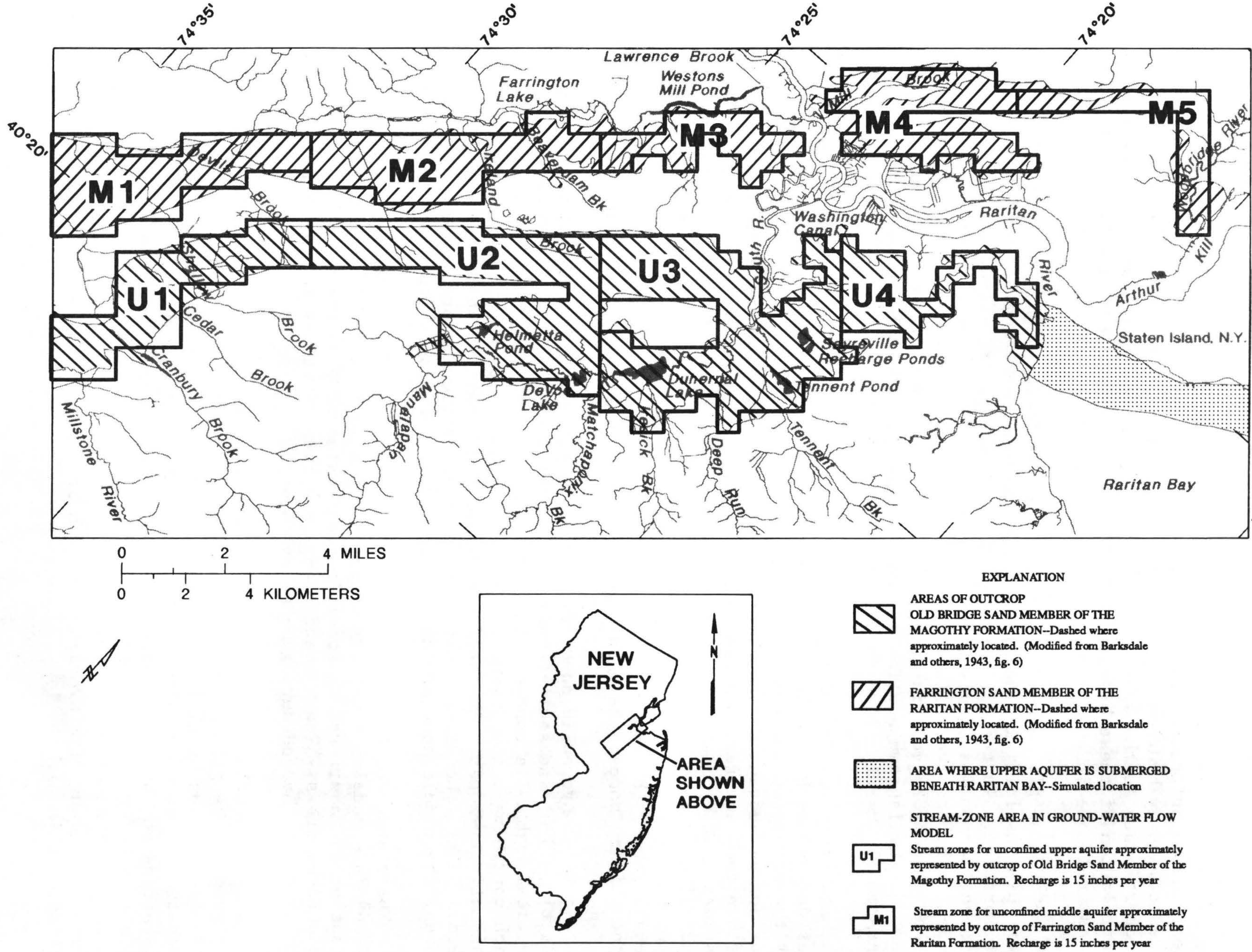


Figure 28.--Simulated stream zones in the outcrop areas of the upper and middle aquifers.

Streambed conductances initially were estimated by use of the following assumptions (Harbaugh and Tilley, 1984): a stream width of 10 ft, a depth of 1 ft, a streambed thickness of 2.5 ft, a vertical hydraulic conductivity of the streambed material of 0.2 ft/d (Harbaugh and Tilley, 1984, p. 15), and the stream length within the model cell area. Streambed (or riverbed) conductance is a property of a streambed reach that controls vertical fluxes between the stream and the hydrologic unit. Streambed conductances were adjusted during calibration so that net simulated ground-water flow for each stream zone (fig. 28) would discharge to the streams under predevelopment conditions. The stream zones were groups of active stream cells within parts of the outcrop areas of each aquifer for which ground-water discharge to streams was aggregated for model analysis. For the final calibrated model (discussed later), four stream zones were defined for the upper aquifer and five stream zones were defined for the middle aquifer. The mean of the final calibrated streambed conductances was 1.2 ft/d, and the range was 0.1 to 3.0 ft/d. Higher streambed conductances generally were assigned to cells near the downdip edge of the unconfined-aquifer area in the calibrated model.

Model simplifications in representing the water-table/stream interactions in the confining-unit outcrops prevented the determination of ground-water discharge to streams in the confining-unit outcrops; therefore, total ground-water discharge to a stream could not be computed and compared to measured base-flow data. The calibrated ground-water discharge in the streams zones, therefore, was considered to be an indicator of net gaining or losing stream reaches within the zones and not as an accurate means for computing the base flow of the streams. An attempt was made to have all streams gaining for predevelopment flow.

Initial head values for the confined areas of the upper and middle aquifers for the steady-state flow model were assigned by use of the map of predevelopment heads of the upper aquifer (fig. 8). The predevelopment heads in the upper aquifer also were used as initial heads in the middle aquifer because few measurements of predevelopment heads in the middle aquifer were available. Heads resulting from steady-state, predevelopment simulations then were used as initial head values for transient simulations (fig. 29).

Water-table altitudes used for the confining-unit outcrops and initial predevelopment heads in the aquifer outcrops (fig. 27) were assigned by use of a contour map of the water table based on water levels in wells in the aquifer outcrop and from stream elevations on U.S. Geological Survey 1:24,000-scale topographic maps and, where possible, from estimates of the altitude of the stream surface in flood-insurance studies.

Revisions of model parameters representing hydraulic properties of the aquifer system in the South River model area during calibration resulted in a need to recompute the boundary fluxes in the South River model. These revisions were made periodically by updating the New Jersey RASA model with newly computed parameters derived from the South River model. Updates were made by arithmetically averaging input parameters in the South River model for grid cells that corresponded to each New Jersey RASA model cell. Parameters representing hydraulic properties in the four rows or columns of cells of the New Jersey RASA model adjacent to the South River model boundary also were updated to eliminate sharp differences in parameters between the two models. Differences in scale of discretization or modeling approach between the New Jersey RASA and South River models precluded updating of some parameters in the New Jersey RASA model, including vertical hydraulic conductivity of streambeds above the aquifer outcrops and vertical hydraulic conductivity in confining-unit outcrop areas.

Calibration

Steady-state and transient model calibrations were done by adjusting hydrogeologic parameters and comparing the model response to (1) areal distribution of measured heads for predevelopment and for the end of 1984, (2) hydrographs of long-term measured heads at certain wells, (3) intuitive understandings of the system, such as the assumed prevalence of gaining stream reaches during predevelopment conditions, and (4) estimates of water-budget components, such as net recharge.

Parameters that primarily affected calibration of the hydraulic heads in transient model included horizontal hydraulic conductivities of the aquifer, vertical hydraulic conductivities of the confining units, and recharge rate. Streambed conductances, elevations of stream surface, and water-table altitudes in the confining-unit outcrops primarily were adjusted so that most stream cells were simulated as gaining in the predevelopment system; however, these changes had little effect on simulated heads in the confined-aquifer areas.

The model was considered to be calibrated when the following criteria were met:

1. The simulated 1984 potentiometric surfaces of the upper and middle aquifers generally matched interpreted potentiometric surfaces within 10 ft (figs. 31 and 32), and the location and shape of the simulated cones of depression were representative of the measured data. Results for heads in the unconfined-aquifer area are not considered as sensitive because of model design and model response in unconfined areas.

2. The simulated predevelopment potentiometric surface of the upper aquifer matched the interpreted predevelopment potentiometric surface (fig. 29) within 15 ft. Because of the paucity of measured predevelopment water-level data for the middle aquifer, predevelopment model calibration was judged by consistency with the hydrologic concepts of the aquifer system and with simulated surfaces from other model studies (Farlekas, 1979; Martin, 1990).

3. Heads in all simulated hydrographs for the transient model were within 15 ft of the measured heads at the end of each stress period, and 90 percent were within 10 ft.

4. Flow rates, flow-budget components, and calibrated hydrogeologic properties were consistent with measured values, observed trends, and the hydrologic concept of the aquifer system discussed earlier in this report.

5. The interpreted 1983 potentiometric surfaces of the overlying aquifers (the Englishtown aquifer system and Wenonah-Mount Laurel aquifer) agreed closely with results of the New Jersey RASA analysis (Martin, 1990).

The accuracy of the calibration criteria was judged by considering (1) the accuracy of measured data and (2) the intended use of the model as a tool for water-resources management. As discussed earlier, the head measurements probably are accurate to within 10 ft or more. The model is intended to provide a sense of the effect of various withdrawal scenarios on heads within cones of depression that range in depth from more than 90 ft below sea level to 30 ft below sea level. It is also intended to provide general flow-budget information about relative source and sink areas for regional flow. On the basis of these objectives, head-calibration criteria of 10 ft generally were judged to be appropriate. Calibration criteria of 15 ft were judged to be acceptable where the number of water-level measurements was very small, and for about 10 percent of the monitoring-well water-level measurements used in the transient calibration.

Simulated heads for the end of 1984, the end of stress period 11, and the interpreted potentiometric-surface maps of the middle and upper aquifers for early November 1984 were compared during calibration. Simulated heads were interpolated for each well location by use of the simulated heads at the three nearest model nodes. Although the properties of the overlying Wenonah-Mount Laurel aquifer and Englishtown aquifer system were not changed during calibration, heads in these aquifers were within 5 ft of the simulated heads in the New Jersey RASA model analysis (Martin, 1990) and for the interpreted potentiometric surfaces for 1983 (Eckel and Walker, 1986).

During calibration, simulated and measured heads were compared for wells in the modeled area and one well outside the modeled area for which long-term hydrographs are available. Of these wells, 11 are screened in the upper aquifer (fig. 31) and 12 are screened in the middle aquifer (fig. 32). Most of these wells are in or near the aquifer outcrops. Heads in simulated hydrographs were calculated by interpolating the heads simulated at the three nearest nodes to define the value at each well. The hydrograph for well 23-306 was used in calibration, although the well is just outside the model grid, on Sandy Hook in Monmouth County.

Simulated components of the ground-water-flow budget were compared to known and estimated ranges of fluxes. Simulated flow between the confined and unconfined areas, through confining units, to and from Raritan Bay, and to and from recharge ponds was analyzed by use of ground-water-flow budgets for selected areas. Similarly, simulated ground-water budgets of net discharge to and from streams were computed for areas, or zones, in each aquifer outcrop (fig. 28). Previously reported estimates of the recharge rate at the recharge ponds at Duhernal Lake, Tennent Pond, and the

Sayreville Recharges Ponds (Barksdale and others, 1943, p. 87; Barksdale and DeBuchananne, 1946, p. 729; Geraghty & Miller, Inc., 1976, p. 15) were compared with the simulated recharge rates during model calibration.

Predevelopment Steady-State Conditions

Upper aquifer

The simulated predevelopment potentiometric surface of the upper aquifer (fig. 29) satisfies the calibration criteria in most of the area. The predevelopment surface interpreted from measurements (figs. 8 and 29) is similar in much of the area to the simulated surface; maximum altitudes are in the southwestern part of the modeled area, in Monroe and Cranbury Townships. The maximum altitude of 90 ft above sea level for the simulated surface is in South Brunswick Township. Altitudes of the simulated and interpreted surfaces decrease from the regional areas of recharge in the southwest toward the regional discharge areas near the South River and Raritan Bay in the northeast and east. In the downdip areas, ground-water discharge moves upward through the overlying hydrogeologic units and ultimately to the Atlantic Ocean.

The simulated heads generally are about 15 ft lower than interpreted heads in the southwestern part of Middlesex County and the central part of Mercer County and about 10 ft higher than interpreted heads near Red Bank in Monmouth County. The match between simulated and interpreted heads in the vicinity of the upper-aquifer outcrop in East Brunswick is relatively poor. The simulated potentiometric surface is similar to the simulated predevelopment potentiometric surface reported in the RASA study (Martin, 1990, fig. 32).

A net ground-water discharge to streams was simulated in the predevelopment period in each designated stream zone for the upper aquifer (U1-U4, table 12). The amount of ground-water discharge to streams in these zones ranges from 2.8 in/yr (zone U4, a topographically high area in Sayreville Borough and Old Bridge Township containing few streams) to 17.6 in/yr (zone U3, in the low-lying areas of Old Bridge Township and Sayreville and Spotswood Boroughs, which are drained by many streams). The rate of ground-water discharge to streams in zone U1 (5.6 in/yr) and zone U4 (2.8 in/yr) is much less than the applied recharge rate of 15 in/yr; therefore, most of the ground-water recharge is flowing into the confined system in these zones. Discharge in zones U2 (16.7 in/yr) and U3 (17.6 in/yr) is greater than the applied recharge rate of 15 in/yr because ground-water discharge in these zones includes local and regional ground-water discharge. Although all stream segments were assumed to be gaining ground-water discharge under predevelopment conditions, simulated ground-water flow from five active stream cells could not be simulated as gaining. All three ponds and lakes in the unconfined area of the upper aquifer during predevelopment (Tennent Pond, Helmetta Pond, and Devoe Lake) were simulated as receiving ground-water discharge during the predevelopment period.

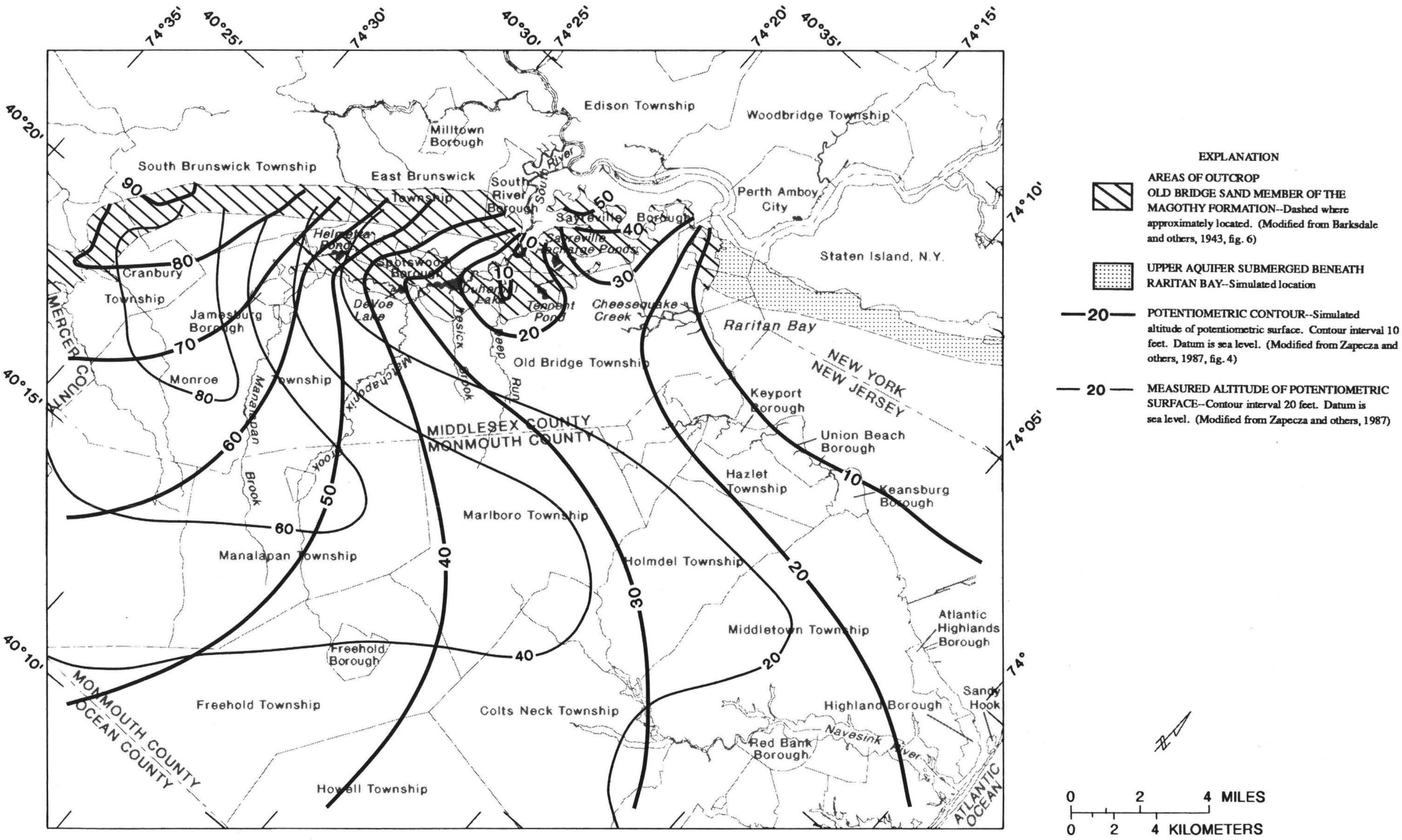


Figure 29.--Simulated and interpreted predevelopment potentiometric surfaces in the upper aquifer.

Table 12.--Simulated ground-water discharge to stream cells in stream zones and net recharge rate, by stream zone, for predevelopment steady-state and 1984 transient conditions

[Discharge and recharge reported as average flow rate in in/yr (inches per year). Net recharge for stream zones reported in in/yr. Net recharge is the applied ground-water recharge rate (15 in/yr) plus the simulated ground-water discharge to stream cells in each stream zone and represents simulated ground-water recharge to the confined-aquifer system; negative net-recharge values represent areas of discharge from the confined-aquifer system; positive net-recharge values represent areas of recharge to the confined-aquifer system. Stream zones shown in fig. 28; mi², square miles]

	STREAM ZONE								
	Upper aquifer				Middle aquifer				
	U1	U2	U3	U4	M1	M2	M3	M4	M5
Area (mi²)	6.25	9.8	11.5	4.2	6.25	5.8	2.9	4.8	3.1
Number of stream cells	11	12	24	12	12	9	4	12	4
PREDEVELOPMENT STEADY-STATE CONDITIONS									
Ground-water discharge to streams in stream zone	-5.6	-16.7	-17.6	-2.8	-12.3	-12.4	-18.2	-19.1	-12.9
Net recharge	9.4	-1.7	-2.6	12.2	2.7	2.6	-3.2	-4.1	2.1
1984 TRANSIENT CONDITIONS									
Ground-water discharge to streams in stream zone	2.9	-5.8	-4.8	-0.8	-6.7	-2.6	2.1	-13.1	-6.4
Net recharge	17.9	9.2	10.2	14.2	8.3	12.4	17.1	1.9	8.6

Middle aquifer

The maximum altitude of the simulated predevelopment potentiometric surface of the middle aquifer (fig. 30) is about 80 ft above sea level in South Brunswick and Cranbury Townships, in the southwestern part of the study area. The altitude of the simulated surface decreases from this main regional recharge area toward discharge areas near Raritan Bay and toward the Atlantic Ocean in the northeast and east. Ground-water gradients are less steep toward the South River during predevelopment than for the upper aquifer. As explained earlier, available measured-head data are insufficient for comparison with the simulated predevelopment results. Throughout the modeled area, heads are generally 5 to 10 ft higher than the heads simulated by the New Jersey RASA model, and the regional gradients to discharge areas are not as steep (Martin, 1990, fig. 31). The regional potentiometric-surface pattern and range of heads are similar to those for the simulated predevelopment potentiometric surface of the middle (Farrington) aquifer reported by Farlekas (1979, fig. 18), except locally near the South River, Raritan Bay, and Staten Island. Differences in these areas are probably caused by refinements to the hydrogeologic framework incorporated into the South River model, including the pinchout of the aquifer in Sayreville Borough and the hydraulic connection to Raritan Bay.

Simulation results showed net gains in ground-water discharge to streams for the predevelopment period were simulated for stream zones in the middle aquifer (M1-M5, table 12). Simulated streamflow in these zones ranges from 12.3 in/yr (zone M1, in South Brunswick Township, a regionally elevated area in the southwestern part of the modeled area) to 19.1 in/yr (zone M4, in the area of Edison Township) (fig. 28). Simulated discharge from stream zones M1, M2, and M5 is about 12 to 13 in/yr. Discharge in zones M3 and M4, which is about 18 to 19 in/yr, is greater than the applied recharge rate of 15 in/yr and includes local and regional ground-water discharge to streams. Only stream cells along the upper reaches of Mill Brook, in zone M4, are losing reaches. Mill Pond, the only lake simulated in the unconfined area of the middle aquifer, received discharge from the ground-water system during the predevelopment period. Raritan River and Arthur Kill are above confined areas of the middle aquifer and were not simulated as streams.

1984 Transient Conditions

Upper aquifer

The simulated potentiometric surface for 1984 transient conditions and the interpreted potentiometric surface for November 1984 for the upper aquifer are shown in figure 31. Simulated heads in the recharge area in the southwestern part of the modeled area generally are 5 to 10 ft lower than the interpreted heads, but the general flow direction is the same. Simulated heads and heads measured at 81 wells for 1984 generally agreed well. The mean error between the measured head and the simulated head was -0.65 ft, and the standard deviation was 7.0 ft. Simulated heads were within 10 ft of the measured head for 86 percent of the measured wells. Simulated heads in the southwestern part of the modeled area generally were 5 to 10 ft lower than the measured heads. Head differences greater than 10 ft were not concentrated in any particular area. The relative magnitude and distribution of the residuals between the predicted and measured heads for the upper aquifer were considered to be unbiased and acceptable.

Several major regional ground-water flow features are reproduced by the model. The simulated cone of depression in southern Marlboro Township, Monmouth County, reasonably matches the interpreted cone (fig. 31); however, the 30-ft contour in Colts Neck and Howell Townships, Monmouth County, did not match as well because of the proximity to the lateral, southeastern boundary fluxes from the New Jersey RASA model (Martin, 1990). The map of the November 1983 synoptic water-level measurements indicates that the potentiometric surface in this area is a potentiometric high, or saddle

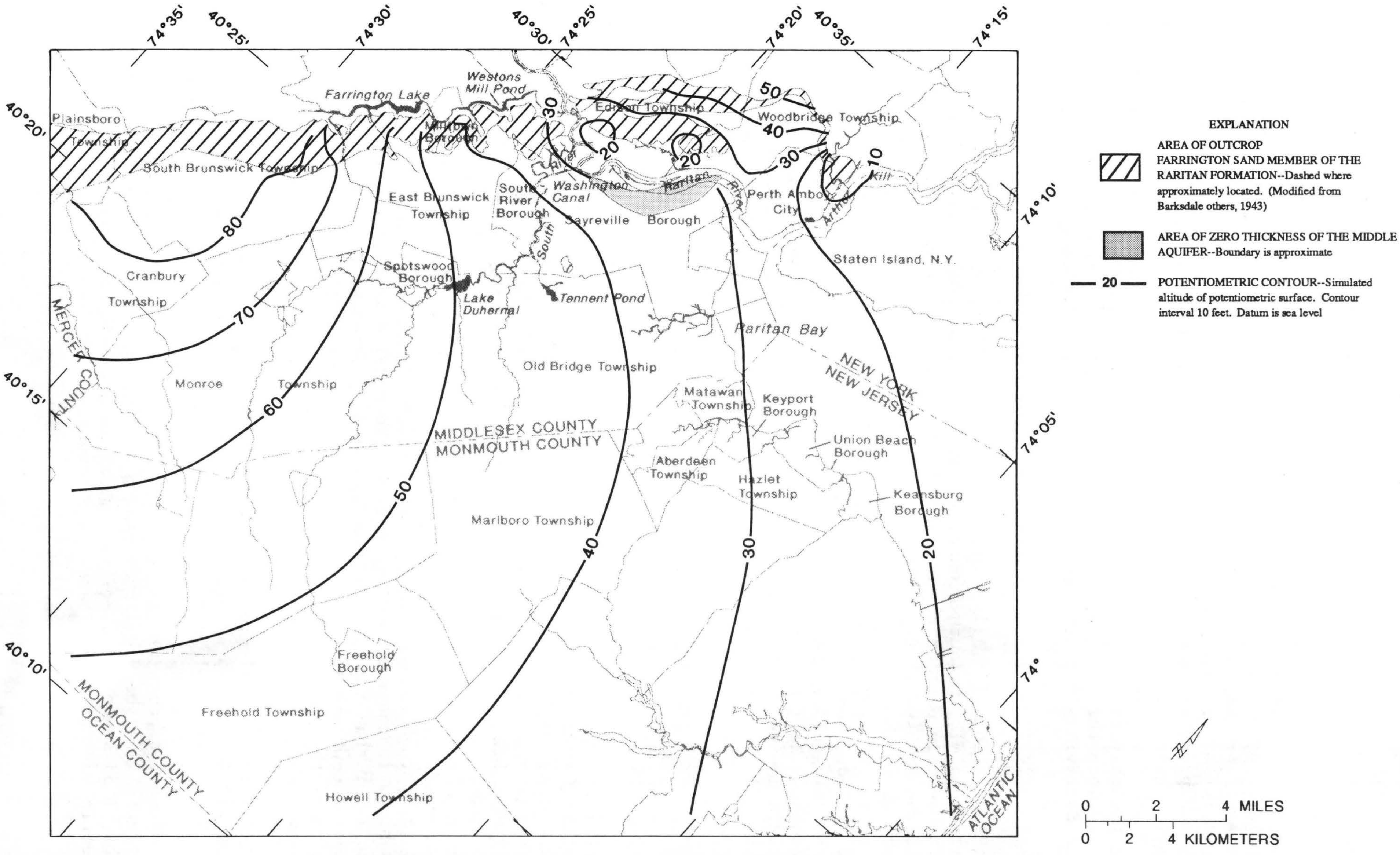


Figure 30.--Simulated predevelopment potentiometric surface in the middle aquifer.

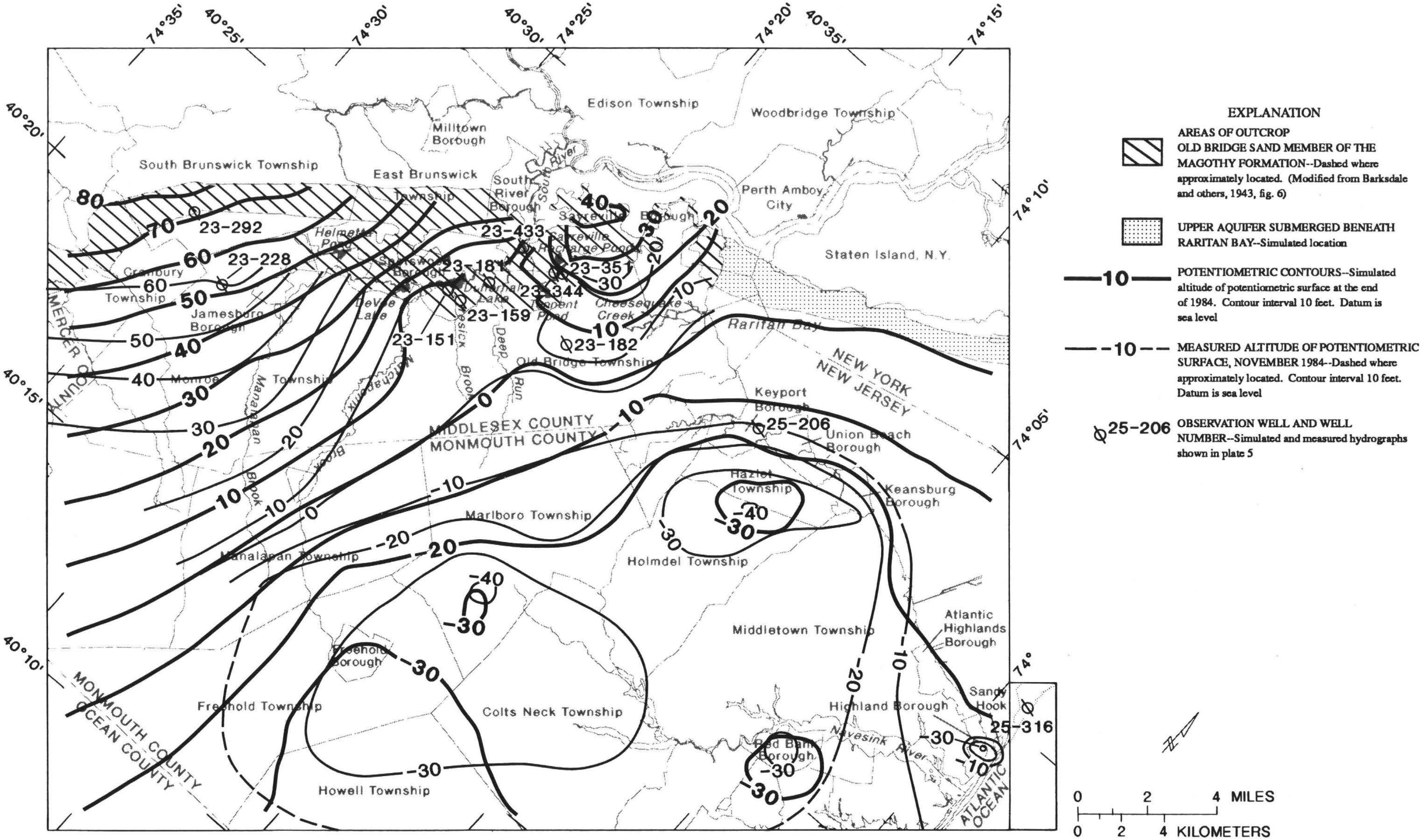


Figure 31.--Simulated and interpreted potentiometric surfaces in the upper aquifer, 1984.

region, between Hazlet Township and Colts Neck Township, where flow magnitudes are small and flow direction is uncertain (Eckel and Walker, 1986, pl. 3). The position of the potentiometric high simulated by the New Jersey RASA model was southeast of the surface measured in 1983 (Eckel and Walker, 1986). Therefore, the boundary fluxes for cells along the southeastern boundary (columns 1 to 27) were changed to no-flow during calibration. The cone of depression centered at Red Bank Borough was closely simulated. The shape of the cone in Hazlet Township was simulated, although the simulated heads are about 10 ft higher than the measured heads. The localized cone of depression in Atlantic Highlands Borough near Sandy Hook was not simulated because of its proximity to the model boundary; the simulated potentiometric surface in the area near Sandy Hook generally is 10 ft higher than the interpreted surface, and is similar to the surface simulated in the New Jersey RASA model (Martin, 1990).

Ground-water discharge to streams for the 1984 transient simulation is considerably different from that in the predevelopment simulation (table 12). Ground-water withdrawals have reduced the discharge to streams or caused simulated streams to recharge the ground-water system. Many more stream cells provide ground-water recharge to the confined aquifer than during predevelopment. The net ground-water recharge rate is 2.9 in/yr from streams in zone U1. Stream cells in zones U2 and U3 receive ground-water discharge as during predevelopment conditions, but at reduced rates of 5.8 and 4.8 in/yr, respectively. Therefore, about 10 in/yr of recharge to the confined aquifer system is simulated from each of these stream zones. Simulated net ground-water discharge to streams in zone U4, which contains the large withdrawal centers at Duhernal Lake and Tennent Pond (table 6), is 0.8 in/yr, but some stream cells provide ground-water recharge. Much of the pumpage from these withdrawal centers, as simulated, is diverted ground-water discharge to streams.

In addition to Tennent Pond, Helmetta Pond, and Devoe Lake, the transient model included Duhernal Lake (from 1946) and Sayreville Recharge Ponds (from 1968) as constant-head cells overlying the unconfined areas of the upper aquifer. All of the above simulated lakes and ponds provided recharge to the upper aquifer in 1984. The simulated recharge rate from Duhernal Lake was 2.9 Mgal/d (4.5 ft^3/s), which is less than the estimated range of 3.0 Mgal/d to 8.0 Mgal/d (4.6 to 12.4 ft^3/s) (Barksdale and DeBuchanane, 1946). The simulated recharge rate from Tennent Pond was 2.8 Mgal/d (4.3 ft^3/s)--a rate less than the rate of 4.9 Mgal/d (7.5 ft^3/s) estimated by Geraghty & Miller, Inc. (1976), but within the estimated range of 0.19 to 7.8 Mgal/d (0.3 to 12.1 ft^3/s) of Barksdale and DeBuchananne (1946). The simulated recharge rate for Sayreville Recharge Ponds was 2.4 Mgal/d (3.7 ft^3/s), less than the estimated rate of 4.0 Mgal/d (6.2 ft^3/s) of Geraghty & Miller, Inc. (1976, p. 15).

Hydrographs of simulated and measured long-term heads at selected wells are shown on plate 2. The simulated heads do not show the effects of seasonal pumpage variations and meteorological changes because simulated ground-water withdrawals are averaged for the entire stress period and recharge is constant. Hydrographs of simulated and measured heads at wells in or near the outcrop area of the upper aquifer are shown for wells 23-433 in South River Borough, 23-159 in Old Bridge Township, and 23-292 in South Brunswick Township. The observed and simulated heads of all these wells match closely. Hydrographs for selected wells screened in the deep, confined area of the upper aquifer are shown for wells 23-182 near Browntown in Old Bridge Township, 25-206 in Keyport Borough, and 25-316 in Middletown Township near Sandy Hook. For well 23-182, the general trends in measured-head fluctuations are observed in the simulated heads, but the simulated heads are consistently about 10 ft lower than the measured heads. The match in heads for well 25-206 for the period 1974-85 is excellent. Simulated heads for well 25-316, just outside the eastern corner of the modeled area, are consistently 12 to 15 ft lower than measured heads, in part because simulated heads are extrapolated to the well location from the adjacent modeled area.

Middle aquifer

The simulated and interpreted potentiometric surfaces for the middle aquifer are shown in figure 32. Simulated heads compared favorably to heads measured at 89 wells in 1984. Simulated heads at the well locations were within 10 ft of the measured heads for 83 percent of the wells. The mean error between the 1984 measured and simulated heads for all wells was -2.4 ft, and the standard deviation was 8.4 ft. Head differences greater than 10 ft were concentrated in a few areas. Simulated heads in the southern part of South Brunswick Township were at least 10 ft below the measured heads. Simulated heads north of the Raritan River, in Perth Amboy City and Woodbridge Township, ranged from 20 ft above to 15 ft below the measured heads. Other areas where differences were greater than 10 ft were near the withdrawal centers in Sayreville Borough, near Duhernal Lake, near Union Beach Borough, and near Hazlet Township. Simulated heads in the recharge area in the southwestern part of the study area generally were 5 to 10 ft lower than measured heads, but the gradient of the potentiometric surface was reasonably reproduced. The relative magnitudes and distribution of the residuals between the simulated and measured heads for the middle aquifer were considered to be unbiased and acceptable.

The simulated potentiometric surface indicates regional flow away from the recharge area in the southwestern part of the study area toward major cones of depression near Duhernal Lake, and toward Aberdeen and Hazlet Townships. The cone of depression centered in Hazlet Township, as simulated, is similar to the interpreted cone, although heads near the center are about 10 ft higher. The simulated heads to the east of the cone are about 10 ft lower than measured heads and the gradient of the simulated potentiometric surface is not as steep as that for the interpreted surface; this result is similar to that of the New Jersey RASA model (Martin, 1990, fig. 31). Lateral boundary fluxes from the New Jersey RASA model were directed out of the South River model area rather than into the area as indicated by the interpreted potentiometric surface. Therefore, fluxes along column 42 on the model-area boundary (in rows 36 and 37) were changed during calibration (fig. 25).

Simulated ground-water discharge to streams is reduced compared to that for the predevelopment period for the unconfined part of the middle aquifer (table 12); additionally, many more stream cells were providing recharge to the aquifer system in 1984. For stream zone M4, 13.1 in/yr of ground water

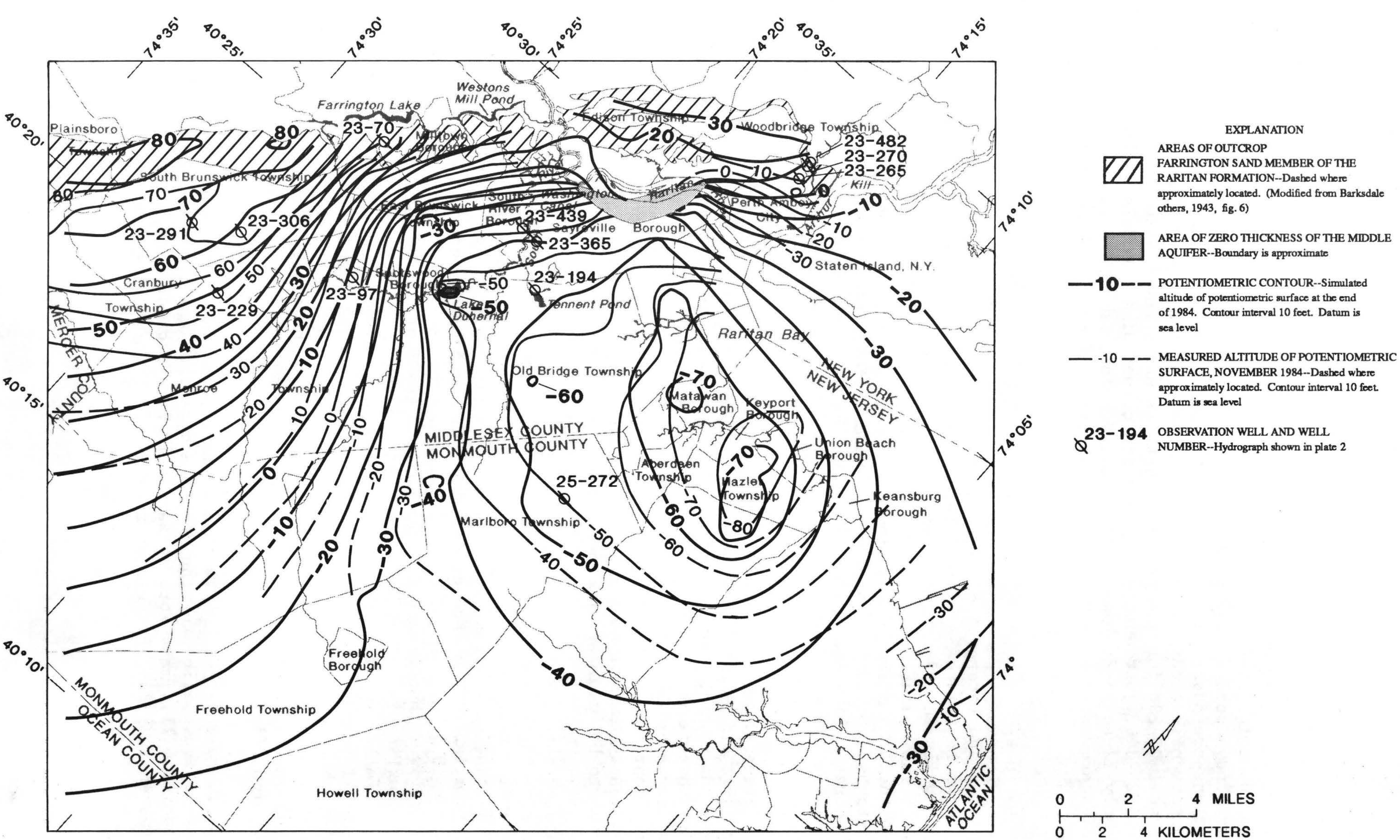


Figure 32.--Simulated and interpreted potentiometric surfaces in the middle aquifer, 1984.

discharged to streams in 1984. Ground-water discharge to streams in stream zones M1 and M5 decreased by about 6 in/yr from predevelopment rates to 6.7 and 6.4 in/yr, respectively; discharge to streams in stream zone M2 decreased about 10 in/yr from predevelopment to 2.6 in/yr in 1984. In zone M3, 18 in/yr of simulated ground-water discharge to streams during predevelopment conditions changed to 2.1 in/yr of simulated ground-water recharge from streams. Although this result reasonably represents the effect of withdrawals in stream zone M3, the simulated interaction of Farrington Lake in East Brunswick Township and Mill Pond in Milltown Borough with the middle aquifer is limited and, therefore, the simulated hydraulic connection between these lakes and the middle aquifer through the water-table system is limited. Only two cells represent these lakes in the model, and the simulated lakes never become areas of recharge to the ground-water system.

Hydrographs of simulated and measured heads at five wells screened in the middle aquifer are shown on plate 2. Hydrographs of heads in or near the outcrop are shown for wells 23-265, near the outcrop area in Perth Amboy City, and 23-291, in South Brunswick Township. The simulated heads for well 23-265 match the measured heads for the period 1951-85. The hydrograph for well 23-291, screened in the area where the Merchantville-Woodbury confining unit thins and becomes sandy, is similar to that for well 23-292, which is screened in the upper aquifer at the same location. In this area, there is a small head difference between the middle and upper aquifers; however, the aquifers seem well connected because water levels responded in a similar manner, as they would in a single aquifer system.

Hydrographs for wells in the confined area of the middle aquifer are shown for wells 23-365 in Sayreville Borough, 23-194 in Old Bridge Township near Tennent Pond, and 25-272 in Marlboro Township. The simulated heads in well 23-365 in the early stress period are slightly lower than the measured heads but match the measured heads in later periods. The simulated heads for well 23-194 match the measured heads for the periods 1935-53 and 1968-85. Simulated heads are 15 to 25 ft higher than measured heads for the period 1953-67, during stress periods 4 through 6; the discrepancies could be caused by inaccuracies in the ground-water-withdrawal data. Simulated heads for well 25-272, in the deep part of the confined aquifer in Monmouth County, match the measured heads.

Hydrogeologic Properties and Flow-System Characteristics

Representation of hydraulic properties of the Potomac-Raritan-Magothy aquifer system in the South River model was refined during calibration. The horizontal hydraulic conductivity of the upper and middle aquifers and the vertical hydraulic conductivity of confining units are shown in regional maps (figs. 33-36). Aquifer transmissivity can be estimated by multiplying the horizontal hydraulic conductivity by aquifer thickness. Ranges of values for hydraulic properties in the calibrated model and reported and measured values for hydrogeologic units are presented in table 13.

Table 13.--Range of values for hydraulic properties in the calibrated model and comparison to reported values for aquifers and confining units

Aquifer unit Potomac-Raritan-Magothy aquifer system	South River Model results: Transmissivity (feet squared per day)	South River Model results: Hydraulic conductivity (feet per day)	Reported values: Transmissivity (feet squared per day)	Reported values: Hydraulic conductivity (feet per day)
Upper aquifer	900 - 18,000	45 - 175	[a,b]1,760 - 20,000	[a]26 - 329
Middle aquifer	90 - 12,250	40 - 150	[b,c]42 - 22,000	[a]36 - 200

Confining unit	South River Model results: Leakance (feet per day) per (feet)	South River Model results: Vertical hydraulic conductivity (feet per day)	Reported values: Leakance (feet per day) per (feet)	Reported values: Vertical hydraulic conductivity (feet per day)
Merchantville-Woodbury confining unit	3.4×10^{-7} - 4.2×10^{-4}	8.4×10^{-5} - 3.5×10^{-3}	[a,b]1.3×10^{-7} - 8.0×10^{-3}	[c]3.6×10^{-6} - 5.9×10^{-5}
Confining unit overlying the middle aquifer	1.6×10^{-7} - 9×10^{-4}	1.8×10^{-5} - 4.5×10^{-2}	[b]1.8×10^{-7} - 2.4×10^{-3}	[d]8.6×10^{-6} - 3.6×10^{-2}

[a] Aquifer-test data, shown in tables 4 and 5

[b] Martin (1990, model results)

[c] Nichols (1977, table 6)

[d] Farlekas (1979, p. 32 and 51)

Flow rates for the predevelopment steady-state ground-water system and the 1984 transient system also were computed by use of the calibrated model. For each confining unit, vertical flow rates (in inches per year) were determined at nodes throughout the study area. These flow rates represent recharge to and discharge from the upper and middle aquifers. For each aquifer, flow rates (in million gallons per day) were computed in a volumetric flow budget. The flow budget accounts for net regional recharge to, or discharge from, each aquifer.

Horizontal Hydraulic Conductivity and Transmissivity of Aquifers

Upper aquifer

Horizontal hydraulic conductivities for the upper aquifer (fig. 33) are greater in updip areas (near the aquifer outcrop areas) than in downdip areas in the calibrated model, as was reported and observed previously. Hydraulic conductivities for nine zones generally updip of the Middlesex-Monmouth County line (fig. 33) range from 85 to 175 ft/d. Hydraulic conductivities for seven zones in the deep, confined area downdip from the Middlesex-Monmouth County line (fig. 33) range from 45 to 55 ft/d. For updip areas in and near the outcrop areas in Old Bridge Township and Sayreville Borough, the hydraulic conductivities in the calibrated model generally are higher than the reported hydraulic conductivities (tables 4 and 13) and the results computed from the transmissivities in the New Jersey RASA model (Martin, 1990).

For downdip areas, hydraulic conductivities estimated by the calibrated model are from 5 to 15 ft/d lower than reported hydraulic conductivities and from 20 to 40 ft/d lower than values computed from results of the New Jersey RASA model. Model-estimated transmissivities (not shown) for the downdip areas are slightly less than those estimated by the calibrated New Jersey RASA model, but transmissivities in and near the outcrop area for the South River model are nearly twice those estimated by the New Jersey RASA model. Several factors may explain these discrepancies: the availability of more field data for the South River model, changes that were made to the representation of the hydrogeologic framework, and differences caused by the scales of the models.

Middle aquifer

Horizontal hydraulic conductivities for the middle aquifer also are greatest in updip areas near the aquifer outcrops and are lower in downdip areas in the calibrated model (fig. 34). Hydraulic conductivities in 17 zones estimated to be updip of the Middlesex-Monmouth County line (fig. 34) range from 40 to 150 ft/d; hydraulic conductivities in five zones, which are approximately downdip of the County line, range from 40 to 75 ft/d. Where the aquifer thins or is absent near the Raritan River in Sayreville Borough, hydraulic conductivity was assigned a value of zero. Hydraulic conductivity in the northern and eastern parts of the modeled area (in the area from northern Old Bridge Township, in Middlesex County to Sandy Hook in northern Monmouth County) is 40 ft/d. Hydraulic conductivities in the outcrop areas are 20 to 30 ft/d lower than those estimated from point data (tables 5 and 13). Hydraulic conductivities in Monroe Township and the southern part of

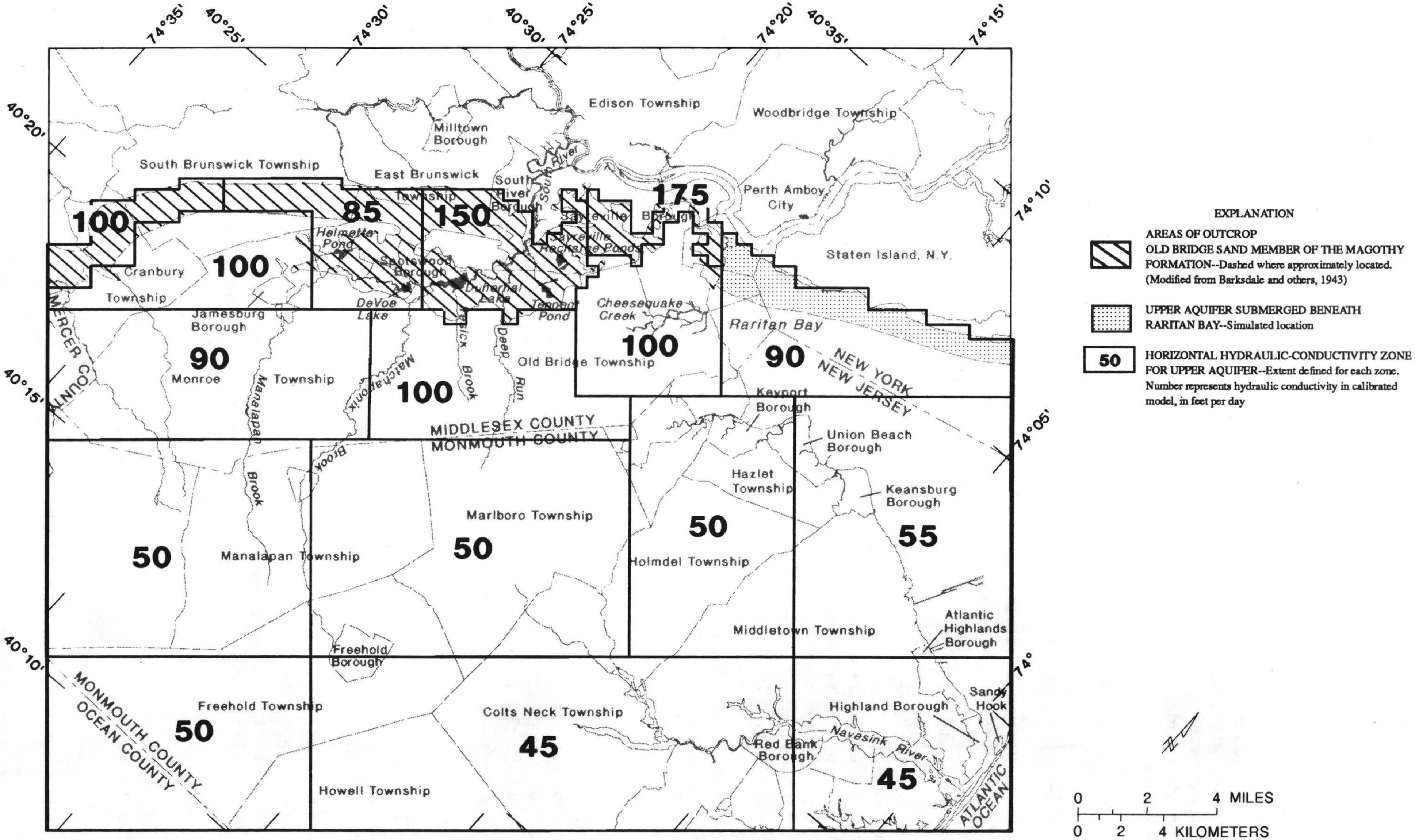


Figure 33.--Horizontal hydraulic conductivities estimated by the calibrated model for the upper aquifer.

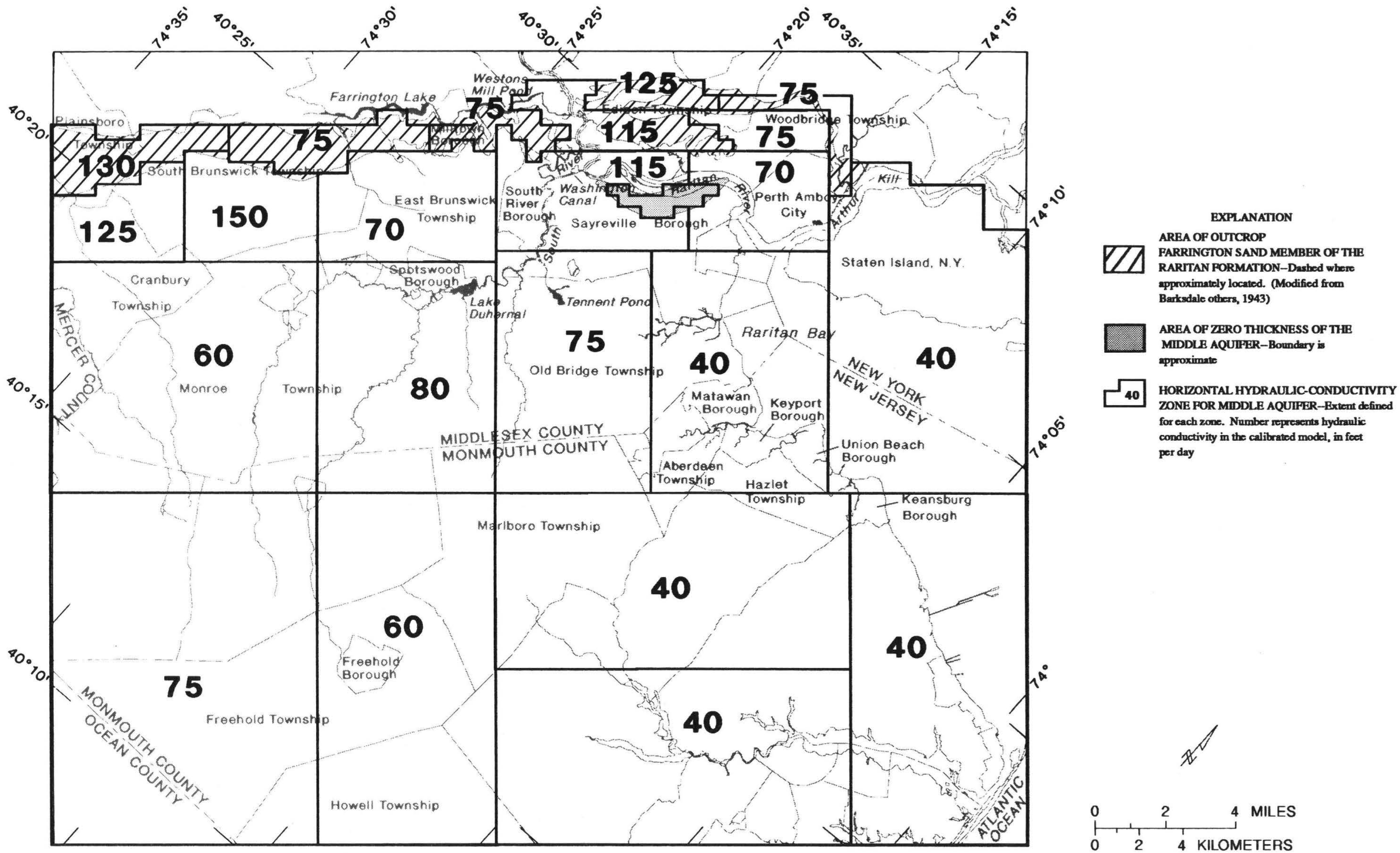


Figure 34.--Horizontal hydraulic conductivities estimated by the calibrated model for the middle aquifer.

Old Bridge Township in Middlesex County are 20 to 40 ft/d lower than estimates derived from the data for the area.

Hydraulic conductivities in the downdip areas tend to be only slightly lower in the calibrated model than in the reported data, but they are 50 to 130 ft/d less than hydraulic conductivities estimated by the calibrated New Jersey RASA model. The computed transmissivities for the downdip areas (not shown) are generally less than half those in the New Jersey RASA model (for which far fewer calibration data were available) but of similar magnitude in and near the outcrop area of the middle aquifer. The hydraulic conductivities in the calibrated model (fig. 34) also tend to be lower than the single value of 132 ft/d, estimated from the average of well-acceptance tests, that was used for Farlekas' model (1979, p. 30).

Vertical Hydraulic Conductivity and Leakance of Confining Units

Merchantville-Woodbury confining unit

The vertical hydraulic conductivities estimated by the calibrated model for the confining unit overlying the upper aquifer are shown in figure 35 and summarized in table 13. The highest values for the modeled area are in the outcrop areas of the upper confining unit, where they range from 8.4×10^{-4} to 2.1×10^{-3} ft/d, and near Raritan Bay and Sandy Hook, where they range from 1.4×10^{-3} to 3.5×10^{-3} ft/d. In updip areas near the outcrop of the upper aquifer where the vertical hydraulic conductivity is high, the confining unit includes sands, silts, and clays from the upper part of the Magothy Formation. In the area west of Jamesburg, Middlesex County, the confining unit is sandier, and the maximum estimated vertical hydraulic conductivity is 1.1×10^{-3} ft/d (fig. 35). The upper aquifer and the overlying water-table system are well connected in this area.

In the outcrop near Old Bridge Township and Sayreville Borough, the confining unit also consists primarily of Magothy Formation sediments, and vertical hydraulic conductivity estimated by the model is high, ranging from 1.4×10^{-3} to 2.1×10^{-3} ft/d. Near Raritan Bay, Navesink River, and Sandy Hook, the confining unit consists mainly of the Woodbury Clay and Merchantville Formation, and estimated vertical hydraulic conductivities, which range from 1.4×10^{-3} to 3.5×10^{-3} ft/d, tend to be higher than the values observed for core samples of these formations reported at sites elsewhere in the Coastal Plain of New Jersey (Nichols, 1977, table 3), which range from 3.6×10^{-6} to 5.9×10^{-5} ft/d. Vertical hydraulic conductivities estimated by the calibrated model are similar to those estimated by the New Jersey RASA model in these areas on the basis of leakance reported in the New Jersey RASA model (Martin, 1990). As discussed later, the method by which the model simulates the confining units can lead to oversimplification. Estimated vertical hydraulic conductivities for the southern and central parts of the modeled area range from 8.4×10^{-5} to 1.4×10^{-4} ft/d; these values approximate the range of values reported by Nichols (1977) for cores. In these areas, the Merchantville-Woodbury confining unit is massive and consists of clayey material. Leakance values for the Merchantville-Woodbury confining unit, computed from results of aquifer tests, range from a high of 4.2×10^{-4} (ft/d)/ft near the edge of the confining-unit outcrop in Sayreville Borough to a low of 3.4×10^{-7} (ft/d)/ft near Freehold Township (table 13).

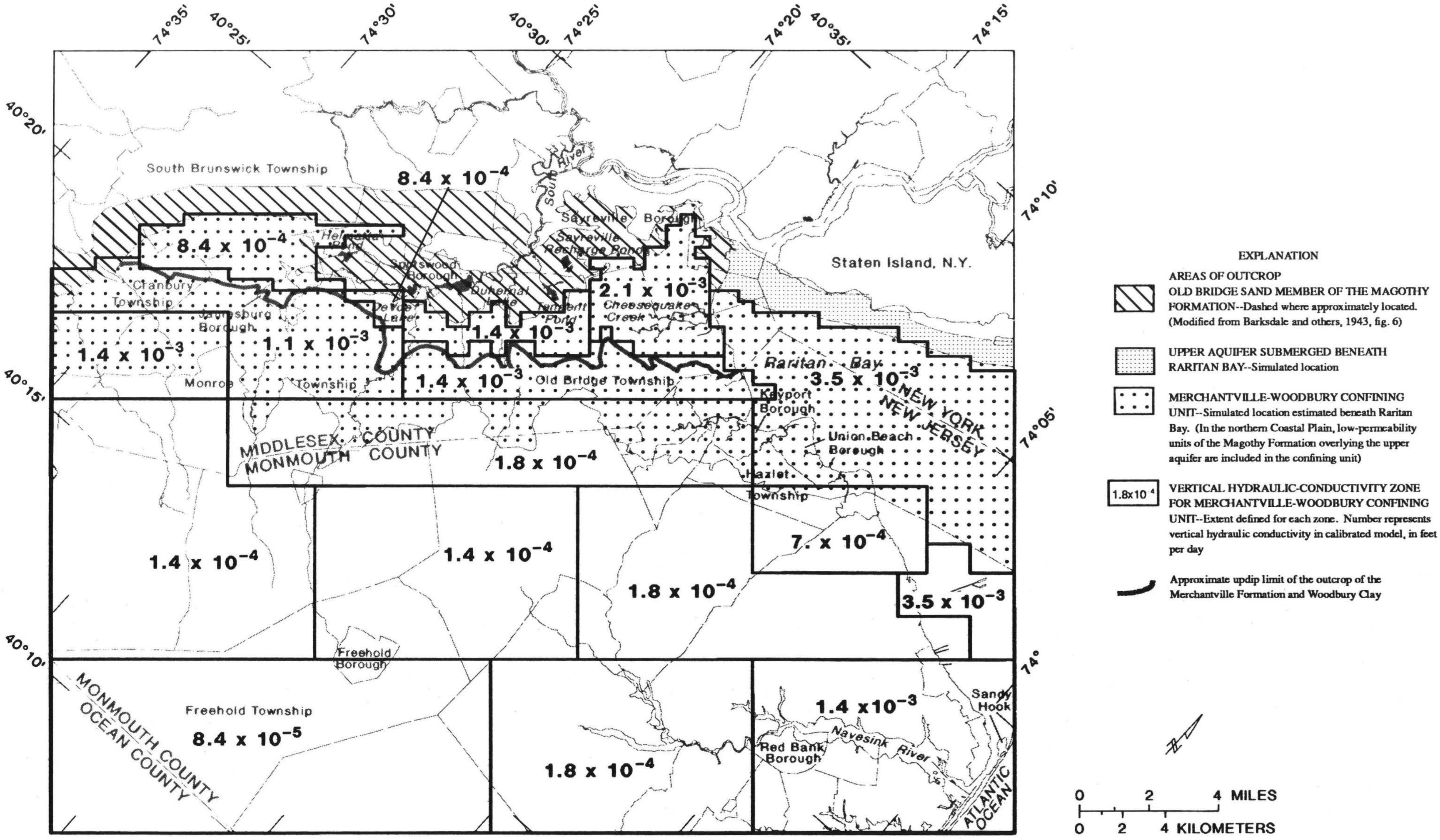


Figure 35.--Vertical hydraulic conductivities estimated by the calibrated model for the Merchantville-Woodbury confining unit.

Confining unit overlying the middle aquifer

Vertical hydraulic conductivities estimated by the calibrated model for the confining unit overlying the middle aquifer range from 1.8×10^{-5} to 4.5×10^{-2} ft/d, as shown in figure 36 and table 13. The vertical hydraulic conductivities in the southwestern part of the modeled area (beneath and near outcrop areas of the upper aquifer in Cranbury, Monroe, and South Brunswick Townships) are the highest in this range. The difference in lithology of the Woodbridge Clay Member of the Raritan Formation in this area causes these relatively high values. Farlekas (1979, p. 33) reported a vertical hydraulic conductivity of 3.6×10^{-2} ft/d for the confining unit in South Brunswick Township; vertical hydraulic conductivities computed from leakance values from aquifer tests in South Brunswick (table 5) and Monroe Townships (table 4) for this confining unit range from 0.1 to 0.5 ft/d.

The lowest vertical hydraulic conductivities estimated by the calibrated model, which range from 1.8×10^{-5} to 9.0×10^{-5} ft/d, are in the northern part of of the modeled area in South Brunswick Township, Sayreville Borough, and Staten Island; beneath Raritan Bay; and near Matawan Borough and the Boroughs of Keyport and Union Beach (fig. 36). Farlekas (1979, p. 33) reported that the lowest vertical hydraulic conductivities estimated by his model were for Sayreville Borough. Inspection of aquifer-test leakance data (table 5) shows that, in the deep system near the Middlesex-Monmouth County line, leakance is low, with a maximum value of less than 7.0×10^{-4} (ft/d)/ft.

Predevelopment Steady-State Flow System

The simulation of the predevelopment flow in the Potomac-Raritan-Magothy aquifer system shows that the features of the upper and middle aquifers are similar, including a potentiometric surface that resembles topography, flow patterns that originate in topographically high areas and terminate in low-lying wetlands and surface-water-discharge areas, and stream reaches that typically are gaining in the outcrop areas. Because of the availability of data, the model probably is more accurate for the upper aquifer than for the middle aquifer, but the potentiometric-surface maps derived from the calibrated model can be used to provide a reasonable approximation of flow directions in the confined parts of both aquifers.

Upper Aquifer

Results of simulations by the calibrated model suggest that the unconfined-aquifer and shallow confined-aquifer areas in the southern parts of South Brunswick, Cranbury, and Monroe Townships were the major areas of recharge to the upper aquifer during the predevelopment period. Net recharge from stream zone U1 (fig. 28), which corresponds roughly to the unconfined-aquifer area in these townships, is about 9 in/yr (table 12). Just downdip, in areas of Cranbury and Monroe Townships, vertical flow downward through the overlying leaky confining unit provides as much as 10 in/yr of recharge into the upper aquifer (fig. 37). In parts of these recharge areas, the upper and middle aquifers can respond as a single aquifer because of the relatively high vertical hydraulic conductivity in the confining unit from the upper part of the Magothy Formation and confining unit overlying the middle aquifer (figs. 35 and 36).

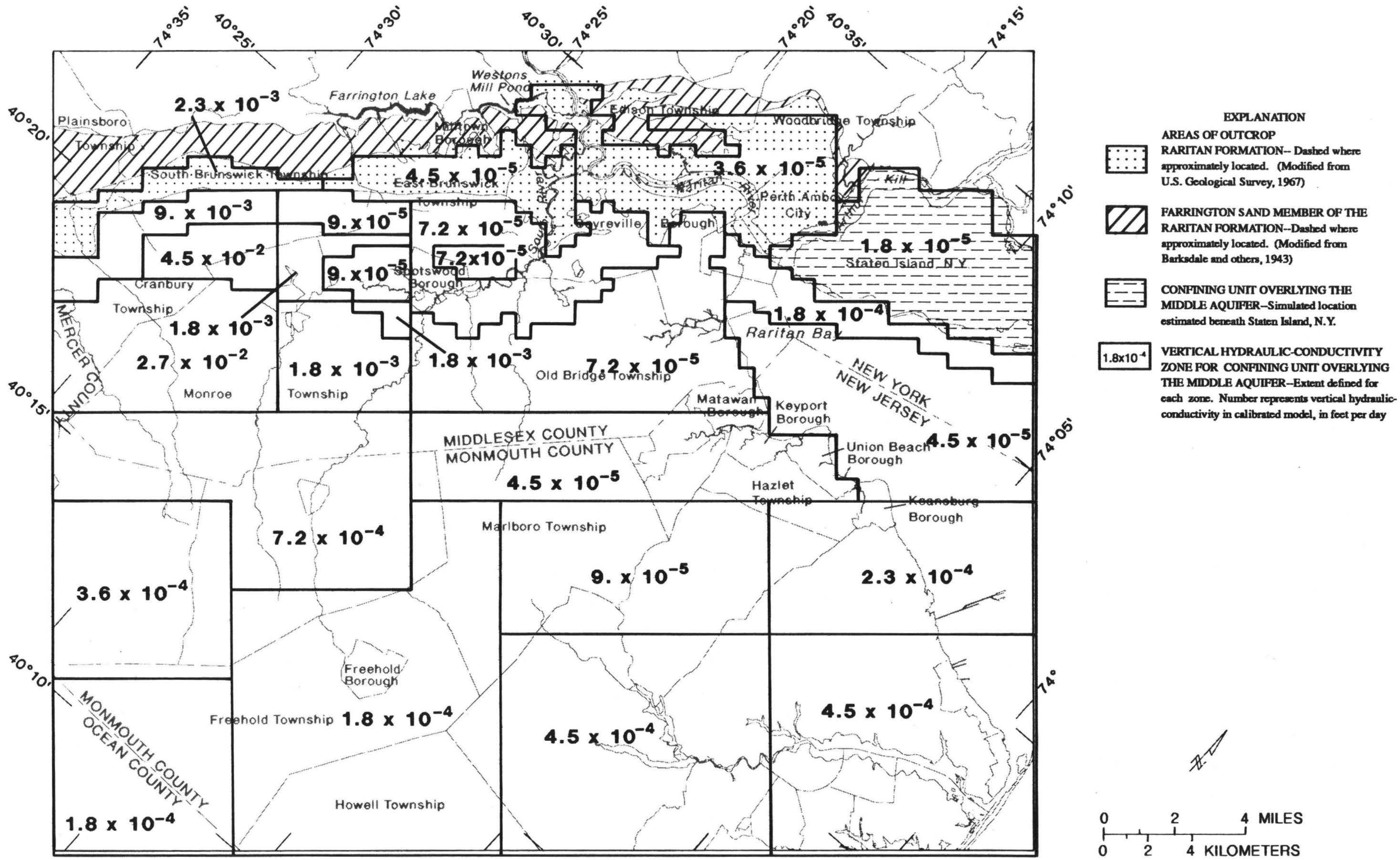


Figure 36.--Vertical hydraulic conductivities estimated by the calibrated model for the confining unit overlying the middle aquifer.

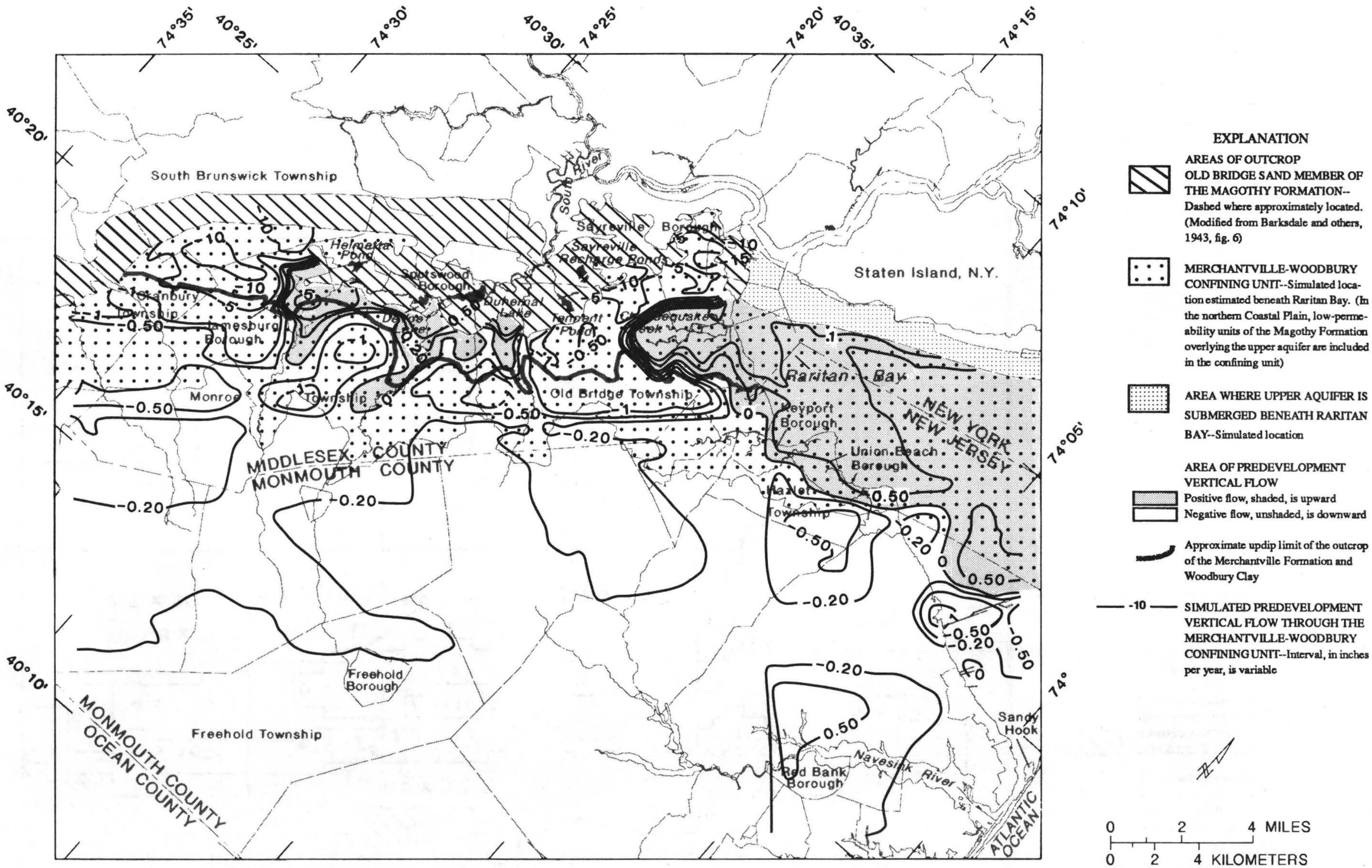


Figure 37.--Simulated predevelopment vertical flow through the Merchantville-Woodbury confining unit.

Consequently, results of model simulations suggest that about 5 in/yr flows from the upper aquifer downward to recharge the middle aquifer (fig. 38).

As indicated by the steep head gradients away from these main areas of recharge (fig. 29), water moves laterally through the unconfined and shallow confined system to discharge to Manalapan, Matchaponix, and Iresick Brooks and Deep Run, which are the regional surface-water drains that flow into the South River. Simulated net ground-water discharge to streams for stream zone U3 (fig. 28), which contains parts of these streams, is about 3 in/yr greater than the applied recharge (table 12). Upward flow from the confined upper aquifer to the overlying water-table system discharges near Helmetta and Tennent Ponds.

As described earlier, the confining unit overlying the upper aquifer restricts vertical flow between the Englishtown aquifer system and the upper aquifer. Still, vertical flow downward through the Merchantville-Woodbury confining unit from the Englishtown aquifer system and the water-table system overlying the confining unit is a significant source of recharge for the confined upper aquifer (fig. 38). The vertical recharge is caused by higher heads in the Englishtown aquifer system, which range from about 10 to 75 ft higher and generally are more than 50 ft higher than heads in the upper aquifer in about half the modeled area. Vertical flow downward into the upper aquifer from the Englishtown aquifer system generally is less than 1 in/yr, and averages about 0.2 in/yr.

The regional gradients in the upper aquifer (fig. 29) also cause lateral flow to deep parts of the aquifer; this flow eventually discharges upward to the overlying units and then the Atlantic Ocean (Martin, 1990) or to Raritan Bay. Discharge to the bay occurs both as flow to the submerged outcrop of the upper aquifer in the bay (fig. 27) and as upward flow through the Merchantville-Woodbury confining unit to the bay (fig. 37).

A local feature of predevelopment recharge and discharge is found in eastern Sayreville Borough and northern Old Bridge Township. Recharge to the upper aquifer in this area through the overlying confining unit ranges from 5 to 10 in/yr (fig. 37), and net recharge in stream zone U4, in the unconfined-aquifer area, is 12.2 in/yr (table 12 and fig. 28). Discharge from this recharge area is either through the Merchantville-Woodbury confining unit into the marshy area near Cheesequake Creek or to Raritan Bay.

The total inflow and outflow budget for the upper aquifer in the predevelopment period is about 35 Mgal/d. The nine components of the predevelopment and 1984 flow budgets, as listed in figure 38, are (1) sum of recharge and water released from storage, (2) net ground-water discharge to streams, or "flow to and from streams," (3) net recharge from ponds, (4) flow from the outcrop of the Merchantville-Woodbury confining unit, (5) flow to and from the submerged upper aquifer outcrop in Raritan Bay, (6) cross-formational flow to and from the Englishtown aquifer system, (7) flow to wells, (8) cross-formational flow to and from the middle aquifer, and (9) lateral flow to and from the boundaries of the modeled area. Inflow-budget components are presented as positive values, which are sources of water to the upper aquifer; outflow-budget components are negative values, which are sinks for water for the upper aquifer. Water is released from storage as a result of a decline in head; therefore, storage is negligible for the predevelopment simulation.

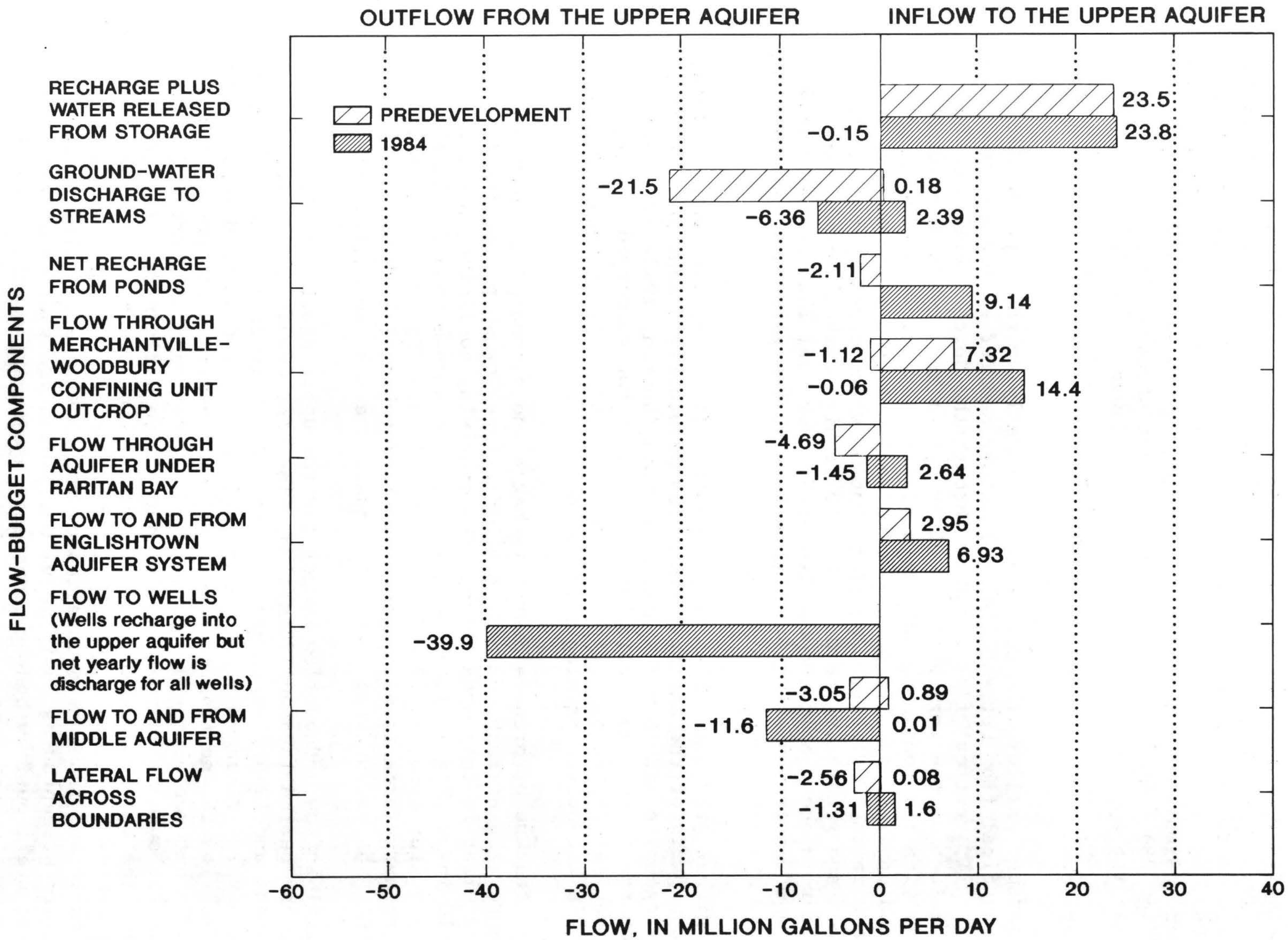


Figure 38.--Flow budgets for the upper aquifer in the predevelopment and 1984 transient flow systems.

Under predevelopment conditions, the major sources of water are recharge from the upper-aquifer outcrop area (23.5 Mgal/d, or 67 percent of total inflow) and leakage from the outcrop area of the Merchantville-Woodbury confining unit (7.3 Mgal/d, or 21 percent of total inflow). Only cross-formational flow from the Englishtown aquifer system (3.0 Mgal/d, or 8 percent of inflow) and from the middle aquifer (0.9 Mgal/d, or 2.5 percent of inflow) provide other significant, but smaller, amounts of inflow. Most of the discharge of ground water is to streams, most of which flow into the South River (21.5 Mgal/d, or 61 percent of total outflow). Other significant discharges are discharge to Raritan Bay (4.7 Mgal/d, or 13 percent of outflow), discharge to the middle aquifer (3.1 Mgal/d, or 9 percent of outflow), lateral discharge across model boundaries (2.6 Mgal/d, or 7 percent of outflow), and discharge to lakes (2.1 Mgal/d, or 6 percent of outflow). Most of the lateral-boundary discharge is outside of the modeled area, along the southeastern boundary toward the downdip parts of the upper aquifer and along the northeastern boundary into Raritan Bay.

Middle Aquifer

The major recharge areas for the middle aquifer south of the Raritan River for predevelopment conditions are the unconfined- and confined-aquifer areas in northeastern Plainsboro Township, southern South Brunswick Township, and northeastern Cranbury Township. For the middle aquifer north of the Raritan River, the major recharge area is the unconfined-aquifer area in Woodbridge Township. The net recharge rate to the ground-water system in stream zones M1 and M2 (fig. 28) south of Milltown Borough is about 3 in/yr (table 12). Just downdip from the outcrop area of the Farrington Sand Member and beneath the outcrop of the Old Bridge Sand Member of the Magothy Formation in South Brunswick Township, the vertical flows into the middle aquifer are large, as much as 7.5 in/yr (fig. 39). Some upward discharge into the unconfined part of the upper aquifer also occurs in Cranbury Township (fig. 39). Net recharge to the confined area of the middle aquifer in stream zone M5 (fig. 28) in northern Woodbridge Township is about 2 in/yr. Recharge to the middle aquifer through the overlying confining unit in this area is relatively low, generally less than 0.5 in/yr.

Under the simulated predevelopment conditions, water flows laterally from the main areas of recharge of the middle aquifer (fig. 30) and discharges to the unconfined areas of the middle aquifer and to low-lying wetlands in the outcrop of the confining unit overlying the middle aquifer near Raritan River and the mouth of the South River (fig. 39). Additional lateral flow is downdip and then out of the modeled area, through the southwestern boundary into Mercer County and along the southeastern boundary into Ocean County and Howell Township. The simulated ground-water discharge to stream cells in stream zones M3 and M4 (fig. 28) is 3 to 4 in/yr greater than the calibrated rate of recharge (table 12). Simulated upward discharge to Raritan River though the confining unit overlying the middle aquifer is as much as 1.5 in/yr.

Simulated vertical flow for the confining unit overlying the middle aquifer changes direction along the zero-flow contour, which separates downward flow at the southwestern boundary of the modeled area from upward flow in the central and northwestern parts of the modeled area (fig. 39).

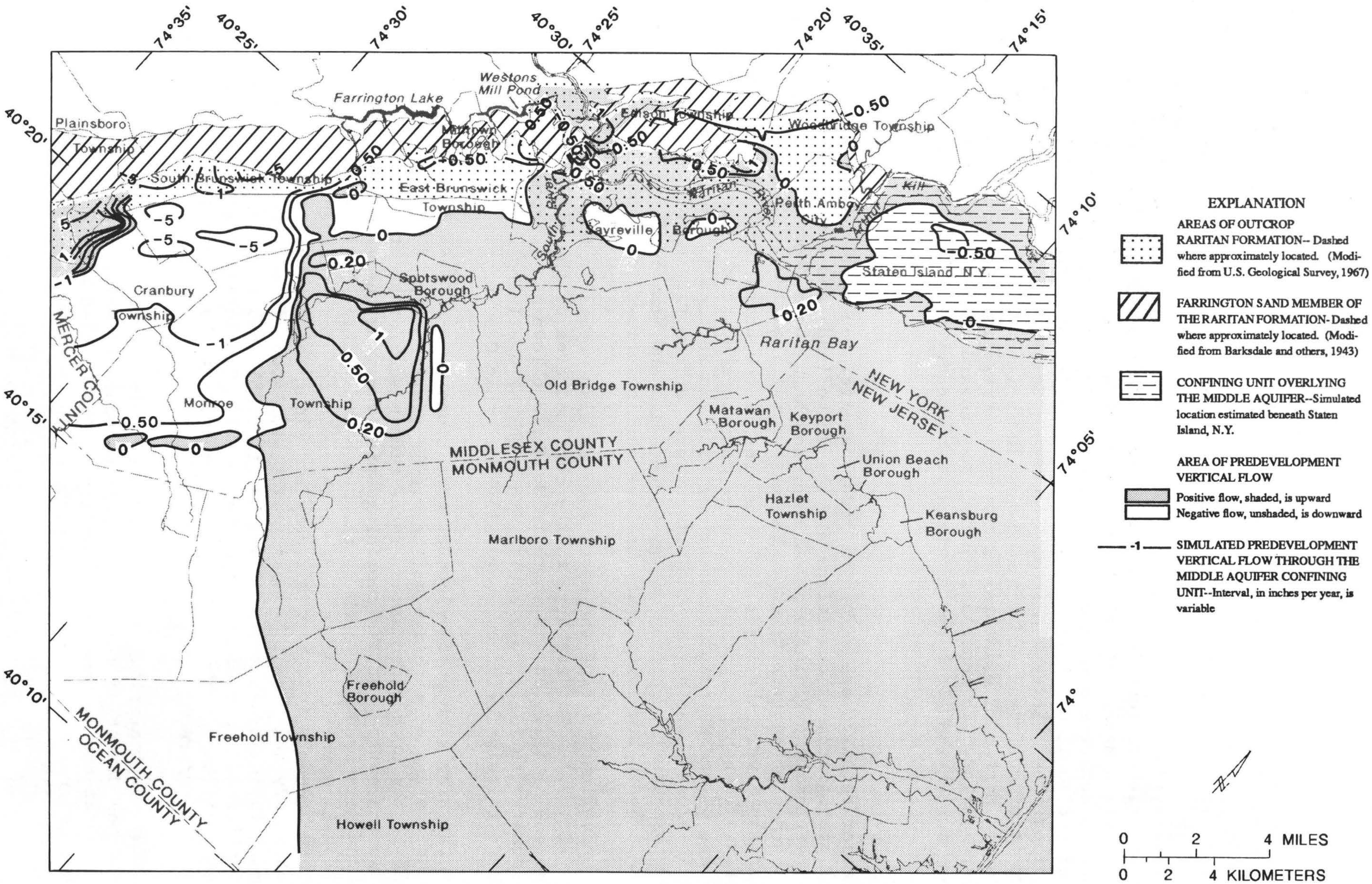


Figure 39.--Simulated predevelopment vertical flow through the confining unit overlying the middle aquifer.

In much of the modeled area, simulated heads in the middle aquifer are less than 10 ft higher than interpreted heads in the upper aquifer; however, simulated heads in the middle aquifer are more than 10 ft higher than interpreted heads in the upper aquifer in most of Old Bridge Township and beneath Raritan Bay. Upward flow to the upper aquifer averages 0.1 in/yr. Vertical discharge from the middle aquifer to the upper aquifer is greatest in Monroe Township, just south of Spotswood Borough, where the flow rate is about 1.5 in/yr.

The simulated potentiometric surface of the middle aquifer (fig. 30) shows that the flow systems on both sides of Raritan River could have been separated from each other because of the pinchout of the middle aquifer and the effect of the Raritan River as a flow boundary. Because of the pinchout and streamline caused by the constant-head boundary of the river, which act as lateral no-flow boundaries, ground water in the middle aquifer must either flow around the pinchout or discharge to the overlying river.

The total simulated flow budget for the middle aquifer during predevelopment conditions is about 20.5 Mgal/d. The six components of the flow budget (fig. 40) are (1) sum of recharge and water released from storage, (2) water from ground-water discharge to streams or "flow to and from streams," (3) flow through the outcrop of the confining unit overlying the middle aquifer, (4) cross-formational flow to and from the upper aquifer, (5) flow to wells, and (6) lateral flow at the boundaries of the modeled area.

The major predevelopment sources of inflow to the middle aquifer are recharge in the unconfined area of the middle aquifer (16.7 Mgal/d, or 81 percent of total inflow) and cross-formational flow from the upper aquifer, mainly in Cranbury Township and the southern part of South Brunswick Township (3.1 Mgal/d, or 15 percent of total inflow) (fig. 40). The major discharge of ground water from the middle aquifer is to streams (16.5 Mgal/d, or 80 percent of total outflow). Other significant discharge occurs across the lateral model boundaries (2.2 Mgal/d, or 11 percent of outflow), upward discharge to the confining-unit outcrop near the Raritan River (0.9 Mgal/d, or 4 percent of outflow), and as upward discharge to the upper aquifer (0.9 Mgal/d, or 4 percent of outflow).

1984 Transient Flow System

The 1984 transient simulation of the flow system in the upper and middle aquifers differs in several significant ways from the predevelopment system. Differences include (1) a lowered regional potentiometric surface and the formation of major cones of depression, (2) redistribution of recharge and discharge areas, (3) reduced ground-water discharge to streams, and (4) induced recharge from streams. The maps of the simulated potentiometric surface, which can be used to determine flow directions in the confined parts of the upper and middle aquifers, are most accurate in areas where data were available for calibration.

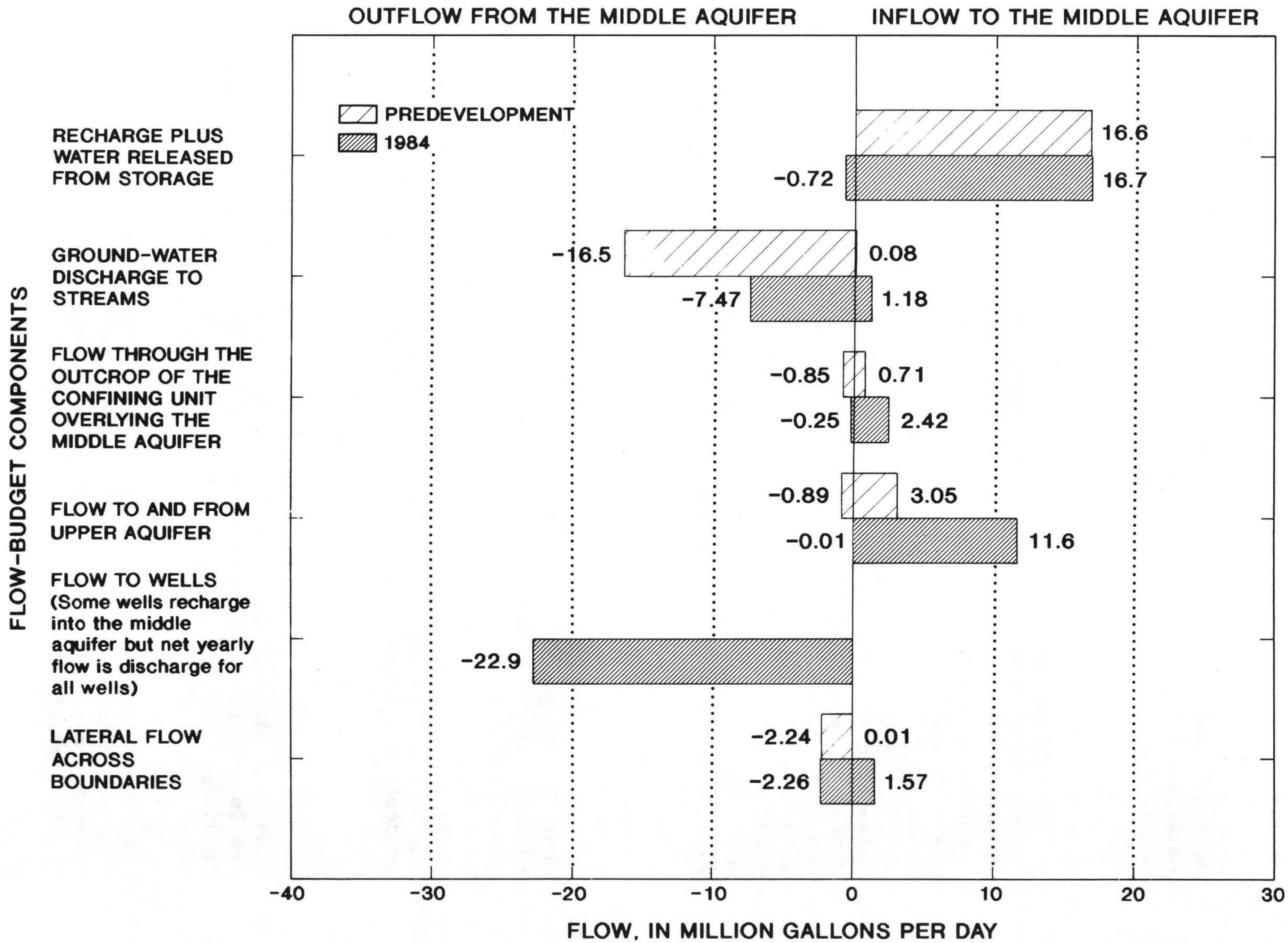


Figure 40.--Flow budgets for the middle aquifer in the predevelopment and 1984 transient flow systems.

Upper Aquifer

Recharge from unconfined areas of the upper aquifer is greater in the 1984 transient simulation than in the predevelopment simulation. Downward recharge through the Merchantville-Woodbury confining unit occurs in most of the outcrop area (fig. 41) rather than primarily in the southwestern part of the modeled area as determined for the predevelopment simulation. Ground-water stresses in unconfined-aquifer areas in area U1 (fig. 28) exceed available recharge and cause the recharge of ground water from stream cells in zone U1 at a rate of 3 in/yr (table 12). The area of high vertical flow through the Merchantville-Woodbury confining unit downward into the upper aquifer in Monroe Township is larger, and the rates of recharge to the aquifer increased from 5 to 13 in/yr during predevelopment conditions to 10 to 20 in/yr in the 1984 simulation (fig. 41). Flow from this area is a combination of lateral flow toward the withdrawal centers in the confined aquifer (fig. 6) and downward flow into the middle aquifer.

The large ground-water withdrawals from the upper aquifer in the area of Spotswood Borough and Old Bridge Township have significantly altered the flow budgets in the shallow parts of the aquifer system. Comparison of predevelopment and 1984 ground-water discharge to streams in stream zones U2 and U3 (fig. 28 and table 12) and examination of the vertical flow through the confining unit overlying the middle aquifer (fig. 39 and fig. 42) indicate that the primary sources of water for 1984 ground-water withdrawals in the area are captured base flow, infiltration from recharge ponds, and capture of discharge through confining units. Although zones U2 and U3 are still zones with gaining streams, the net ground-water discharge to streams is reduced by 11 to 13 in/yr, to about 5 to 6 in/yr. Vertical flow through the Merchantville-Woodbury confining unit near the regional drains, Helmetta and Tennent Ponds and Devoe Lake, is downward, the reverse of the flow direction under predevelopment conditions (fig. 41). The hydraulic gradients in this area also indicate that a signficant part of the recharge flows to the deeper, confined area of the aquifer system.

Flow from the Englishtown aquifer system and the water-table system through the Merchantville-Woodbury confining unit occurs in terrestrial areas and beneath Raritan Bay (fig. 41). As under predevelopment conditions, the vertical recharge is caused by heads in the Englishtown aquifer system that are about 10 to 75 ft higher (and generally more than 50 ft higher) than heads in the upper aquifer in about half the study area. Vertical flow into the upper aquifer from the Englishtown aquifer system generally is less than 1 in/yr and averages about 0.2 in/yr.

Recharge to the upper aquifer from the Englishtown aquifer system through the Merchantville-Woodbury confining unit is more than twice that for the predevelopment flow model; most of the increased flow is seen in northern Monmouth County (fig. 41). Vertical leakage from the Englishtown aquifer system near the Boroughs of Keyport and Union Beach, Hazlet Township, and Red Bank Inlet increased to more than 1 in/yr. In most other areas, the vertical flow from the Englishtown aquifer system into the upper aquifer remains less than 0.5 in/yr, although head differences between these aquifers locally exceed 130 ft. The simulated average flow from the Englishtown aquifer system into the upper aquifer is about 0.44 in/yr for the 1984 simulation.

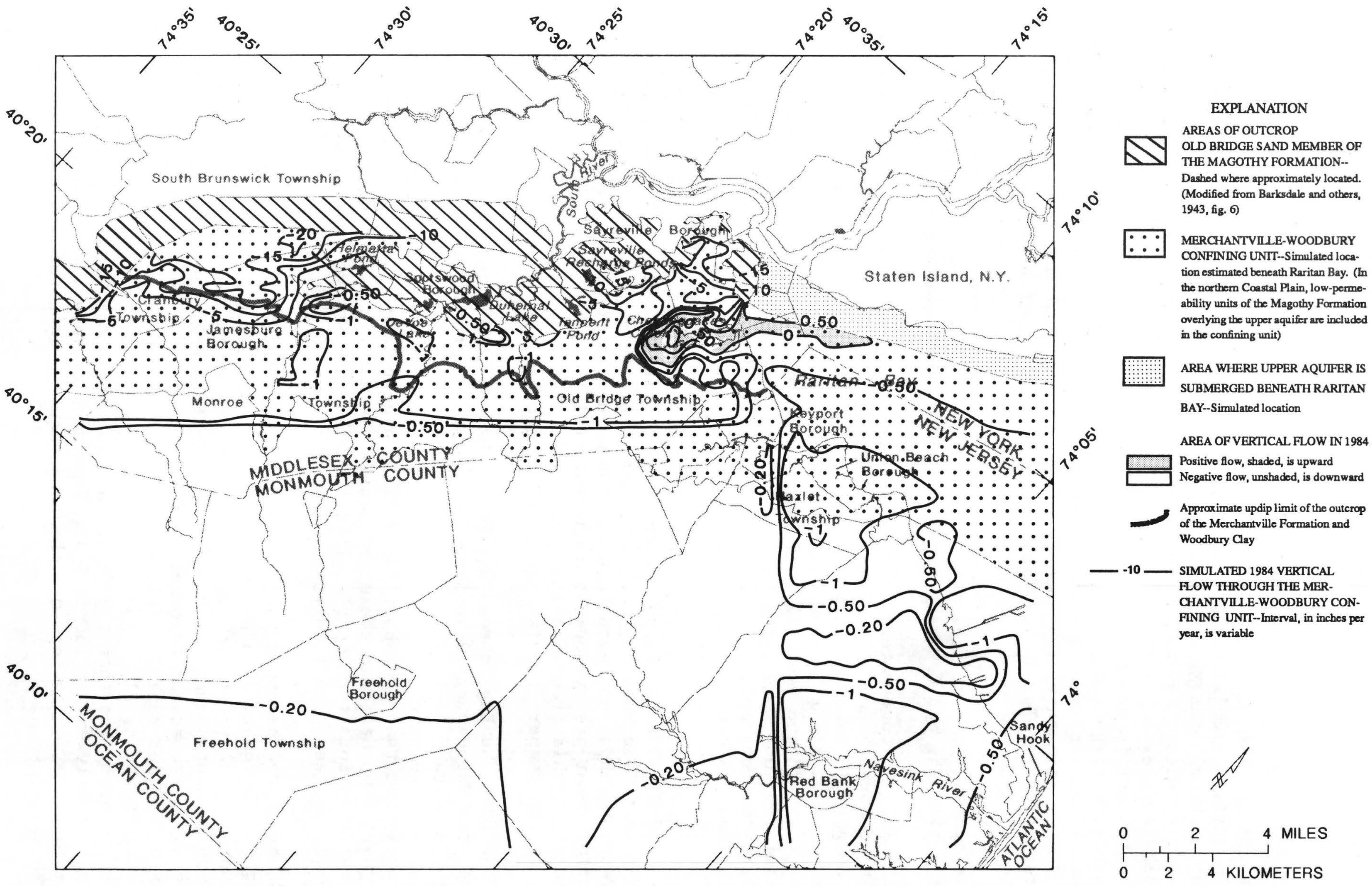


Figure 41.--Simulated vertical flow through the Merchantville-Woodbury confining unit, 1984.

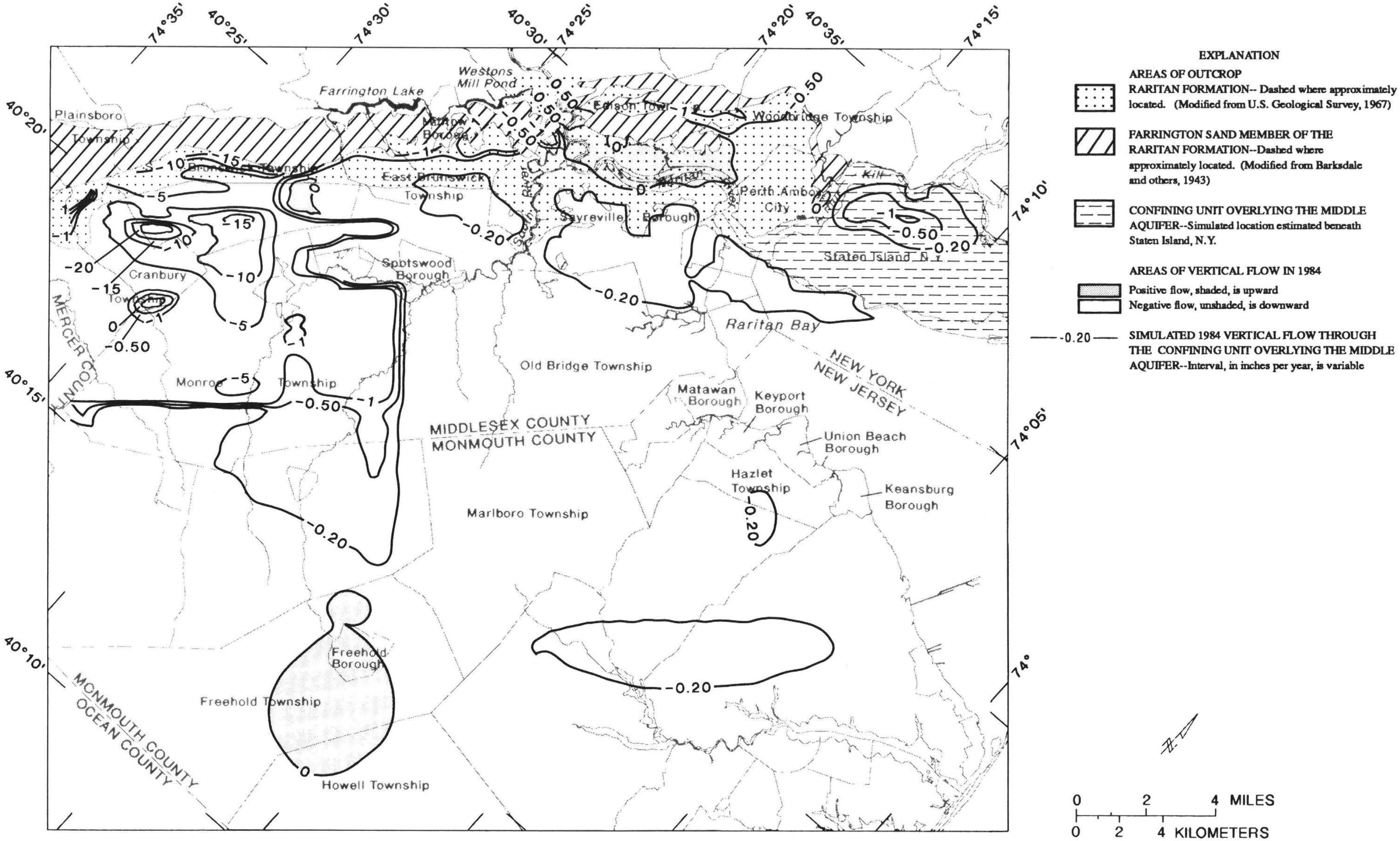


Figure 42.--Simulated vertical flow through the confining unit overlying the middle aquifer, 1984.

The direction of flow in the upper aquifer through lateral boundaries in the area of Raritan Bay and downdip areas has reversed from "out of" the modeled area under predevelopment conditions to "into" the modeled area for 1984. Recharge from Raritan Bay by lateral flow in the submerged outcrop and downward flow through the Merchantville-Woodbury confining unit occurred in most areas of the bay in 1984. This salty recharge water caused saltwater intrusion, which is discussed later in this report. The model shows that slightly more than half the water that enters the upper aquifer from Raritan Bay does so where the upper aquifer crops out in the bay. The remaining water from Raritan Bay is from leakage through the Merchantville-Woodbury confining unit, from which flows range from 0.5 to 1.0 in/yr (fig. 41).

The simulated localized flow system in eastern Sayreville Borough and northern Old Bridge Township is relatively unchanged from predevelopment conditions to 1984. Net recharge in stream zone U4, in the unconfined area of the aquifer, is about 2 in/yr more than under predevelopment conditions (table 12). Flow into the upper aquifer from the confining-unit outcrop in the topographically high area is about the same, and upward flow through the confining unit to the Cheesequake Creek area is only slightly less than under predevelopment conditions (fig. 41). Simulated local flow from this area into Raritan Bay remains at nearly the same rate; this is the only area of freshwater discharge to Raritan Bay.

The total flow into and out of the upper aquifer in the 1984 transient simulation is about 61 Mgal/d. In addition to Tennent Pond, which was simulated in the predevelopment model, Duhernal Lake and Sayreville recharge ponds also are included as recharge ponds. A small component of outflow in the "recharge and storage" budget component is caused by some water-level recovery in the unconfined areas in 1984.

The two major simulated inflows of water to the upper aquifer for 1984, which coincide with the two major inflows under predevelopment conditions, are recharge in the aquifer-outcrop area (23.8 Mgal/d, or 39 percent of total inflow) and vertical leakage from the outcrop area of the Merchantville-Woodbury confining unit (14.4 Mgal/d, or 24 percent of total inflow). The largest vertical velocities through this confining unit are through the Magothy sediments in the confining unit in the southwestern part of the modeled area. Other significant inflows of water are cross-formational flow from the Englishtown aquifer system (6.9 Mgal/d, or 11 percent of inflow), recharge from artificial-recharge ponds (9.1 Mgal/d, or 15 percent of inflow), and induced ground-water flow from streams (2.4 Mgal/d, or 4 percent of inflow).

The major outflow of water from the upper aquifer in the 1984 simulation is a discharge to wells (40 Mgal/d, or 66 percent of total outflow; fig. 38). Other significant outflows are cross-formational discharge to the middle aquifer (11.6 Mgal/d, or 19 percent of total outflow) and ground-water discharge to streams (6.4 Mgal/d, or 10 percent of outflow).

Comparison of the flow budgets for the predevelopment conditions and 1984 flow systems allows for the determination of the source of water for the ground-water withdrawals. Total demand for ground water from the upper aquifer is 40 Mgal/d. Because recharge in the model is treated as relatively constant, the flow budgets indicate that 97 percent of the water used to meet the ground-water withdrawals in the 1984 simulation comes from (1) captured ground-water discharge to streams and induced recharge from streams (net change, 17.4 Mgal/d), (2) decreased discharge to and induced recharge from artificial-recharge ponds (net change, 11.2 Mgal/d), (3) increased downward flow and decreased upward flow through the Merchantville-Woodbury confining-unit outcrop (net change, 8.2 Mgal/d), and (4) increased cross-formational flow from the Englishtown aquifer system (net change, 4.0 Mgal/d).

Middle Aquifer

The primary areas of recharge to the middle aquifer south and north of Raritan River are the same as for predevelopment conditions. Ground-water discharge to streams in stream zones M1 and M2, generally south of Milltown Borough, (fig. 28) is decreased by 6 to 10 in/yr (table 12) because of withdrawals. Recharge from the upper aquifer through the confining unit overlying the middle aquifer in Cranbury, Monroe, and Plainsboro Townships is 5 in/yr (fig. 42); near the withdrawal center at South Brunswick Township, where the confining unit is thin and leaky (fig. 11), recharge is as much as 15 in/yr.

The ground-water withdrawals that cause the cones of depression in the confined area of the upper aquifer in the northeastern part of the modeled area (fig. 16) induce water to flow from the southwestern part of the modeled area and decrease the ground-water discharge to streams. Part of the wetlands area in the outcrop area of the overlying confining unit near Raritan River continues to receive ground-water discharge by upward flow through the confining unit but at a lower rate than under predevelopment conditions (fig. 42); upward flow through this confining unit no longer occurs in other areas. Ground-water discharge to streams in zones M1, M2, and M3 (fig. 28) is greatly reduced (by 6 to 16 in/yr; table 12) and stream cells in stream zone M3 recharge the ground-water system for 1984. Ground-water discharge also is reduced north of Raritan River in stream zones M4 and M5, but considerably less than south of the river in zone M3. The less substantial reduction in discharge north of the river probably is the result of the relative isolation caused by the aquifer pinchout in the Sayreville Borough area, the constant-head boundary, flow-divide effect of Raritan River, and the distance of these stream zones from the withdrawal centers (fig. 16). Likewise, heads in the middle aquifer north of Raritan River also have been affected less by withdrawals than have heads in areas to the south; simulated heads for 1984 are within 10 to 20 ft of predevelopment heads.

Lateral flow out of the modeled area in 1984 occurs only across the southeastern boundary. This flow is the result of pumpage from withdrawal centers, outside the modeled area to the southeast in Ocean County, and Howell Township, Monmouth County. Eckel and Walker (1986, p. 16) described the effects of withdrawals on water levels in this area. These effects are simulated in the New Jersey RASA model (Martin, 1990) from which boundary fluxes were calculated.

Simulated vertical flow between the middle and upper aquifers for 1984 is downward almost everywhere in the downdip area (fig. 42). Flow from the upper aquifer to the middle aquifer averages 0.5 in/yr, even in northeastern Middlesex County where heads in the middle aquifer are 50 to 70 ft below heads in the upper aquifer. This is the largest difference in head between the two aquifers in the modeled area. The largest component of flow from the upper aquifer to the middle aquifer is through the leaky confining unit in the southwestern part of the modeled area, even though the head differences are less than 10 ft. A small upward component of flow to the upper aquifer, which averages 0.02 in/yr and has a maximum of 0.05 in/yr, is restricted to a small area centered near Freehold Township where heads in the upper aquifer are 5 to 10 ft below heads in the middle aquifer.

The total simulated flow budget for the middle aquifer in the 1984 transient simulation is about 34 Mgal/d, 13.5 Mgal/d more than under predevelopment conditions. As in the upper aquifer, some recovery in water levels and the accompanying movement of water into storage in the unconfined areas in 1984 causes a small amount of outflow in the recharge and storage budget component (fig. 40).

The two major sources of ground-water inflow to the middle aquifer in the 1984 transient simulation are recharge in the unconfined area of the middle aquifer (16.7 Mgal/d, or 49 percent of total inflow) and downward vertical flow from the upper aquifer (11.6 Mgal/d, or 34 percent of inflow). Other sources of water, including recharge from streams, vertical flow from the overlying confining-unit outcrop area, and boundary fluxes, are much less significant (about 5.0 Mgal/d, or 15 percent of inflow, combined). The major outflows in the 1984 simulation are discharge to wells (22.9 Mgal/d, or 67 percent of total outflow) and ground-water discharge to streams (7.5 Mgal/d, or 22 percent of outflow). Other outflows listed in figure 40 are negligible.

Ground-water withdrawals exceed the amount of recharge to the aquifer-outcrop areas, which is equal to recharge in the simulation of predevelopment conditions (fig. 40). A comparison of simulated flow budgets for predevelopment and 1984 indicates that 95 percent of the additional water for ground-water withdrawals (22.9 Mgal/d) is supplied from three sources: (1) captured ground-water discharge to and induced recharge from streams (net change, 10.1 Mgal/d), (2) reduced discharge and induced cross-formational flow from the upper aquifer (net change, 9.4 Mgal/d), and (3) increased downward flow and decreased upward flow through the confining-unit outcrops (net change, 2.3 Mgal/d). Changes in boundary flows account for a small amount of additional water.

Sensitivity Analysis

Sensitivity analysis is an evaluation of changes in model response to systematic changes in the representation of the hydrogeologic framework, hydraulic properties, and boundary conditions. Examination of the response of the South River ground-water flow model to variations in input allows for (1) an assessment of the appropriateness of model assumptions and the relative importance of input variables and model components (model limitations and functional sensitivity), (2) an analysis of the relation of inaccuracy of model output to inaccuracy of model input (error analysis), and (3) an evaluation of the accuracy of the model in representing the Potomac-Raritan-Magothy aquifer system in the study area (model accuracy). Operationally, the sensitivity analysis is included in all components of model development, including model construction, calibration and evaluation, and predictions. Results of sensitivity analysis that affect the reliability of the model for predicting the response of the ground-water system under a variety of scenarios and its usefulness as a basis for making resource-management decisions are discussed below.

Model Limitations and Functional Sensitivity

Sensitivity analysis during model development was done as an iterative procedure in which the model was formulated, simulations were executed, and results were examined for consistency with either observed response of the real system or the conceptual knowledge of the system. Five major factors that affect sensitivity are (1) discretization scale, (2) availability, distribution, and types of data, (3) representation of the outcrop areas, (4) representation of storage, and (5) artificially located model boundaries. Factors 1 and 2 were considered earlier in the report; factors 3, 4, and 5 are discussed below.

Errors in measured estimates of hydrogeologic properties were caused by differences in reliability and accuracy of the diverse sampling methods used. As an example, the hydrogeologic framework of the modeled area was determined from several sources, including geologists' logs, borehole geophysical logs, terrestrial and marine geophysical surveys, and drillers' logs. Data were insufficient for constructing the shallow water-table aquifer over confining-unit outcrop areas, and an unconfined aquifer was not constructed in outcrop areas of the confining units for the model; however, estimates of the regional hydrogeologic framework were considered to be reliable.

The accuracy of estimates of aquifer hydraulic properties depends on the method of data collection. Aquifer tests provide the most accurate data, but specific-capacity data from well-acceptance tests and lithologic logs also were used in calibration, especially for the downdip part of the confined aquifer system. Estimates of confining-unit leakances derived from aquifer tests could have been affected by differences in aquifer-test procedures, such as the test duration, which may not have been sufficiently long to detect leakance in some instances.

Estimates of the altitude of the water table and stream elevation obtained from topographic maps and flood-insurance maps were used as model input. Errors are introduced in this process as a result of (1) inherent errors in the source maps; (2) the subjective process of estimating one altitude for an entire cell area, which varies in difficulty depending on the amount of relief in a cell; and (3) the extent of the cell. In addition, because the interaction of stream cells and water-table cells in the unconfined aquifer areas is affected by their spatial discretization, the simulations probably are sensitive to assignment of the model-grid location. No systematic examination was made of model sensitivity to grid location in the unconfined-aquifer areas.

Representation of the outcrop areas

Sensitivity of the calibrated model to changes in the representation of the unconfined parts of the upper and middle aquifers was tested by changing several model-input parameters. The range of these parameter changes was based on subjective evaluation of the model and estimated uncertainty in the data. The sensitivity tests included (1) increasing and decreasing the hydraulic-conductivity values in the aquifer outcrop areas by 50 percent, (2) increasing and decreasing the value of streambed vertical hydraulic conductivity by 50 percent, (3) varying the elevation of the stream surface in active stream cells by as much as 5 ft, (4) increasing and decreasing leakances in the confining-unit outcrops by 50 percent, and (5) varying the recharge rate from 12 in/yr to 20 in/yr.

The model sensitivity to the changes in aquifer hydraulic conductivity, streambed conductances, and elevation of the stream surface was small. The mean residual between the 1984 simulated heads and the 1984 measured heads at wells was no more than 2 ft in the upper aquifer and about 4 ft in the middle aquifer. The changes in stream discharges caused by these parameter changes for predevelopment steady-state simulation and 1984 transient simulation also were minor.

The model was sensitive to the changes in vertical hydraulic conductivities in the confining-unit outcrops. Sensitivity tests involving vertical hydraulic conductivity caused the average 1984 simulated hydraulic heads at measured wells to vary by about 6 ft in the upper aquifer and by about 7 ft in the middle aquifer. These variations caused other components of the unconfined system to compensate for the change. For example, the 50-percent decrease in vertical hydraulic conductivity reduced the availability of water from the constant-head nodes in the confining-unit outcrop, and simulated flow to the confined system from the aquifer outcrops increased. This change in flow decreased the volume of ground water available to discharge to stream cells in the aquifer-outcrop areas, and additional losing stream reaches were simulated, even in the steady-state simulation. This decrease in confining-unit vertical hydraulic conductivity also induced flow in excess of 30 in/yr through the leakiest areas of the confining-unit outcrops.

Variations in recharge rates affected the number of gaining and losing stream cells and the distribution of ground-water discharge to streams in the steady-state and transient models. These sensitivity tests resulted in a fairly uniform response in simulated heads in both aquifers for the transient model. Average heads varied between 5 and 7 ft in the upper aquifer and between 7 and 10 ft in the middle aquifer. The sensitivity tests resulted in simulated 1984 water levels that varied about 9 ft in well 23-070, screened in the middle aquifer in East Brunswick Township, and about 6 ft in well 23-291, screened in the upper aquifer in South Brunswick Township. Water-level changes in unconfined areas closer to constant-head stream cells showed less sensitivity.

Storage coefficient

Simulations were used to evaluate the sensitivity of the model to changes in storage coefficient by increasing and decreasing the value of this property by one order of magnitude from the value in the calibrated model. This variation caused the mean value of heads computed for the 1984 synoptically measured wells to vary by less than 1 ft; changes in hydrographs were minute. Although the storage coefficient represents storage in the aquifers and in the confining units, it inherently underestimates release of water from confining-unit storage to supply ground-water withdrawals. This underestimation, in turn, causes errors in estimation of the rate at which water moves between hydrologic units in the simulated transient ground-water system. The model represents transient leakage from confining units poorly and propagates pressure gradients between aquifers too rapidly; it also probably distorts the magnitude of pressure gradients and the time in which they are propagated between adjoining aquifers. Simulated hydrographs show that water levels in wells stabilize within two or three time steps in each model pumping period. Nichols (1977, p. 56) estimated the average time for a pressure gradient to propagate from the Englishtown aquifer system through a typical section of the Merchantville-Woodbury confining unit in the northern Coastal Plain to the upper aquifer to be 146 years. He estimated the average time required for a steady cross-formational flow in the same system to be 734 years. Vertical fluxes through the confining units where the confining unit is simulated as thin or absent, as in the South Brunswick Township area, are likely to be more accurate than vertical fluxes elsewhere in the transient model. Cross-formational-flow components of water budgets for each aquifer are, therefore, most likely higher than those in the real system, where much of this water actually is released from storage in the confining units.

Boundary fluxes

The reliability of the lateral fluxes used for the boundary conditions cannot be determined experimentally. Rather, the reliability of these fluxes depends on the accuracy of the larger New Jersey RASA model and the interfacing methodology. The sensitivity of simulated water levels to lateral-flux boundary locations and magnitudes was tested by increasing fluxes at all lateral boundaries by 50 percent, 100 percent, and 1,000 percent from the values used in the calibrated model. For a 50-percent increase, the average change in predicted water levels in 1984 measured wells was less than 1 ft in the upper and middle aquifers, and head changes occurred mainly along boundaries. For a 100-percent increase, the change in simulated water levels also was less than 1 ft in both aquifers. For a 1,000-percent increase, however, large gradients developed in both aquifers in the central part of the modeled area, from Sandy Hook and Raritan Bay out of the modeled area into Ocean County to the south.

No significant change was noted in the simulated heads in the upper and middle aquifers when vertical fluxes from the New Jersey RASA model to the overlying layers were increased up to 100 percent. The sensitivity of the model to changes in the vertical fluxes between the vertical boundaries of the Potomac-Raritan-Magothy aquifer system and the overlying hydrogeologic units in the modeled area depends, in part, on the values for hydraulic properties of the overlying layers. Properties of the overlying units were not varied during sensitivity analysis, however.

Error Sensitivity

Calibration can introduce bias in the determination of hydraulic properties of the modeled ground-water system because these properties are determined by optimizing the fit of the model output to the characteristics of the observed system, rather than by studying each individual property. The error sensitivity analysis of data modified during calibration assesses how reliably the calibration procedure estimates the selected parameters by examining the effect of varying these parameters on model output.

The error sensitivity analysis is accomplished by observing the model output, such as changes in the altitude of the water-table or in ground-water discharge to streams, while varying the values of input parameters one at a time from their calibrated values (values of all other parameters are held constant). The calibrated model is sensitive to a model component if a small change in the component causes a large change in model output. Consequently, the model is most effective in calibrating the parameters to which it is most sensitive because their effect on output can be gaged by the calibration criteria. Because the hydrologic parameters are highly correlated and similar model results can be achieved from various nonunique combinations of parameter values, field data are valuable for estimating the less sensitive parameters.

The error sensitivity analysis of the model is discussed below for those parameters that had the largest effects on regional heads, including (1) horizontal hydraulic conductivity of the aquifer, (2) confining-unit leakance, (3) ground-water withdrawals, and (4) water-table altitude. Although the last two parameters are not calibrated parameters, they are helpful in assessing the reliability of the model. The range of values for which each parameter was tested was guided by subjective judgment of the relative uncertainty of the initial estimates of the parameters before calibration.

The effects of these parameter changes were evaluated by comparing their effects on simulated heads at those wells that were measured in November 1984, long-term well hydrographs, ground-water discharge to streams in each stream zone, and volumes of water in each component of the ground-water budget. Differences in heads along part of one model row for each aquifer for the calibrated model and sensitivity simulations for 1984 output are shown in figures 43 through 46. These model rows pass through large cones of depression where sensitivity to the input changes is expected to be maximal. The section for the upper aquifer passes through the cone of depression in Freehold Township, located along row 36 between columns 4 and 30 in the model grid. The section for the middle aquifer passes through the cone of depression in Hazlet Township, located along row 30 between columns 8 and 38 in the model grid.

Horizontal hydraulic conductivity of aquifers

Sensitivity of the model to horizontal hydraulic conductivity was tested by alternately increasing and decreasing the values of this parameter throughout the aquifers by 50 percent from the calibrated values. These changes caused the simulated heads in the upper aquifer in the cone of depression in the Freehold Township area to increase by 10 to 15 ft with increased hydraulic conductivity and to decrease by 30 to 45 ft with decreased hydraulic conductivity (fig. 43). Additionally, the simulated heads in the middle aquifer in the cone of depression in the Hazlet Township area increased by 15 to 28 ft with increased hydraulic conductivity and decreased by 35 to 70 ft with decreased hydraulic conductivity (fig. 44).

Areal differences in simulated hydraulic heads caused by these changes in model parameters are related to the regional trends in hydraulic conductivity, boundary configuration, and available water sources in updip unconfined-aquifer areas and downdip confined-aquifer areas. Sensitivity to the changes in horizontal hydraulic conductivity was greatest in the downdip areas for both aquifers where horizontal hydraulic conductivities are low (45 to 55 ft/d for the upper aquifer and 40 to 75 ft/d for the middle aquifer) and in the cones of depression where the rates of ground-water withdrawal are high. The unequal areal sensitivity to hydraulic-conductivity changes is explained, in part, by the control exerted by horizontal hydraulic conductivity on lateral flow. The induced changes in the potentiometric surface would be larger in areas of low hydraulic conductivity than in areas of high hydraulic conductivity in order to sustain equal rates of ground-water flow to withdrawal centers where withdrawals are equal.

The unequal areal response also results from differences in water availability to satisfy ground-water withdrawals in the updip and downdip areas. Generally, water for withdrawals must come from either a decrease in storage or from the capture of water (either through reduction of ground-water discharge or increased recharge). More sources of water are available in and near the outcrop areas than in the downdip areas. In updip areas, sources of water in the model include water released from aquifer storage as specific yield, induced recharge from confining-unit outcrops, diverted ground-water discharge to streamflow, and diverted flow to downdip areas. In downdip areas, additional sources of water include only release from storage, induced cross-sectional flow, and reduced discharge to discharge areas.

Sensitivity to the changes in hydraulic conductivity was larger in the cone of depression in Hazlet Township in the middle aquifer than in the cone of depression in Freehold Township in the upper aquifer because hydraulic conductivities in Hazlet Township generally were lower. Greater sensitivity also may be attributed to the no-flow boundary in the lower confining unit for the middle aquifer, however. For this reason, proportionately more water is available to meet the withdrawals in the upper aquifer from increased cross-formational flow from above and below; for the middle aquifer, water is available only from increased flow from above.

<u>Vertical hydraulic conductivity of confining units</u>

Model sensitivity to vertical hydraulic conductivity was tested by increasing and decreasing this value by 50 percent, first for the Merchantville-Woodbury confining unit and then for the confining unit overlying the middle aquifer. For the sensitivity tests in the Merchantville-Woodbury confining unit, the simulated mean head at wells measured in 1984 in the upper aquifer varied by 13.5 ft, and the mean head at the wells measured in 1984 in the middle aquifer varied by 10.5 ft.

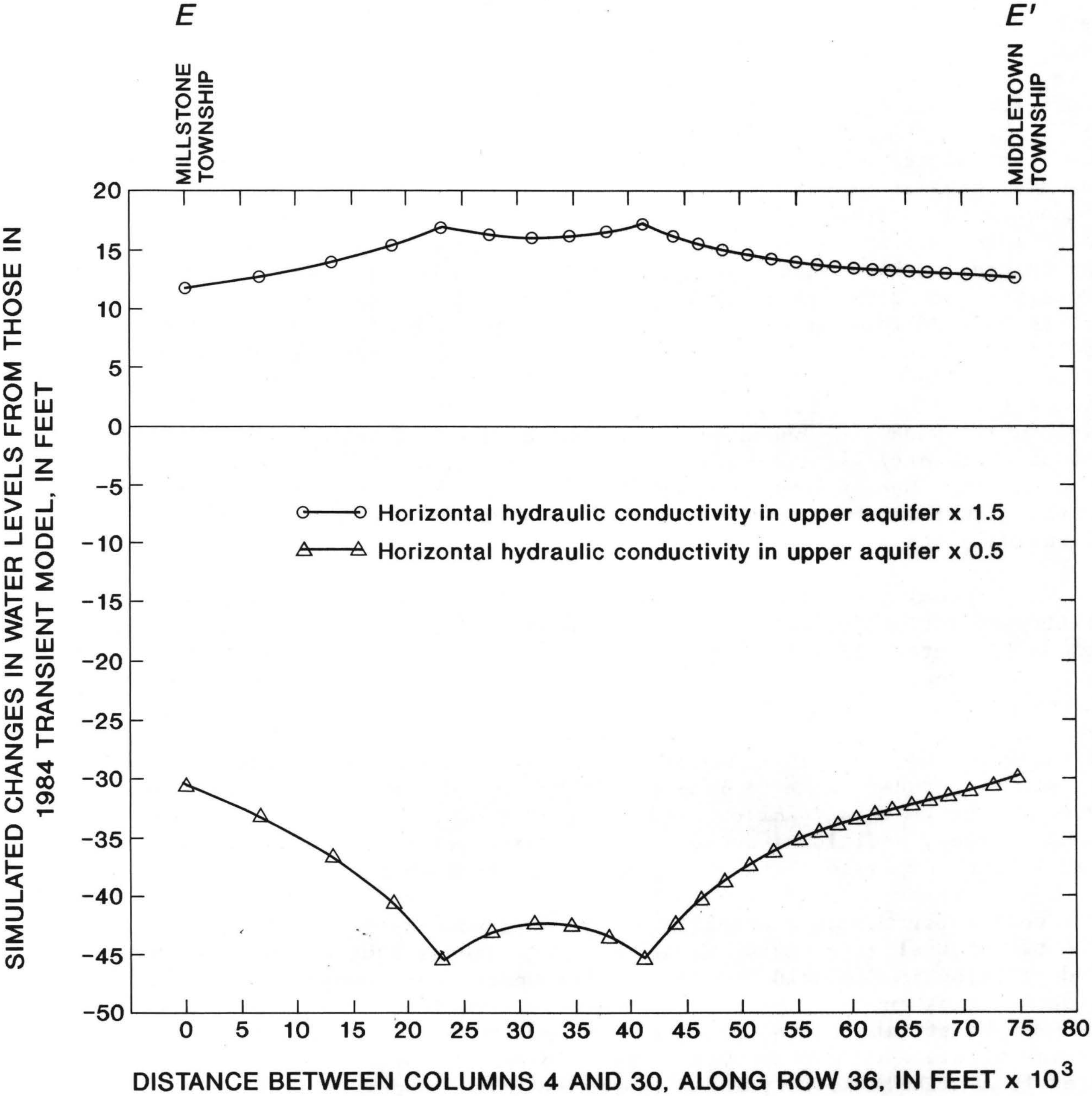


Figure 43.--Simulated head changes in the upper aquifer along model row 36 in response to sensitivity tests of horizontal hydraulic conductivity. (Location of row shown in fig. 25)

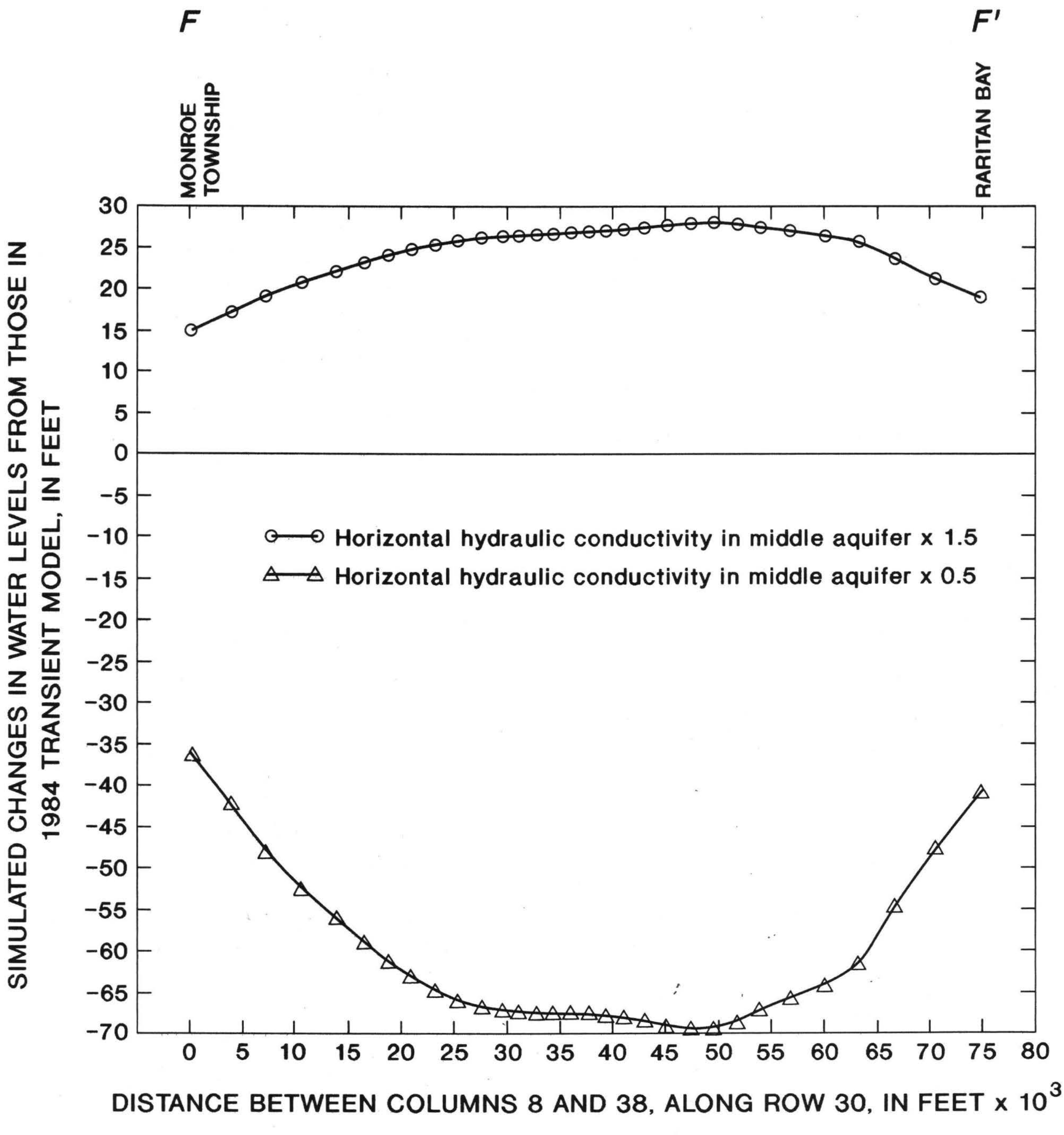


Figure 44.--Simulated head changes in the middle aquifer along model row 30 in response to sensitivity tests of horizontal hydraulic conductivity. (Location of row shown in fig. 25)

Increasing the vertical hydraulic conductivity in the Merchantville-Woodbury confining unit caused simulated upper-aquifer heads in the cone of depression in Freehold Township to increase by about 10 ft, whereas decreasing the vertical hydraulic conductivity caused heads to decrease by about 15 ft (fig. 45). Increasing the vertical hydraulic conductivity in the Merchantville-Woodbury confining unit caused simulated middle-aquifer heads in the cone of depression in Hazlet Township to increase by about 10 ft, whereas decreasing the hydraulic conductivity caused heads to decrease by 5 ft (fig. 46).

In response to changes in vertical hydraulic conductivity of the confining unit overlying the middle aquifer, the simulated mean head at wells measured in 1984 varied by 3.8 ft in the upper aquifer and by 10 ft in the middle aquifer. The effect of a 50-percent increase and decrease in the vertical hydraulic conductivity in the confining unit overlying the middle aquifer was a variation of less than 5 ft in the simulated upper-aquifer heads in the Freehold Township cone of depression (not shown). Changing the vertical hydraulic conductivity in the confining unit overlying the middle aquifer caused the simulated middle-aquifer heads in the Hazlet Township cone to vary by about 10 to 15 ft (fig. 46).

Changes in vertical hydraulic conductivity for each confining unit caused hydraulic-head responses that were fairly uniform throughout the modeled area, even in the cones of depression (figs. 45 and 46). Changes in vertical hydraulic conductivity of the Merchantville-Woodbury confining unit resulted in nearly equal head responses of the upper and middle aquifers. Changes in the vertical hydraulic conductivity of the confining unit overlying the middle aquifer caused larger variations in the middle aquifer than in the upper aquifer. This response shows that, in the calibrated model, much of the water in the middle aquifer is derived from the upper aquifer, but little water in the upper aquifer is derived from the middle aquifer.

Sensitivity of the model to high vertical hydraulic conductivities in the confining units in the southwestern part of the modeled area was tested by reducing model vertical-hydraulic conductivities in this area to the magnitude of those in nearby vertical-hydraulic-conductivity zones for each confining unit. Calibrated vertical hydraulic conductivities were about one to two orders of magnitude higher for the confining unit overlying the middle aquifer and about one order of magnitude higher for the Merchantville-Woodbury confining unit in this area than for nearby areas for each confining unit. Reducing vertical hydraulic conductivity generally caused the simulated heads to decline by about 7 ft in the upper confining unit (fig. 45) and by about 6 ft in the middle aquifer. Decreasing the vertical hydraulic conductivity for the middle aquifer caused simulated heads in the upper aquifer to change little and caused simulated heads in the middle aquifer to decline by as much as to 10 ft (fig. 46). Variations in vertical hydraulic conductivity of the confining unit overlying the middle aquifer caused simulated head differences of as much as 40 ft between the middle and upper aquifer in nested wells in this area (wells 23-291 and 23-292, and wells 23-228 and 23-229), whereas observed differences range from 5 to 10 ft.

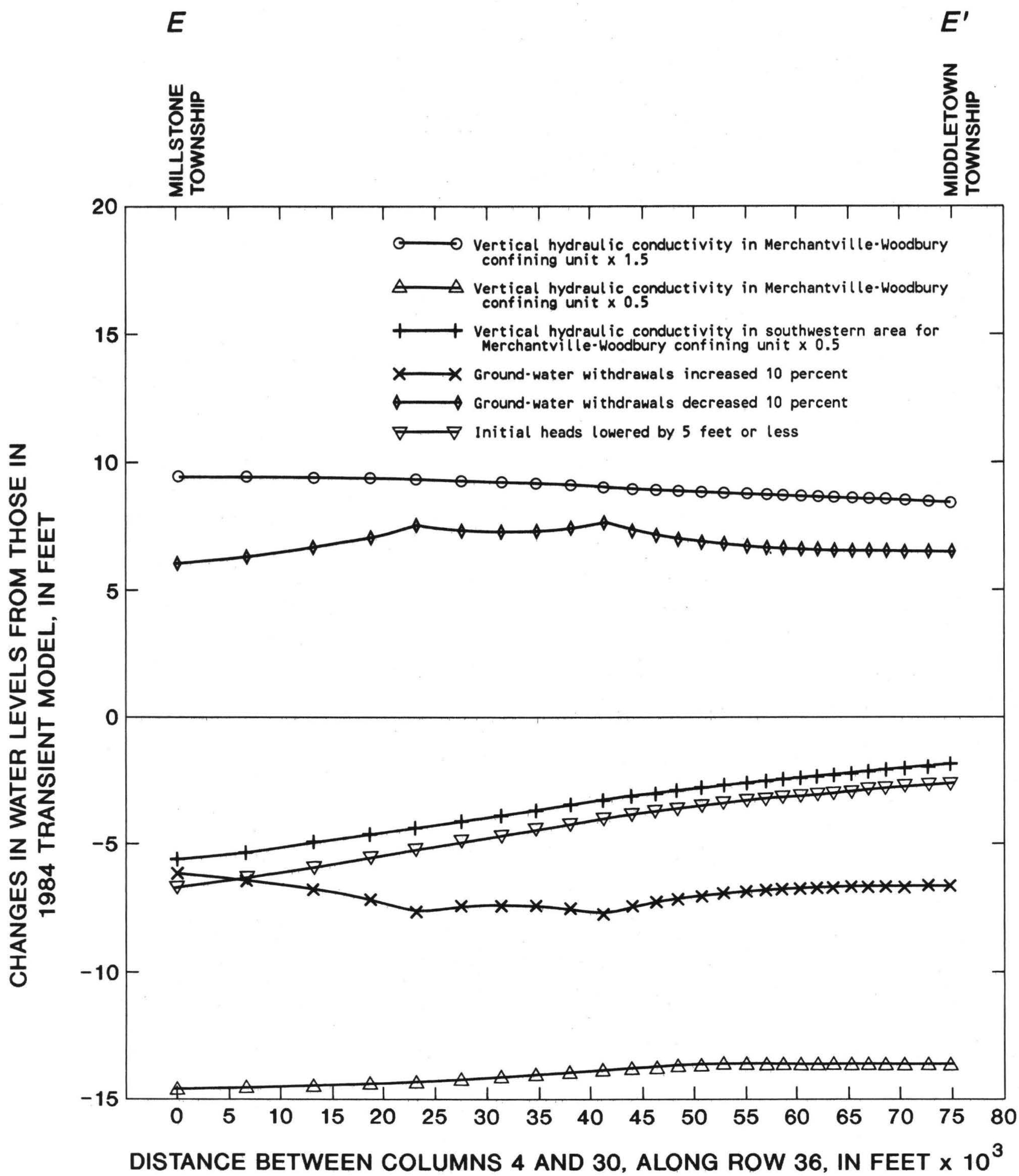


Figure 45.--Simulated head changes in the upper aquifer along model row 36 in response to sensitivity tests of vertical hydraulic conductivity in the Merchantville-Woodbury confining unit, ground-water withdrawals, and initial heads in the aquifer outcrop. (Location of row shown in fig. 25)

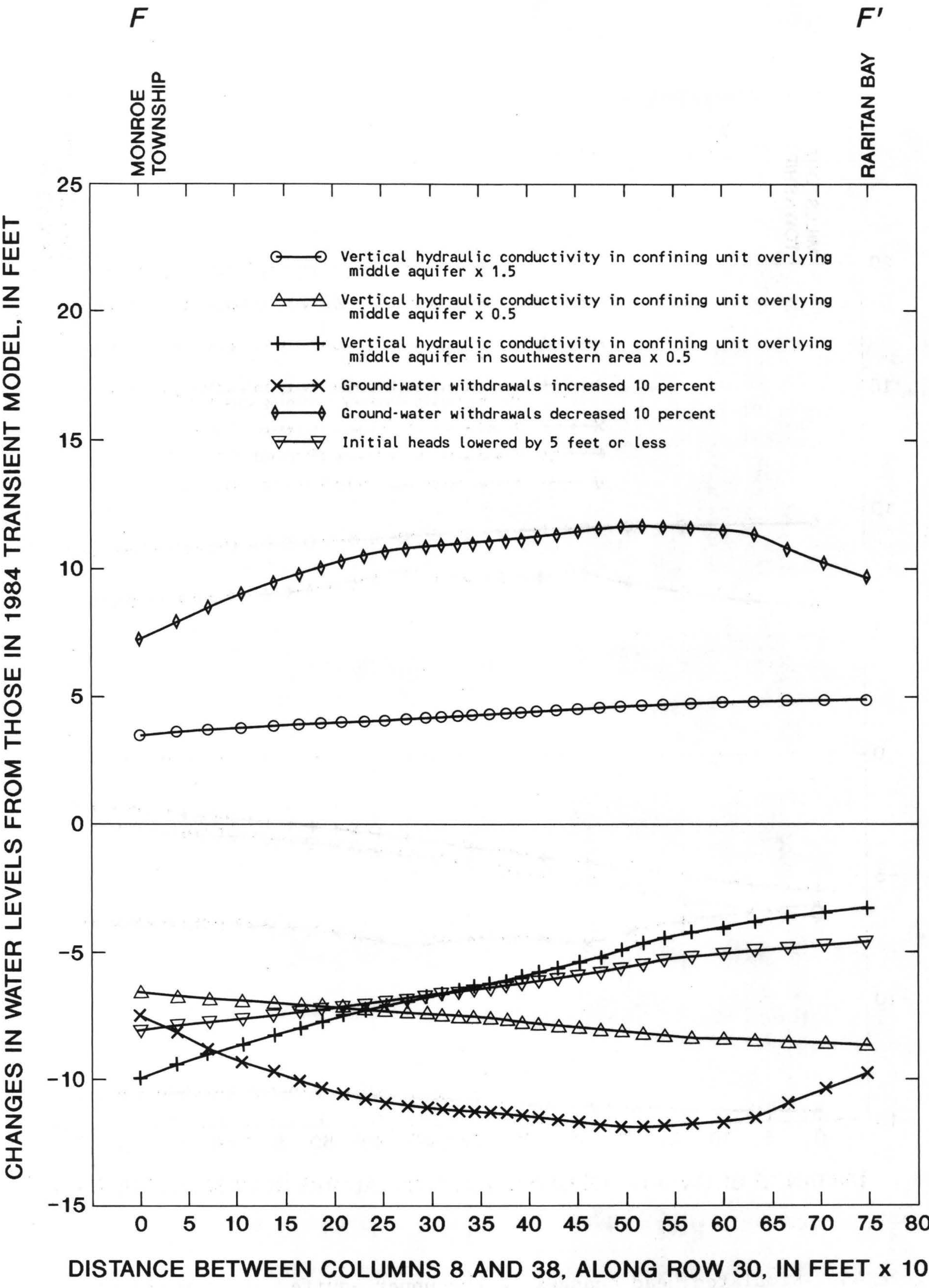


Figure 46.--Simulated head changes in the middle aquifer along model row 30 in response to sensitivity tests of vertical hydraulic conductivity in the confining unit overlying the middle aquifer, ground-water withdrawals, and initial heads in the aquifer outcrop. (Location of row shown in fig. 25)

Ground-water withdrawals

Although ground-water-withdrawal data were not calibrated parameters, withdrawals for all 12 withdrawal periods were increased and decreased by 10 percent to examine sensitivity to this input variable. Withdrawal variations caused a net change in the mean heads of about 7 ft in the upper aquifer and about 13 ft in the middle aquifer. Variations were largest in areas of largest withdrawals--that is, in areas of the regional cones of depression. Increasing the withdrawals caused upper-aquifer heads in the Freehold cone of depression to decline by about 7 ft (fig. 45), whereas decreasing withdrawals caused heads to increase by about 6 to 7 ft. Increasing withdrawals caused middle-aquifer heads in the Hazlet Township cone of depression to decline by about 10 ft, whereas decreasing withdrawals caused heads to increase by about 15 ft (fig. 46).

Predictive Simulations

Two predictive ground-water-withdrawal scenarios--one consisting of increased withdrawals proportional to projected growth and the other consisting of reduced withdrawals based on percentages of 1983 withdrawals--were simulated through 2019. Because the population of the northern Coastal Plain of New Jersey is increasing, the first scenario was chosen to determine the effects of pumping stresses from unrestrained growth on the ground-water system. The second scenario was chosen to determine the effects of reducing and stabilizing ground-water withdrawals on the ground-water system.

If the model is to be used as a planning tool to determine the allowable magnitude of ground-water withdrawals, the hydrologic effects that can be tolerated need to be defined, and reasonable projections of unknown future conditions need to be made. The following discussion addresses the capabilities of the model as related to accuracy of predictions and presents the results of the two predictive simulations.

Accuracy of Simulations

The ability of the model to simulate future hydraulic heads is no better than the accuracy with which the model simulates measured, historic heads. The calibrated model is regarded as acceptable within valid ranges of the data sets used for calibration and within bounds of the underlying model assumptions. The preceding sensitivity analysis indicates the predictive accuracy of the model because it allowed evaluation of the range of uncertainty in model performance within the range of uncertainty in the data sets. Predictive simulations used to extrapolate beyond the valid ranges of the data sets and the model assumptions or much beyond the conditions simulated in the calibrated model create the risk of other errors.

Analysis of model sensitivity to ground-water withdrawals indicated that sensitivity was high; error could be much larger for the predictive simulations in which ground-water withdrawals greatly exceed those of the calibrated-model data set than for predictive simulations in which future ground-water withdrawals are similar to, or less than, those of the calibration period. In addition, accuracy of the predictive simulations is highly dependent on the reliability of estimated ground-water withdrawals, which also can influence the estimated fluxes across the model boundaries. Thus, if any of these future controlling conditions is substantially in error, the model predictions would need to be revised.

Because most water supply in the study area is derived from either decreased aquifer-system storage or capture of water from reduced discharge and increased recharge, and because the design of the South River model emphasizes the processes that affect the regional confined system and deemphasizes the description of the unconfined system, the ability of the model to predict sources of future water supply could be biased. The model was most effective in simulating the capture of water by decreased discharge from lateral flow, decreased cross-formational flow (in areas where vertical hydraulic conductivity is high), and release of water from storage (mining) in the unconfined system. The model did not accurately simulate the transient release of water from confining-unit storage or increased recharge from the unsaturated zone caused by lowering of the water table. Although capture of ground-water discharge to streams was simulated, the accuracy of this budget component could not be evaluated because of the method of simulating the unconfined outcrop areas and the lack of measured streamflow data from the aquifer outcrops.

Results of Simulation of Ground-Water-Withdrawal Scenarios

Each of the two scenarios included seven additional pumping periods--one that extended from January 1, 1986, through the end of 1989, followed by six 5-year pumping periods that together extended through the end of 2019. The magnitudes of lateral fluxes imposed from the regional model were assumed to be unchanged from 1985 magnitudes for both scenarios. All other parameters and input variables in the calibrated ground-water flow model were unchanged for the scenarios. Withdrawal rates for the overlying aquifers also were unchanged from their 1985 values. Continuation of 1985 withdrawal rates to the year 2019 resulted in virtually no change in the budget from the 1985 budgets because the 1985 simulation is already close to equilibrium. Therefore, continuation of 1985 withdrawal rates is not discussed as a predictive scenario.

Ground-water-withdrawal rates in the modeled area were increased to represent unrestricted growth in demand in scenario 1 and restricted growth in scenario 2. In scenario 1, withdrawals were increased linearly by 72 percent from their 1985 values through the seven additional pumping periods on the basis of projected water demand for 2019. A linear regression of historical trends from 1900 through 1983 and the projected water demand from 1983 through 2020 are shown in fig. 47. In scenario 2, ground-water-withdrawal rates for major users (greater than 10,000 gallons per day) were reduced, beginning in 1990, to 40 percent of actual annual 1983 rates for the upper aquifer and to 50 percent of actual annual 1983 rates for the middle aquifer within designated management areas. Also in scenario 2, simulated ground-water use within 3 mi of the designated management areas was restricted to actual annual 1983 withdrawal rates, and withdrawals outside these restricted areas were assumed to increase at the predicted 72-percent growth rate through 2019. These reduced withdrawal rates and designated management areas are based on management studies done for the New Jersey Department of Environmental Protection and Energy (Alfred Crew Consulting Engineers, Inc., and Hazen and Sawyer, P.C., 1987).

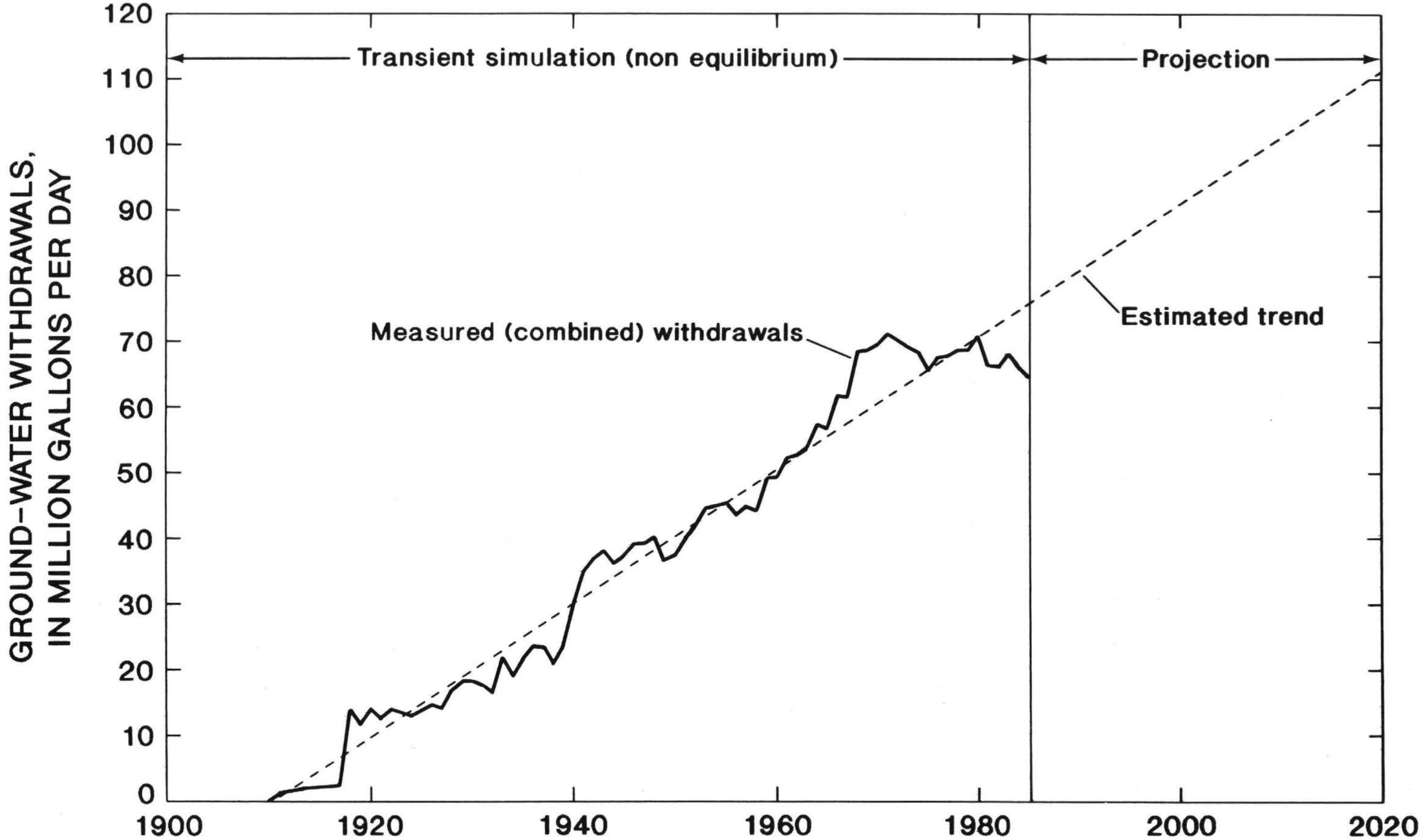


Figure 47.--Historical (through 1985) and projected (1986 through 2019) ground-water-withdrawal rates for the upper and middle aquifers in the modeled area.

The simulated water levels for each scenario are the result of (1) transient effects of changing stresses on the potentiometric surface computed from pre-1986 ground-water withdrawals in the calibrated model and (2) estimated changes in ground-water withdrawals after 1986. Simulated drawdowns for the two scenarios are shown for two locations, each near the deepest parts of a cone of depression in each aquifer (fig. 48). These locations are in model row 39, column 7 (fig. 25), in the upper aquifer model layer (approximately at the center of the Freehold Township cone of depression) and in model row 33, column 35 (fig. 25), in the middle aquifer model layer (approximately at the center of the Hazlet Township cone of depression). The computed drawdowns at these locations illustrate the rapid approach to steady-state conditions (within two time steps of each stress period) near the center of each cone of depression.

Scenario 1

Predicted heads in the upper aquifer in 2019 that result from scenario 1 (fig. 49) are significantly lower than heads in 1984. The shape of the potentiometric surface in the upper aquifer is similar to that of the 1984 potentiometric surface, but the gradients toward the centers of the cones of depression are steeper. The deepest cones of depression are in Freehold and Hazlet Townships; simulated heads at their centers are 100 and 80 ft below sea level, respectively, in 2019. The head at the node in model row 39, column 7, near the Freehold Township cone of depression, declines about 10 ft with each stress period. In comparison to simulated 1984 results for the upper aquifer (fig. 31), the center of the cone of depression in Freehold Township is 60 ft lower in 2019 (fig. 48A), and the center of the cone of depression in Hazlet Township is 70 ft lower in 2019 (fig. 48B). By the year 2019, heads in the southern and southwestern parts of the modeled area are 10 to 30 ft lower than 1984 heads (fig. 49). Head gradients, which are steepened from 1984 gradients, are from the southwestern part of the modeled area toward the withdrawal centers in the downdip areas of Monmouth County.

Simulation of scenario 1 also results in a lowered simulated potentiometric surface in the middle aquifer (fig. 50). The potentiometric surface at the centers of cones of depression decreases to 170 ft below sea level in Hazlet Township and Matawan Borough, to 150 ft below sea level in Old Bridge Township, and to 130 ft below sea level near Duhernal Lake. In comparison to simulated 1984 results for the middle aquifer (fig. 32), the centers of the Hazlet Township (fig. 48B), Matawan Borough, and Old Bridge Township cones of depression are about 90 ft lower, and the center of the cone of depression near Duhernal Lake is about 80 ft lower. The head at the node near the Hazlet Township cone of depression declines about 12 ft with each increase in withdrawals (fig. 48B). Heads in the southwestern part of the modeled area are 10 to 20 ft lower, heads near Sandy Hook are 60 ft lower, and heads beneath Raritan Bay are 50 to 70 ft lower than those simulated for 1984. Head gradients are much steeper toward the cones of depression, especially the gradient from Staten Island, New York, toward Monmouth County, New Jersey.

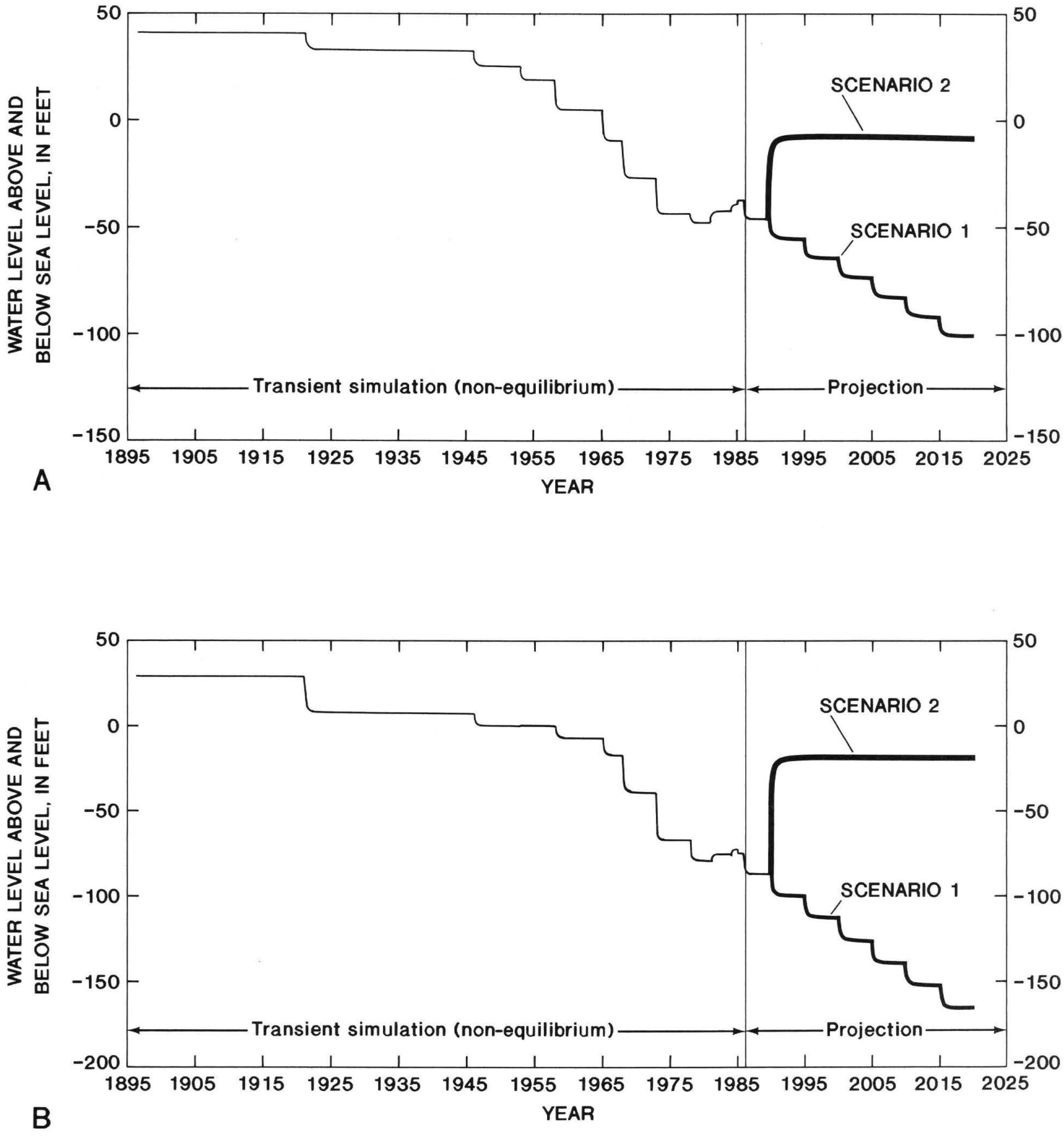


Figure 48.--Simulated heads for 1896 through 2019 near the centers of the major cones of depression in the (A) upper aquifer, Freehold Township (row 39, column 7), and (B) middle aquifer, Hazlet Township (row 33, column 35). (Locations of rows and columns shown in fig. 25)

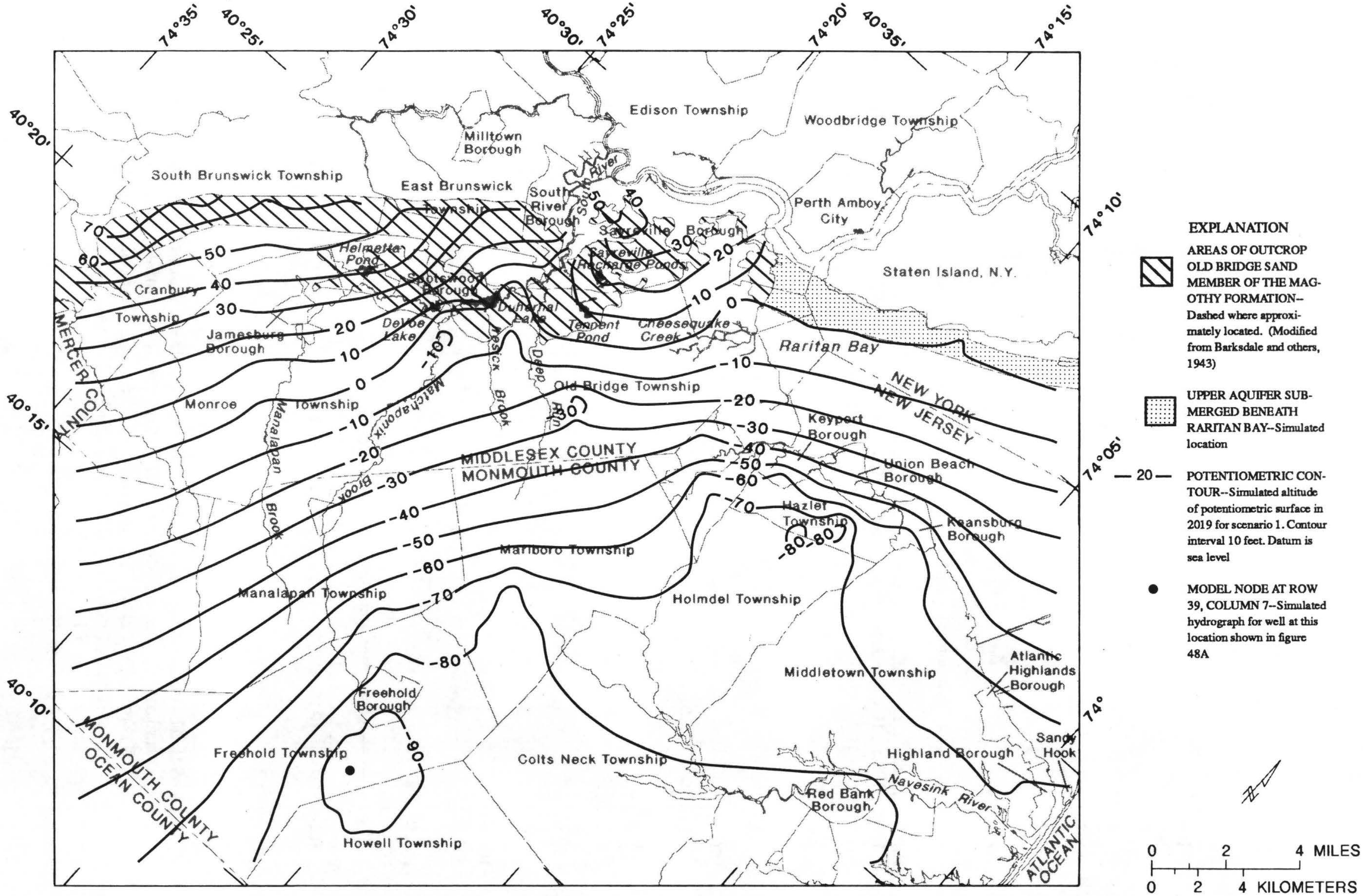


Figure 49.--Simulated potentiometric surface in 2019 in the upper aquifer, scenario 1.

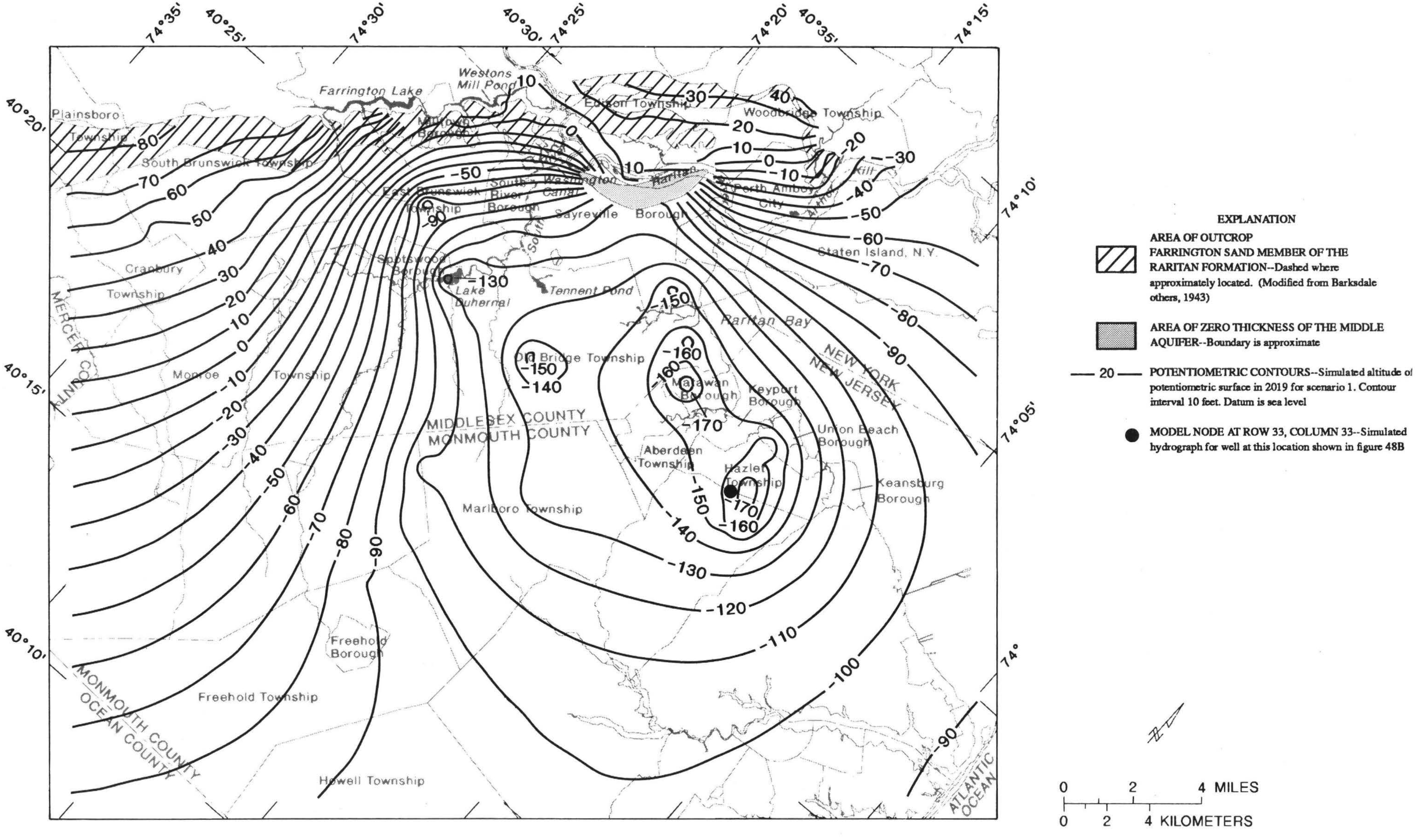


Figure 50.--Simulated potentiometric surface in 2019 in the middle aquifer, scenario 1.

Scenario 2

Reduced withdrawal rates for 1990 through 2019 in scenario 2 cause the potentiometric surface of the upper aquifer (fig. 51) to recover and, by 2019, to be significantly higher than in 1984. The potentiometric surface in the upper aquifer is similar in shape to that in 1984, but the gradients toward the centers of the cones of depression are smaller toward the downdip areas. By 2019, only the area of Hazlet Township has a cone of depression in the upper aquifer whose center is deeper than 10 ft below sea level. Compared to simulated 1984 results for the upper aquifer (fig. 31), the center of the Freehold Township cone of depression is 30 ft higher (fig. 48A), and the center of the Hazlet Township cone of depression is 20 ft higher. Upper-aquifer heads in the southern and southwestern parts of the study area are 20 to 30 ft higher than 1984 heads.

The potentiometric surface in the middle aquifer also recovers in scenario 2 (fig. 52). Heads in the centers of cones of depression in Hazlet Township and Matawan Borough rise to 20 ft below sea level, and cones of depression in Old Bridge Township and near Duhernal Lake no longer are well-defined. Compared to simulated 1984 results for the middle aquifer (fig. 32), the centers of cones of depression at Hazlet Township (fig. 48B), Matawan Borough, Old Bridge Township, and near Duhernal Lake all are at least 50 ft higher. Heads recover 60 ft at the center of the cone of depression in Hazlet Township. Heads are 20 to 30 ft higher in the southwestern part of the modeled area, 30 ft higher near Sandy Hook, and 30 to 40 ft higher beneath Raritan Bay. Although the potentiometric surface has the same general shape, the gradients are much smaller toward the centers of ground-water withdrawal near the Middlesex-Monmouth County line and Raritan Bay.

Analysis of Results of Scenarios 1 and 2

The potentiometric surfaces and ground-water budgets for the upper and middle aquifers are affected strongly by the changes in ground-water withdrawals simulated in the two scenarios. The shape of the potentiometric surface in both scenarios is similar, but heads differ greatly. The most pronounced differences in the potentiometric surfaces are in the deep, confined-aquifer areas and away from the large withdrawals in the unconfined-aquifer areas. A large storage coefficient and the proximity to the constant-head boundary in the overlying streams and in the confining-unit outcrop result in small changes in the simulated head in the unconfined areas.

This result indicates that water to satisfy withdrawals from the unconfined-aquifer areas would be derived from within and near the unconfined areas through captured discharge and release from unconfined storage. The model is less sensitive to processes in the unsaturated zone and does not simulate the local ground-water discharge to streams accurately. Therefore, the amounts of water supplied from diverted ground-water discharge to streams and unconfined-aquifer areas within the confining-unit outcrops could be locally erroneous. Much larger changes in head in the downdip areas caused by scenario 1 withdrawals indicate that lateral flow from the recharge areas through the aquifer would increase with increased withdrawals and would decrease with reduced withdrawals. The

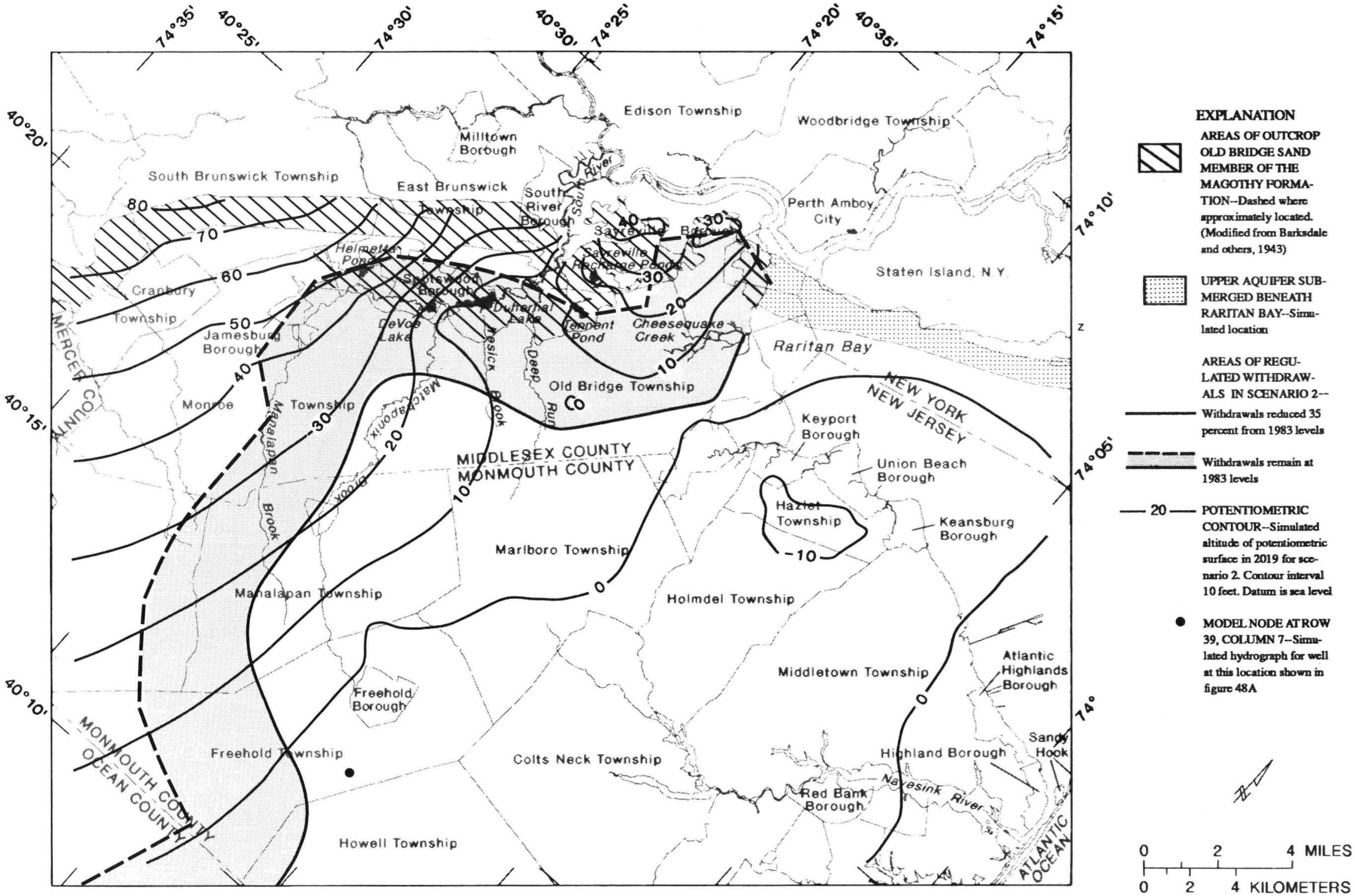


Figure 51.--Simulated potentiometric surface in 2019 in the upper aquifer, scenario 2.

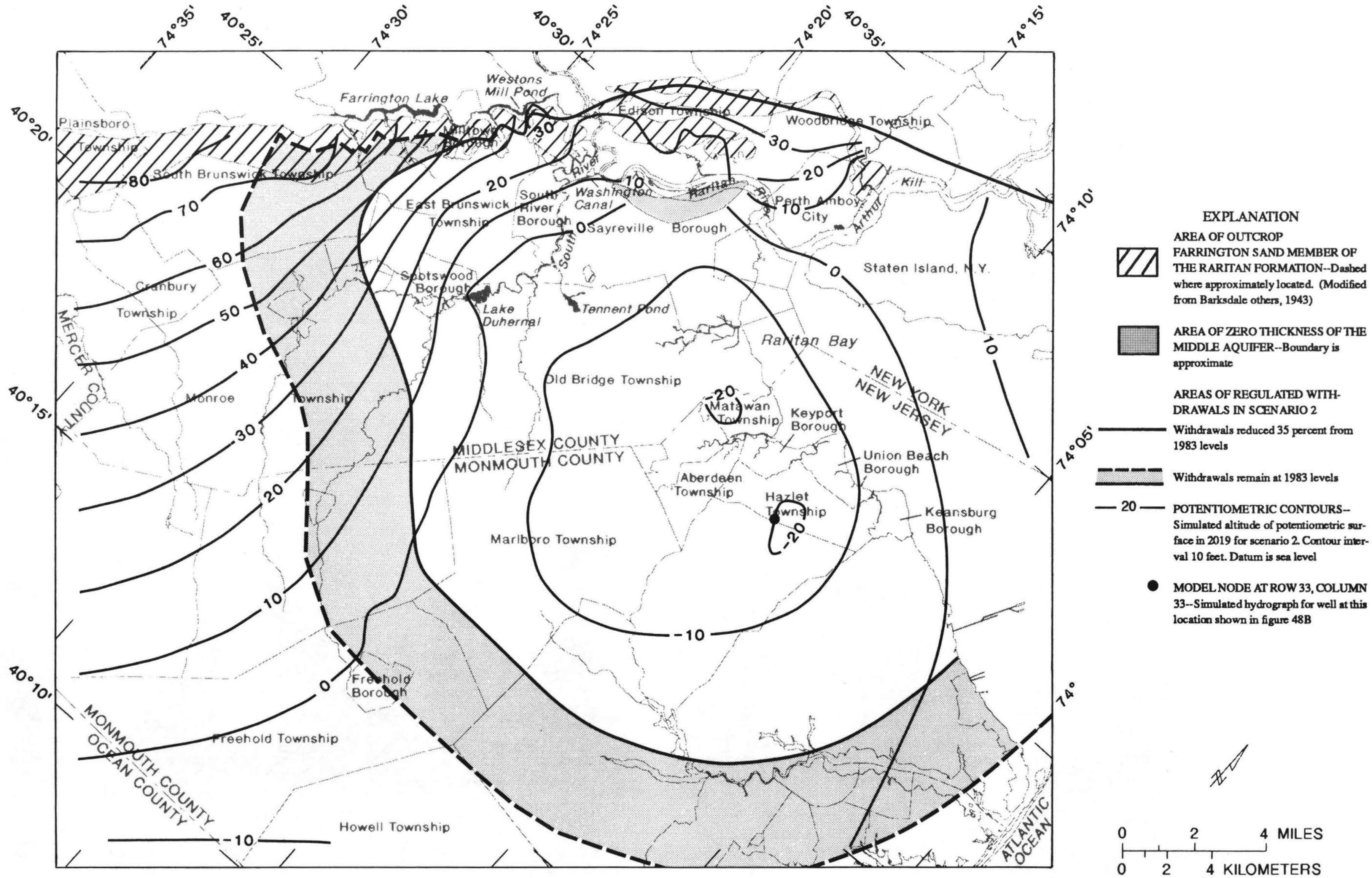


Figure 52.--Simulated potentiometric surface in 2019 in the middle aquifer, scenario 2.

amount of water supplied from lateral flow and cross-formational flow to meet demand downdip is large in scenario 1 because the lateral-boundary fluxes probably are underestimated, and no release of water from confining units is simulated.

The flow-budget components for each aquifer in both scenarios (figs. 53 and 54) indicate that most water supplied to meet future demands in scenario 1 would come from captured stream discharge, induced recharge through the confining-unit outcrop areas, and cross-formational flow. For purposes of evaluating the future availability of water, comparisons of budget components for the scenarios are made to the 1984 flow budget. The net contribution of each flow-budget component for each aquifer can be computed by summing the inflow (aquifer gain) and outflow (aquifer loss) for that component.

For the upper aquifer, withdrawals in scenario 1 cause a decrease of 5.64 Mgal/d in net ground-water discharge to streams from 1984 amounts, an increase of 14.17 Mgal/d in net inflow from recharge-pond areas, an increase of 6.36 Mgal/d in net recharge from the outcrop of the Merchantville-Woodbury confining unit, and an increase of 3.0 Mgal/d in net outflow from cross-formational flow between the Englishtown aquifer system and the upper aquifer and between the middle aquifer and upper aquifer (fig. 53). Although the flow from the Englishtown aquifer system increases, this increase is smaller than the increase in outflow to the middle aquifer. Withdrawals in scenario 2 cause an increase of 0.52 Mgal/d in net ground-water discharge to streams from 1984 amounts, an increase of 4.55 Mgal/d in net recharge from recharge-pond areas, a decrease of 1.16 Mgal/d in net recharge from the Merchantville-Woodbury confining unit, a decrease of 3.69 Mgal/d in outflow from combined cross-formational flow to the middle aquifer, and a decrease of 1.66 Mgal/d in inflow from the Englishtown aquifer system. Inflow from recharge ponds increases in scenario 2 even though withdrawals in the wells near these sites were reduced. For scenario 2, ground-water withdrawals in the upper aquifer are larger than for 1984 because of unrestricted withdrawal increases outside the area of reduced withdrawals (fig. 51).

For the middle aquifer, withdrawals in scenario 1 cause a decrease of 4.71 Mgal/d in net ground-water discharge to streams from 1984 amounts, an increase of 1.91 Mgal/d in net recharge from the outcrop of the confining unit overlying the middle aquifer, and an increase of 6.70 Mgal/d in net cross-formational inflow from the upper aquifer (fig. 54). The flow-budget components in scenario 2 indicate that substantially less water would be derived from the unconfined areas and from cross-formational flow in the confined areas than in scenario 1. Withdrawals in scenario 2 cause an increase of 3.82 Mgal/d in net ground-water discharge to streams, a decrease of 0.55 Mgal/d in net recharge from confining units, and a decrease of 4.01 Mgal/d in the net cross-formational inflow from the upper aquifer.

SALTWATER INTRUSION

In general terms, saltwater moves into the aquifers in the study area for two reasons. First, there is a hydraulic connection between Raritan Bay and its estuaries (which contain salty water) and the Potomac-Raritan-Magothy aquifer system. As an example, the excavation of earth material to

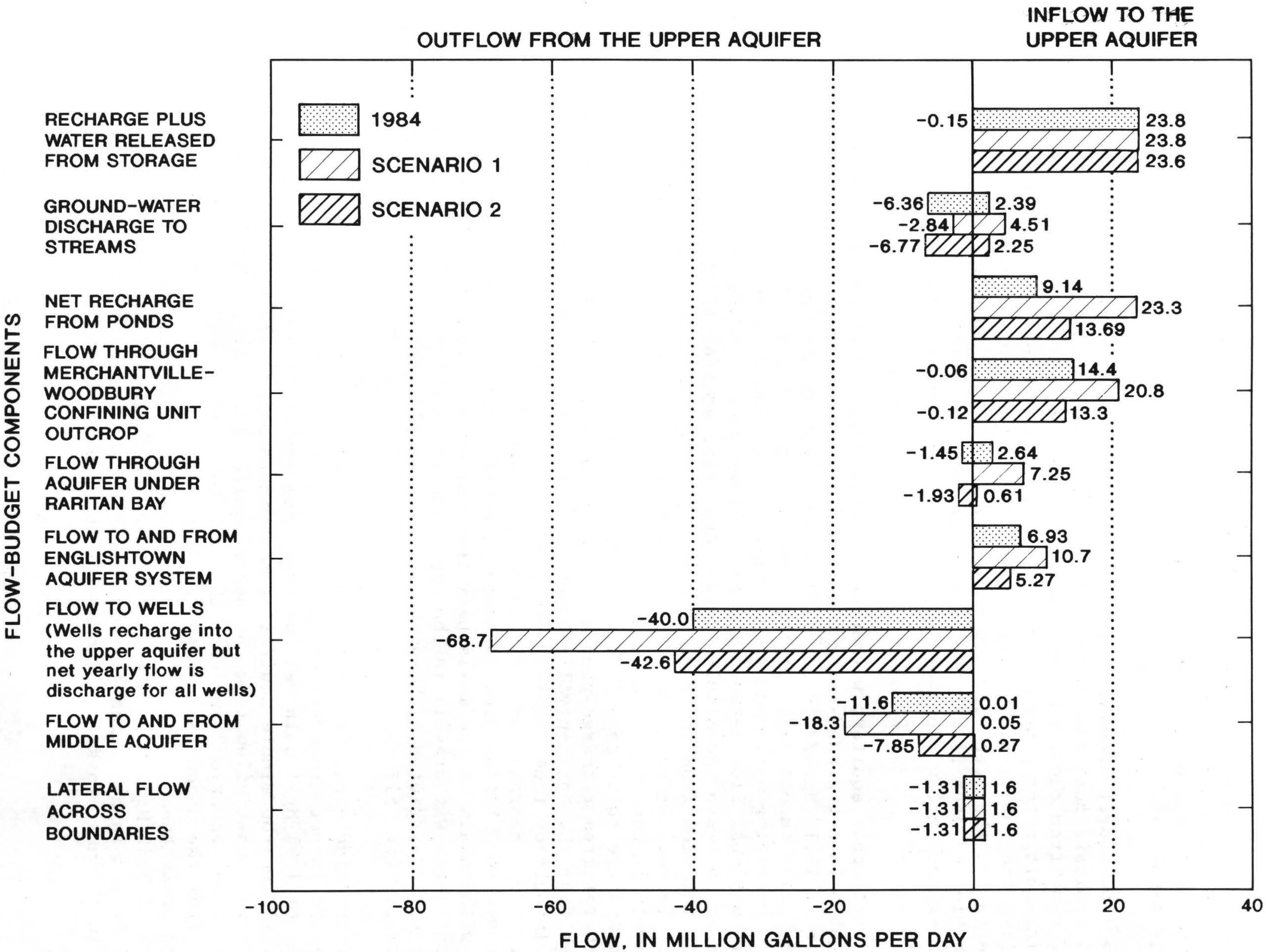


Figure 53.--Flow budget for simulated ground-water flow in 2019 for scenarios 1 and 2 in the upper aquifer.

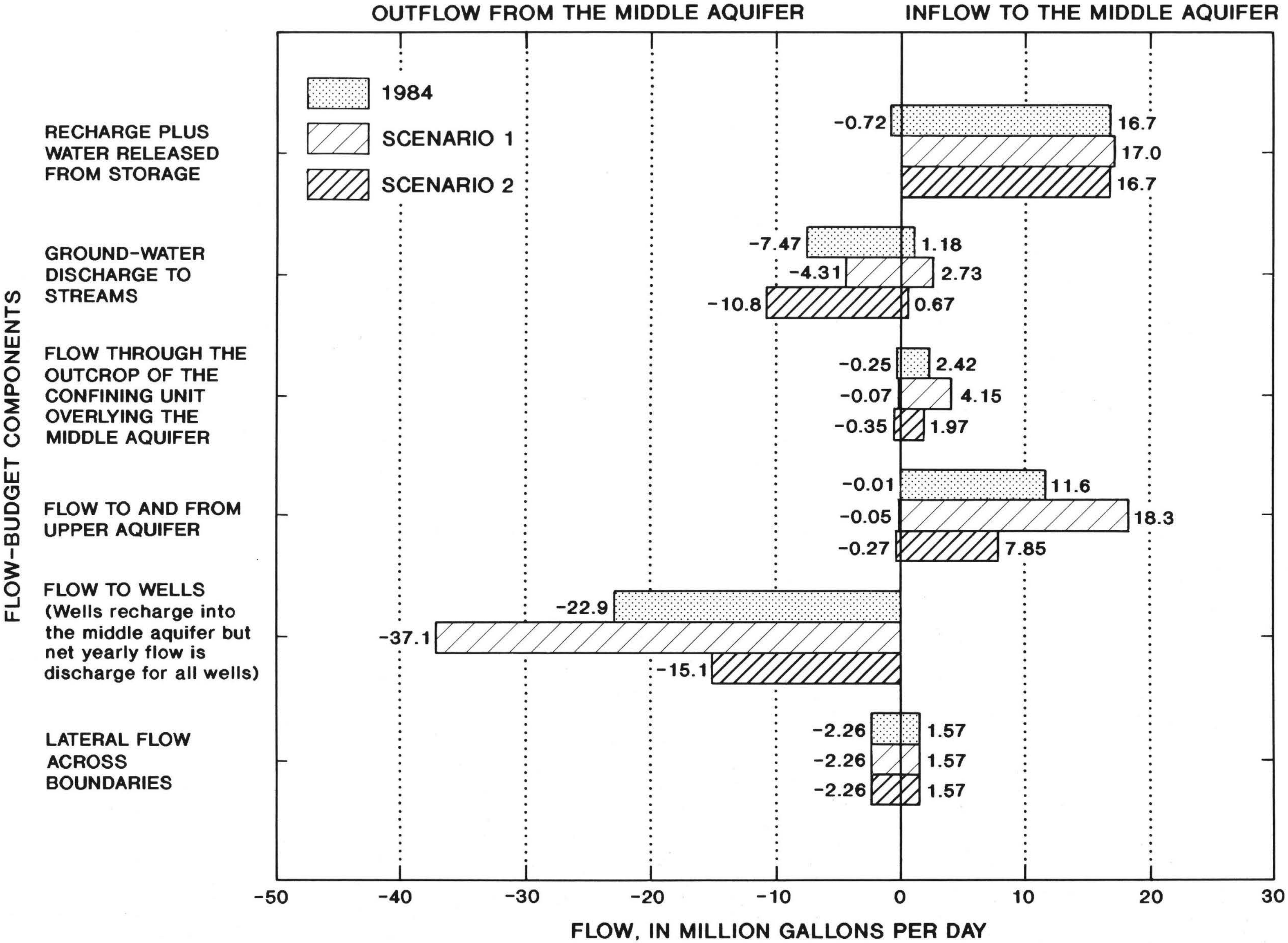


Figure 54.--Flow budget for simulated ground-water flow in 2019 for scenarios 1 and 2 in the middle aquifer.

form and deepen the Washington Canal in Sayreville has exposed the middle aquifer to direct contact with saltwater. Second, as discussed previously, increases in ground-water withdrawals have caused water levels in the aquifer system to decline below sea level, the direction of ground-water flow to reverse, and areas that were once ground-water discharge areas to become recharge areas in the estuarine regions of the Raritan and South Rivers and in Raritan Bay.

Significant saltwater intrusion has occurred in two areas of the Potomac-Raritan-Magothy aquifer system in the northern Coastal Plain of New Jersey. Saltwater intrusion first was detected in 1929 in the area of Sayreville and South River Boroughs and South Amboy City in Middlesex County (H.G. Fairbanks, U.S. Army Corps of Engineers, written commun., 1936). In the area of Keyport and Union Beach Boroughs, saltwater intrusion first was detected in the 1970's (Schaefer and Walker, 1981, p. 14-15). A chronology of the detection of saltwater intrusion is listed in appendix C.

In an effort to minimize saltwater intrusion into the middle aquifer, Barksdale (1937) and M.E. Johnson (New Jersey Geological Survey, written communs., 1925-40) proposed constraints on the development of the area's water resources. Johnson opposed the dredging of the alluvium from the channels of the Raritan River, the South River, and the Washington Canal because it would allow additional saltwater intrusion into the middle aquifer. Barksdale (1937) proposed limiting ground-water withdrawals from the middle and upper aquifers in this area to limit the recharge of saltwater into the ground-water system. The concerns of both investigators were incorporated into policies of restricted ground-water development adopted by the New Jersey Department of Environmental Protection and Energy (NJDEPE) in 1985. Both aquifers have been designated by the NJDEPE as "Critical Water Supply Areas" (Gaston, 1985).

The largest areas affected by saltwater intrusion in the confined part of the upper and middle aquifers are the areas of Union Beach and Keyport Boroughs, Monmouth County, and Sayreville Borough, Middlesex County. The movement of chloride is controlled by regional ground-water flow; as long as the potentiometric head remains below sea level, saltwater intrudes inland in response to the regional gradient and contaminates fresh ground-water supplies.

Saltwater intrusion is spatially uneven because of variations in the local hydrogeology and hydraulic gradients. This spatial unevenness is demonstrated by the chloride concentrations in water from several wells screened in the upper aquifer of the Potomac-Raritan-Magothy aquifer system near Raritan Bay (fig. 55). Factors that affect the direction and rate of saltwater migration include (1) the sources of saltwater; (2) aquifer properties that can cause local variations in flow; (3) the locations and rates of withdrawal at withdrawal centers, which vary with time; and (4) the mechanisms of convection (transport caused by density differences) and advection (transport and mixing processes caused by ground-water flow), which can vary in relative importance with location in the extent of the plume.

The following assessment of saltwater intrusion in each region includes a discussion of (1) the local hydrogeology in each area of saltwater intrusion; (2) the temporal and spatial change of the position of the saltwater plume; (3) the hydrologic processes that control the ground-water flow path and, therefore, the transport of saltwater in each location; and (4) the source area of the saltwater.

Keyport and Union Beach Boroughs

Schaefer and Walker (1981, fig. 6) reported that saltwater was moving into the upper aquifer east of Keyport Harbor and south of Conaskonk Point in Union Beach Borough. They reported a rapid increase in chloride concentrations in wells in this area from background concentrations of less than 5 mg/L to concentrations in excess of 660 mg/L from 1970 through 1977 (Schaefer and Walker, 1981, p. 14). This increase in chloride concentrations led to the abandonment of Keyport Borough Water Department wells 1, 4, 5, and 6 (located near well 25-207 at the shore of Raritan Bay) in the Keyport Borough Myrtle Avenue well field and the Union Beach Department number 1 and number 2 wells (located at the well 25-420 site) screened in the upper aquifer (fig. 55). Although withdrawals were stopped in 1977, the increases in chloride concentrations continued through 1986. For example, although the Union Beach Water Department well number 2 (25-420) is no longer used for production, chloride concentrations in water sampled from the well were 1,700 mg/L in 1983 (Bauersfeld and others, 1984, p. 319) and 2,800 mg/L in 1986 (appendix D; as shown in fig. 55).

Water levels in well 25-206 (fig. 56) have responded to the decreased ground-water withdrawals caused by the saltwater intrusion in this area. The water levels remain below sea level because of regional withdrawals farther from the immediate area of saltwater intrusion. Because the water levels remain below sea level, some landward migration of seawater probably will continue and will cause an increase in chloride concentrations in water in wells in the area.

Sources and Intrusion Factors

Locating the source areas of saltwater intrusion of the upper aquifer in Raritan Bay will help in the understanding of processes that control saltwater intrusion in this area. Possible source areas are (1) a submerged outcrop of the upper aquifer, hydraulically well-connected to the Potomac-Raritan-Magothy aquifer system in Raritan Bay; (2) a breach of the Merchantville-Woodbury confining unit overlying the upper aquifer (Woodbury Clay and Merchantville Formation) near Keyport and Union Beach Boroughs in Raritan Bay; (3) leaky areas in the Merchantville-Woodbury confining-unit beneath Raritan Bay; and (4) a combination of these pathways. Schaefer and Walker (1981, p. 18) concluded that contamination was not caused by migration of saltwater through abandoned, unsealed wells or from excavation of the Merchantville-Woodbury confining unit in the area.

A review of reports on the hydrogeology of the area did not reveal any previous identification of a submerged outcrop (Pucci, 1986). Schaefer and Walker (1981, p. 19) considered lateral movement of saltwater through a submerged outcrop to be the best explanation for saltwater intrusion in the area. Their explanation was based on geologists' and geophysical logs of

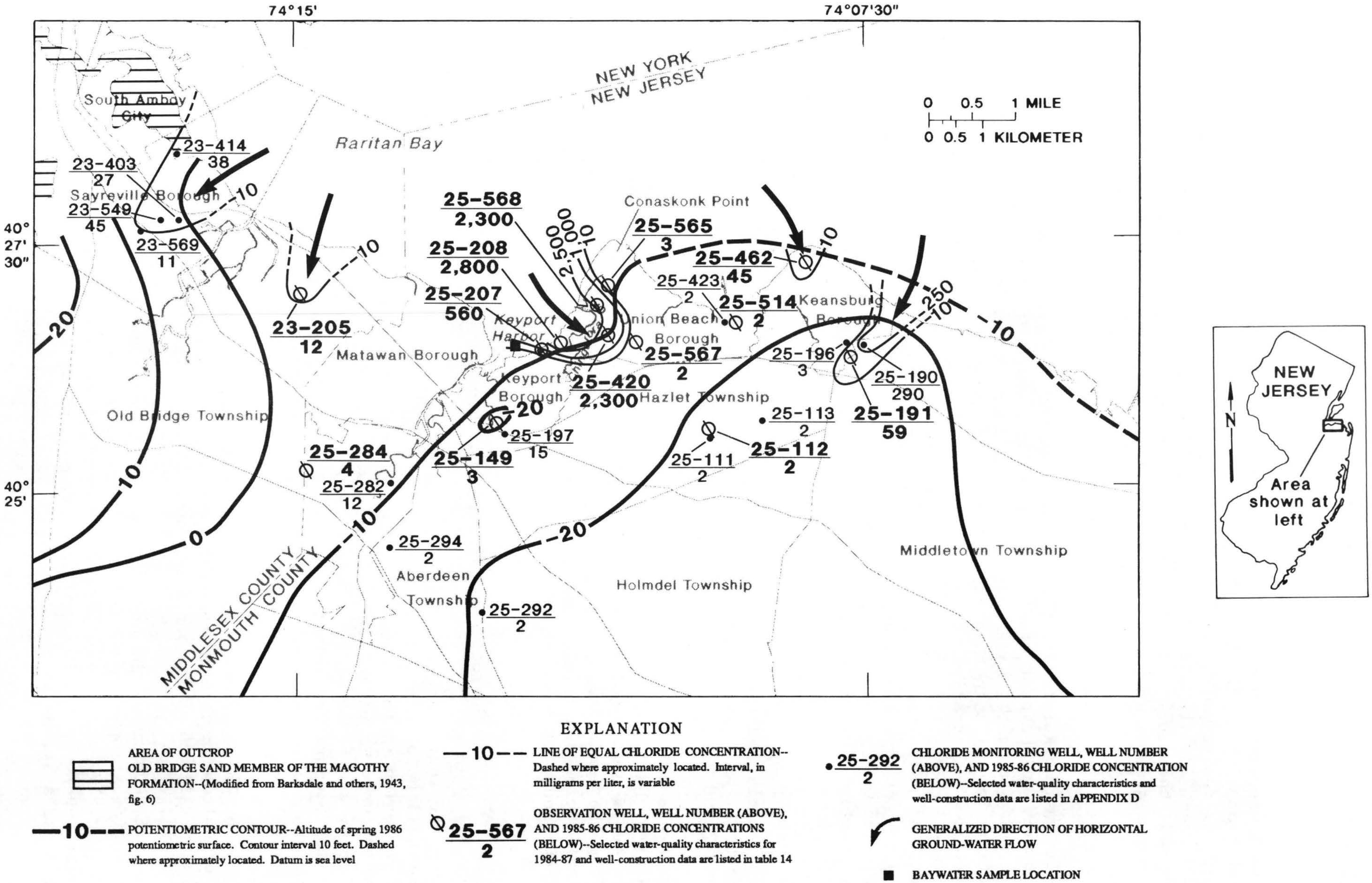


Figure 55.--Well locations, chloride concentrations in 1985-86, and potentiometric surface in spring 1986 in the upper aquifer in and near Keyport and Union Beach Boroughs.

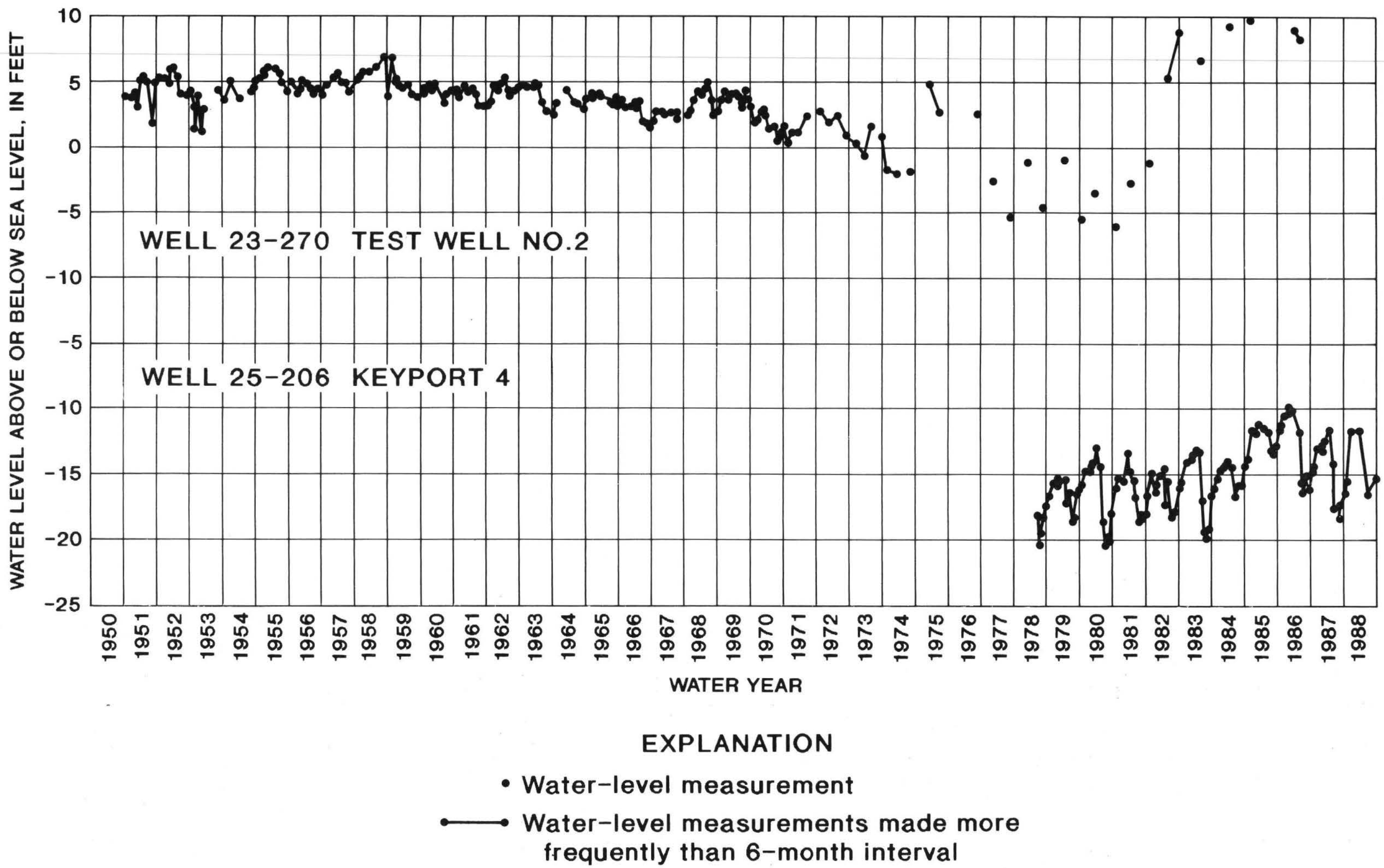


Figure 56.--Water levels in well 23-270, screened in the middle aquifer, and well 25-206, screened in the upper aquifer. (Locations of wells shown in fig. 22)

wells in Middlesex and Monmouth Counties. They did not define the location of the submerged outcrop in Raritan Bay, although it presumably was several miles from Keyport and Union Beach Boroughs.

Pucci and Murashige (1987, p. 673) analyzed trends in the structural surface of the upper aquifer from available well-log data but could not confidently estimate the location of the upper-aquifer outcrop beneath Raritan Bay. This analysis led to the marine seismic data-collection program in Raritan Bay discussed earlier (Declercq, 1986).

Understanding the mechanism of saltwater intrusion has also been complicated by the relatively short period between the major development of the ground-water resources of the area (around 1950) and the formation of the major cone of depression (pls. 1a and 1b) and the first observation of saltwater intrusion in the area (1970). The regional trend of the surface of the upper aquifer (fig. 4) indicates that the area of the submerged outcrop of the upper aquifer, as proposed by Schaefer and Walker (1981, p. 16), probably was several miles from Keyport and Union Beach Boroughs. Migration of saltwater over such a distance during 1950-70 is unlikely.

Data-Collection Programs and Results

Investigation of saltwater intrusion indicates that the most likely cause is the hydraulic gradient created by pumping at the withdrawal centers. Intrusion occurs as the freshwater-saltwater interface migrates toward the withdrawal centers. All observed data for this area indicate that the freshwater-saltwater interface in the upper aquifer probably was beneath Raritan Bay before ground-water withdrawals began (Declercq, 1986).

Several data-collection programs were conducted from 1984 through 1986 to determine the mechanism of saltwater intrusion in the area. These programs included a test-drilling program, an aquifer test, a marine seismic-reflection investigation, and collection of water-quality data. In addition, the location of a freshwater-saltwater interface in the upper aquifer was examined by the use of a steady-state ground-water flow model.

Test drilling

A test borehole (25-565, table 3, and fig. 55) was drilled in 1985 on Conaskonk Point at the Bay Shore Regional Sewer Authority plant in Union Beach Borough. The borehole is about 0.4 mi from the Raritan Bay shore, and about 100 ft from a marshy drainage area that is submerged at extremely high tides. The borehole was drilled 555 ft to bedrock, and the well was screened in the upper aquifer from 201 to 211 ft below land surface. The natural-gamma and electrical-resistivity logs (fig. 57) and lithologic descriptions indicate that the confining unit overlying the upper aquifer is about 200 ft thick. Sediments of the Merchantville Formation crop out at the surface at Conaskonk Point (Lyttle and Epstein, 1987). Logs of this test borehole (25-565) at Conaskonk Point and observation wells (25-568) near Chingorora Creek in Union Beach Borough and at the Union Beach Water Tower site (25-567) show no evidence that the confining unit had been breached by postdepositional erosion of the Merchantville-Woodbury confining unit overlying the upper aquifer (fig. 57). Furthermore, the logs for these three test holes indicate that the sediments overlying the upper aquifer are primarily clayey and silty sands throughout this area (Gronberg and others, 1989).

Aquifer test

In April 1986, a 6-day aquifer test (table 4) was done in the area of saltwater intrusion in Keyport and Union Beach Boroughs (Pucci and others, 1988). One of the reasons for the aquifer test was to determine whether a breach existed in the Merchantville-Woodbury confining unit overlying the upper aquifer in Raritan Bay near Keyport and Union Beach Boroughs. Such a breach could potentially act as a hydraulic conduit for saltwater migration in the direction of the Union Beach Water Department well field and the Keyport Water Department well field at Myrtle Ave. Two production wells (25-419 and 25-420) at the Union Beach Water Department plant were pumped for 3 days at a combined rate of 1,375 gal/min and allowed to recover for 3 days. During the test, water levels were measured in 11 observation wells located as far as 1.6 mi from the pumped wells. All wells used in the aquifer test were screened in the upper aquifer.

A breach of the confining unit overlying the upper aquifer beneath Raritan Bay would have affected drawdowns during the aquifer test (Pucci and others, 1988) by acting as a direct-recharge boundary, and it would have diminished the magnitude of water-level declines in the observation wells during the test period. Because these effects were not observed, it is unlikely that a breach in the confining unit exists under Raritan Bay within about 1 mi of the shore.

The water pumped from production well 25-420 was sampled during the aquifer test at Union Beach. Chloride concentrations decreased uniformly from 2,100 mg/L 30 minutes after the start of the test on April 22, 1986, to 1,800 mg/L 72 hours later, on April 25, 1986 (Harriman and others, 1989). If the chloride concentration in bay water is assumed to be 13,000 mg/L (table 14) and the background chloride concentration in the aquifer is assumed to be less than 5 mg/L (Schaefer, 1983, p. 2), then 16 percent of well water at the start of the test was derived from the bay, and 14 percent of well water at the end of the test was derived from the bay. Changes in water chemistry were attributed to the mixing of saltwater with fresh ground water that could have been derived from either freshwater flow from the aquifer or leakage from the confining unit.

Marine seismic-reflection investigation

A marine seismic-reflection investigation was done in 1984 to determine the location of a submerged outcrop of the upper aquifer beneath the northern part of Raritan Bay (Declercq, 1986). No evidence was found of any breach or discontinuity in the Merchantville-Woodbury confining unit overlying the upper aquifer near Conaskonk Point, New Jersey, or between the point and Sanguine Point, Staten Island, New York (fig. 4) (Declercq, 1986). Declercq (1986) and Gronberg and others (1991) concluded that the outcrop of the upper aquifer is submerged in Raritan Bay near Staten Island.

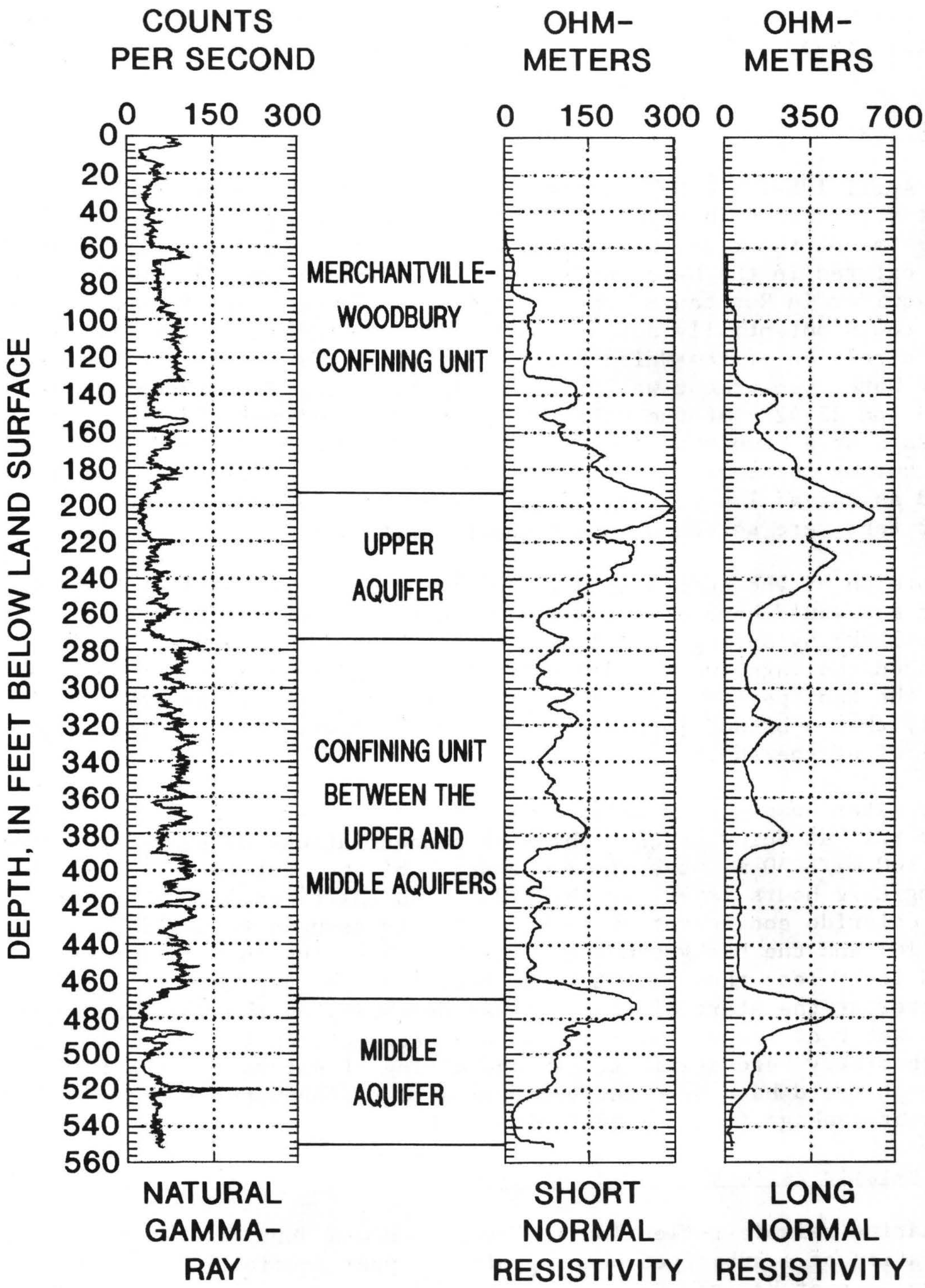


Figure 57.--Natural-gamma and electrical-resistivity logs of test borehole 25-565. (Location of borehole shown in fig. 55)

Other known hydrogeologic features beneath parts of the northern side of Raritan Bay that could cause hydraulic connections with the salty bay water are (1) paleochannel incision of the confining unit overlying the upper aquifer or (2) Holocene sands that directly overlie sands of the Magothy Formation in the eastern part of Raritan Bay.

Ground-water sampling

During 1984-87 chloride concentrations in water samples from the following observation wells were measured in or near the saltwater plume: 25-565, at Conaskonk Point; 25-568, near Chingorora Creek in Union; 25-420, Union Beach production well number 2; 25-567, at the Union Beach Water Tower; and 25-208, at Inferno-therm, Inc., near the shore of Raritan Bay in the western part of Union Beach Borough (table 14 and appendix D). The chloride concentration in well 25-565 (Conaskonk Point observation well), which is screened in the upper 10 ft of the aquifer, was 2.5 mg/L, which is considered to be background concentration. No evidence of dense, saline water in the aquifer below the screen was inferred in the interpretation of the electrical-resistivity logs of the well (fig. 57). A measured chloride concentration of 1.8 mg/L at the Union Beach Water Tower observation well (25-567) also indicates a background concentration of chloride. The chloride concentration was 2,300 mg/L at the Union Beach Water Department Number 2 well (25-420), about 1,700 ft west of the water tower. The chloride concentration at the well near Chingorora Creek (25-568) was 2,300 mg/L in 1986, about the same as the chloride concentration in the Union Beach Water Department number 2 well (25-420). The maximum chloride concentration measured in this area was 2,800 mg/L in 1986 at Inferno-therm 1 well (25-208). Contours of the chloride concentrations in these wells show that the saltwater plume is migrating from Keyport Harbor toward Union Beach Borough. This conclusion is consistent with measured chloride concentrations in water samples from the Union Beach Water Department number 2 well, which increased from about 660 mg/L in 1977 (Schaefer and Walker, 1981) to 2,100 mg/L in 1986.

On the basis of the orientation of the cone of depression in the area of Keyport Borough and Union Beach Borough through time (figs. 9 and 10; and pls. 1 and 2), the chloride plume is oriented from Keyport Harbor eastward toward the major withdrawal centers near the shore--the Keyport Borough Water Department's Myrtle Avenue well field and the Union Beach Water Department well field. A comparison of the location of the 10-mg/L chloride-concentration contour for 1977 (Schaefer and Walker, 1981, fig. 6) and for 1984-87 (fig. 55, appendix D) indicates little or no southward movement of the plume. The background-level chloride concentrations at the Conaskonk Point observation well (25-565) and the Union Beach Water Tower observation well (25-567) (table 14) indicate that the saltwater migration proceeded most rapidly toward a narrow area near these withdrawal centers.

Another recent and locally distinct increase in chloride concentration is at the Keansburg Water Department well number 4 (25-190) (fig. 55, appendix D). Chloride concentrations in water from this well increased from 2.0 mg/L in 1977 to 120 mg/L in 1983 and to 290 mg/L in 1986, as noted in appendix D (Harriman and others, 1988). Keansburg Water Department well number 4 was shut down from production in February 1987 because of chloride contamination (James Davis, Keansburg Municipal Utility Authority, oral

Table 14.--Representative analyses of ground-water samples from the upper aquifer in and near the area of saltwater intrusion in Keyport and Union Beach Boroughs, 1984-87

[All constituents are dissolved; concentrations in milligrams per liter (milliequivalents per liter in parentheses; see footnote 2) unless otherwise noted; µg/L, micrograms per liter; --, data unavailable; "<", less than; locations of all wells shown in figure 55; MUA, Municipal Utility Authority; WD, Water Department; NA, not applicable]

Well no. (trilinear diagram no. in fig. 59)	Owner	Local identifier	Year drilled	Screened interval[1] (feet)	Sample date	Calcium	Magnesium	Sodium	Potassium
23-205 (13)	Old Bridge MUA	Lawrence Harbor #8	1948	193-213	10/24/84	1.1 (0.06)	1.0 (0.08)	2.9 (0.13)	0
25-112 (2)	Shorelands WC Inc.	Shorelands W.C. Hazlet-2	1960	312-352	10/30/84	2.6 (.13)	1.6 (.13)	1.4 (.06)	0
25-191 (3)	Keansburg WD	Keansberg WD #6	1968	302-362	10/31/84	7.1 (.35)	4.2 (.35)	8.9 (.39)	0
25-199 (4)	Kerr Glass Co.	Kerr Glass Co.	1964	285-315	10/25/84	7.1 (.35)	4.2 (.34)	8.9 (.387)	0
25-207 (5)	Keyport Borough WD	Keyport 6	1970	247-277	04/18/86	44.0 (2.19)	28.0 (2.30)	140.0 (6.1)	4.0 (.10)
25-208 (6)	Infern-o-therm Inc.	Infern-o-1	--	-- - 300	04/16/86	160.0 (7.98)	120.0 (9.87)	910.0 (22.18)	6.7 (.171)
25-284 (14)	Matawan Borough WD	Matawan Boro WD #3	1956	231-271	10/23/84	2.2 (.11)	1.5 (.12)	1.8 (.08)	0
25-420 (7)	Union Beach WD	Union Beach WD 2 1969	1969	235-285	04/22/86	110.0 (5.49)	83.0 (6.83)	840.0 (36.54)	9.2 (.235)
25-462 (8)	Keansburg Amusement Pk	1-69	1969	200-250	08/07/85	7.0 (.35)	4.2 (.35)	7.6 (.33)	2.3 (.06)
25-514 (9)	Int. Flavor Frag., Inc.	IFF-2R	1983	266-312	10/31/84	2.5 (.125)	1.6 (.13)	1.3 (.06)	0
25-565 (1)	USGS	Conaskonk Point	1985	201-211	04/23/87	4.3 (.215)	1.7 (.14)	3.0 (.13)	1.3 (.03)
25-567 (10)	USGS	Union Beach Water Tower	1986	250-270	07/15/86	4.4 (.220)	1.5 (.123)	4.8 (.209)	1.3 (.033)
25-568 (11)	USGS	JCP&L Union Beach	1986	245-265	04/15/86	100 (4.99)	78.0 (6.42)	840.0 (36.54)	7.8 (.2)
Baywater (12)	NA	Raritan Bay	NA	NA	11/05/86	250 (12.4)	820.0 (67.5)	6,200.0 (269.7)	230.0 (5.88)

[1] Depth below land surface

[2] Conversions to milliequivalents can be found in Hem (1985, table 9).

[3] Field specific conductance in microsiemens per centimeter at 25 degrees Celsius.

Table 14.--Representative analyses of ground-water samples from the upper aquifer in and near the area of saltwater intrusion in Keyport and Union Beach Boroughs, 1984-87--Continued

Well number	Bicarbonate	Alkalinity (mg/L as $CaCO_3$)	Sulfate	Chloride	Solids dissolved	Specific conductance[3]	Field pH (units)	Lead (µg/L)	Cadmium (µg/L)
23-205	1.22 (.02)	1.0	14.00 (.29)	8.7	--	66	4.7	20	<1
25-112	9.8 (.16)	8.0	9.2 (.19)	1.6 (.04)	--	67	6.0	<10	<1
25-191	1.22 (.02)	1.0	16.0 (.33)	44.0 (2.14)	--	--	6.1	30	2
25-199	3.7 (.06)	3.0	16.0 (.33)	3.2 (.09)	--	74	5.9	20	<1
25-207	41.4 (.68)	34.0	66.0 (1.37)	500.0 (14.1)	896	1,680	6.6	30	12
25-208	25.6 (.42)	21.0	350.0 (7.28)	2,500.0 (70.52)	4,170	7,350	5.7	130	56
25-284	1.22 (.02)	1.0	15.0 (.31)	3.9 (.11)	--	72	5.7	<10	<1
25-420	13.4 (.22)	11.0	270.0 (5.62)	2,100.0 (59.24)	3,670	6,000	5.7	90	23
25-462	24.38 (.40)	20.0	14.0 (.29)	45.0	--	215	6.0	10	<1
25-514	9.75 (.16)	8.0	7.7 (.16)	1.6 (.04)	--	49	5.7	<10	<1
25-565	34.0 (.56)	28.0	8.4 (.17)	2.5 (.07)	59	60	6.2	--	--
25-567	34.0 (.557)	28.0	19.0 (.396)	1.8 (.051)	66	67	6.1	--	--
25-568	13.4 (.22)	11.0	290.0 (6.03)	2,000.0 (56.42)	3,420	6,850	5.6	<50	42
Baywater	122.0 (2.0)	101.0	1,900.0 (39.6)	13,000.0 (366.7)	22,000	35,300	8.0	--	--

commun., 1989). In 1986, chloride concentrations as high as 59 mg/L were measured in Keansburg Water Department well number 6 (25-191), which is less than 0.25 mi south-southwest of well 25-190. In 1986, the chloride concentration at Keansburg Water Department well number 3 (25-196), about 0.5 mi northwest of well 25-190, was near background (2.7 mg/L).

Chloride concentrations in upper aquifer wells are also increasing in other areas near Union Beach and Keyport Boroughs, but chloride contamination has not yet resulted in well shutdowns (fig. 55 and appendix D). The chloride concentration at Keansburg Amusement Park Well number 1 (25-462), about 3 mi northwest of the Keansburg Water Department well field and near the shore of Raritan Bay, was 45 mg/L on August 7, 1985; this concentration represents a sudden increase over several previous measurements (appendix D). In the northeastern part of Sayreville Borough near Raritan Bay, the chloride concentrations in water from Sayreville Borough Water Department wells Q-1973 (23-403) and R-80 (23-549) and South Amboy City Water Department well number 10 (23-414) at the end of the period 1983-86 were about twice the concentrations at the beginning of the period; the maximum was 45 mg/L, at Sayreville Borough well R-80 in 1986. Chloride concentrations were slightly above background (8-12 mg/L) but not increasing during this period at Sayreville Borough Water Department well T-82 (23-569) and at Old Bridge Municipal Utility Authority Lawrence Harbor 8 well (23-205).

The proximity of large withdrawal centers and the regional freshwater-saltwater interface to the coast has significant implications for the movement of saltwater into the areas of Keyport and Union Beach Boroughs and Keansburg Borough, where chloride contamination has already caused well shutdowns. The rate of migration is proportional to the hydraulic gradient, which is steepest near the center of a cone of depression. A cone of depression near the coast, therefore, has a greater effect on the movement of the freshwater-saltwater interface than does a cone of depression farther inland.

The inland extent of saltwater intrusion at (1) Keyport and Union Beach Boroughs, (2) Keansburg Borough, (3) Keansbury Amusement Park, (4) Northeastern Sayreville Borough, and (5) Northeastern Old Bridge Township forms an irregular pattern along the shore of Raritan Bay. These reaches are "fingers of saltwater" that protrude from a relatively continuous regional freshwater-saltwater interface and are drawn toward the centers of large ground-water withdrawal (fig. 55). These fingers moved most rapidly toward the well fields nearest the regional freshwater-saltwater interface in the Boroughs of Keyport and Union Beach during the 1950's and 1960's. Movement toward the Keansburg Borough well field probably is a separate saltwater finger that persists as a result of past and current withdrawals. Recent increases in chloride concentration in Keansburg Borough Water Department wells (wells 25-190 and 25-196) and the distribution of chloride concentrations in this region during 1985-86 confirm this interpretation.

The increase in chloride concentrations over time in northeastern Sayreville Borough seems, at first, to be problematic because the potentiometric surface for fall 1984 (pl. 1a) and spring 1986 (fig. 55) in this area is above sea level; however, the potentiometric contours in this area are based on measurements made in one well (23-408) after water levels were allowed to recover. The actual location of the zero contour of the potentiometric surface, therefore, likely moves farther landward during pumping, which indicates that saltwater flows from Raritan Bay toward these wells during pumping. Chloride concentrations at Keansburg Amusement Park well (25-462) and Old Bridge Municipal Utility Authority Lawrence Harbor well (23-205) correspond to heads that were below sea level in the spring of 1986 (fig. 55).

Steady-State Simulation of Freshwater-Saltwater Interface

As reported for many coastal aquifer systems that are hydraulically connected to seawater (Piper and others, 1953; Cooper, 1959; Counts and Donsky, 1963; Witherspoon and others, 1971; Reilly and Goodman, 1984; Atkinson and others, 1986), saltwater probably was present in the upper aquifer, either nearshore or offshore beneath Raritan Bay, before any ground water was withdrawn from the aquifer in this area. Beneath the bay, part of the aquifer system consists of the confined area of middle aquifer (fig. 14) and the unconfined and confined areas of the upper aquifer (fig. 4). The flow path, C-C′, through Keyport and Union Beach Boroughs in figure 8 shows that the predevelopment potentiometric surface of the upper aquifer sloped toward Raritan Bay. Freshwater directly recharged the upper aquifer on land in unconfined areas or leaked through confining units and then moved down the hydraulic gradient and discharged to the bay. In areas where the upper aquifer is connected hydraulically to Raritan Bay, seawater flows into the upper aquifer because of head gradients and because the density of saltwater is greater than that of freshwater.

By processes described in Cooper (1959) and Frind (1980), saltwater that enters the submerged outcrop either displaces freshwater upward or moves into the confined part of the upper aquifer beneath Raritan Bay. Where freshwater and saltwater are in contact, a transition zone, or freshwater-saltwater interface, is created. The circulation of freshwater and saltwater toward the interface, as illustrated in figure 58 (location shown in fig. 8), causes mixing of freshwater and seawater by mechanical dispersion (Cooper, 1959; Henry, 1964, p. 464). The mixed water in the transition zone also is less dense than seawater; therefore, it is displaced upward along with freshwater and is discharged through the top of the aquifer. Additional saltwater continually moves into the aquifer from the submerged outcrop and causes a recirculation pattern on the saltwater side of the transition zone. The recirculation is necessary to maintain a state of hydrodynamic equilibrium in the ground-water flow system (Henry, 1964; Frind, 1980, p. 2.178).

If the flow of freshwater into the system is constant, a stable dynamic equilibrium is reached in the ground-water system. In this state, the total flow from the landward and seaward sides, plus leakage influx to the upper aquifer from the middle aquifer, is balanced by the upward leakage to the bay (fig. 58). Freshwater flow is toward the bay and prevents the advance of seawater. The confining unit is a route for freshwater discharge, and the area required to accommodate this discharge is determined by the hydraulic properties of the confining unit which, in turn, affect the distribution of head and saltwater in the aquifer and the location of the transition from freshwater to saltwater.

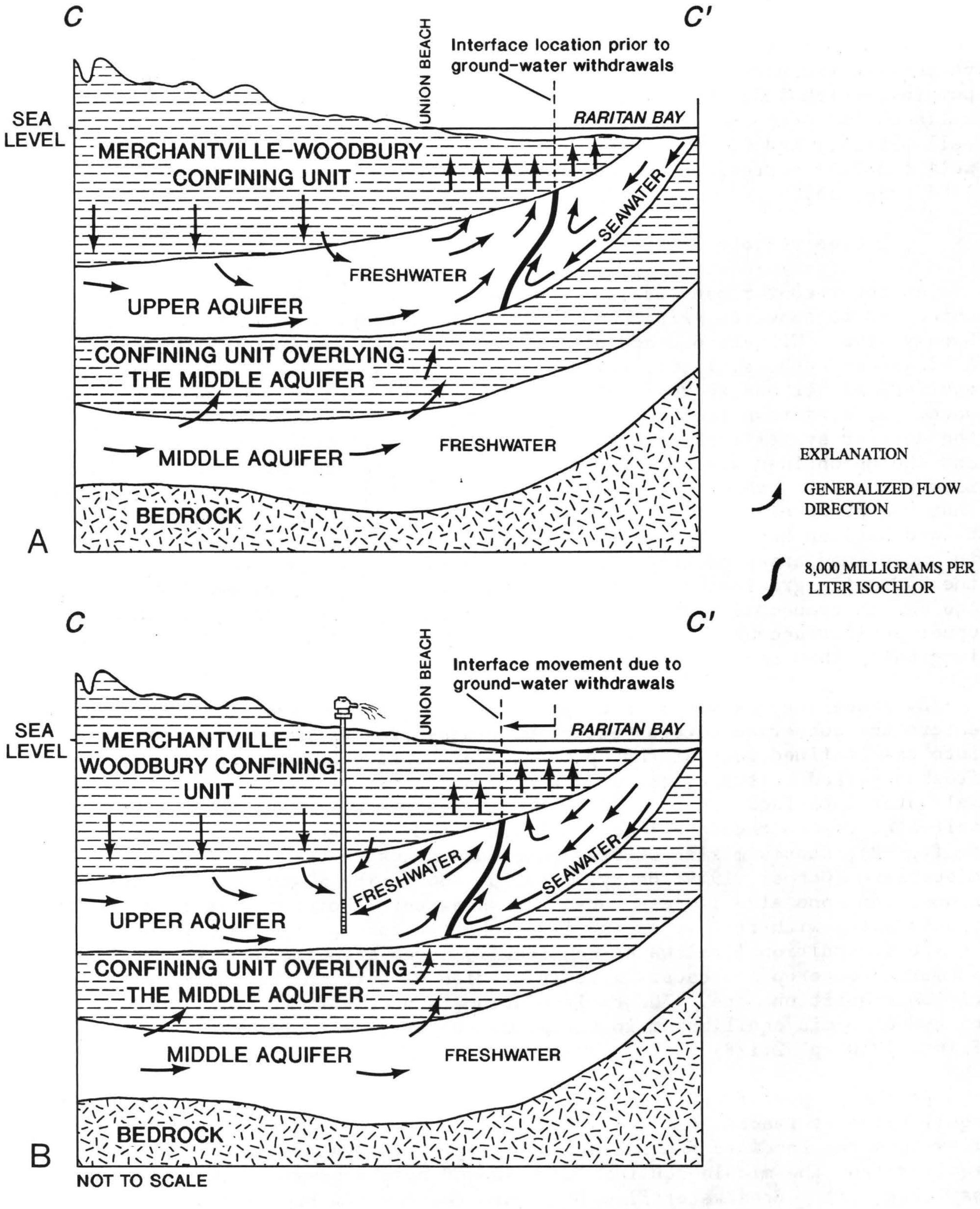


Figure 58.--Diagrammatic section along flow path C-C′ showing generalized hydrogeology in the Raritan Bay area and idealized flow directions (a) before development and (b) after large withdrawals. (Modified from Declerq, 1986. Location of flow line C-C′, shown in fig. 8)

A hypothetical analysis of the location of a sharp freshwater-saltwater interface in the upper aquifer near Keyport and Union Beach Boroughs for the predevelopment period was done by use of a cross-sectional, two-dimensional steady-state flow model (Declercq, 1986). The location of the cross-sectional model coincides with the predevelopment flow path shown in figure 8 and represents the hydraulic interaction of the upper aquifer, the Merchantville-Woodbury confining unit, and Raritan Bay (fig. 58). The ground-water system was assumed to consist of a steady-state freshwater flow field separated from static saltwater by a sharp interface. As shown by the results of simulating the predevelopment-period ground-water system discussed earlier in this report, some leakage probably occurs through the confining unit between the middle aquifer and the upper aquifer beneath the discharge area in Raritan Bay. This leakage was not considered by Declercq (1986); however, this additional flow does not alter qualitatively the description of the movement of the interface in this analysis.

Use of the sharp-interface method to infer the location of a freshwater-saltwater transition zone for areas of saltwater intrusion involves several simplifications (Guswa and LeBlanc, 1985, p. 9; Meisler and others, 1984, p. 7). The method does not simulate the recirculation of saltwater on the saline side of the transition zone, nor can it be used to estimate the width of the transition zone. The location of the sharp interface is approximately where saltwater concentrations are about 40 percent that of seawater, or where chloride concentrations are about 8,000 mg/L (Henry, 1964; Meisler and others, 1984, p. 8).

Declercq (1986) examined the variation in the location of the saltwater interface with respect to several factors, including recharge-boundary conditions, water-table altitudes, and the hydraulic properties of the Merchantville-Woodbury confining unit. Leakance of the overlying confining unit was found to be an important factor controlling the location of the freshwater-saltwater interface, as is typical in coastal aquifer systems (Frind, 1980). For simulations of the Merchantville-Woodbury confining unit overlying the upper aquifer beneath Raritan Bay a leakance of 6.0×10^{-5} (ft/d)/ft was used (Declercq, 1986), which is similar to the leakance reported earlier in this report (6.5×10^{-5} (ft/d)/ft) calculated from results of the aquifer test at Union Beach (table 4). Results of the simulations indicated that the freshwater-saltwater interface for predevelopment conditions in the upper aquifer was between 1.2 and 1.7 mi from the shore of Raritan Bay near Union Beach, along the line of the model cross section (fig. 8).

As described earlier, a cone of depression that still exists developed along the coast when ground-water withdrawals began in the upper aquifer (pl. 1a and 1b). These withdrawals reduce the flow of freshwater toward the freshwater-saltwater transition zone and thereby change the hydraulic equilibrium that controls the location of the freshwater-saltwater interface. As the volume of discharged freshwater is reduced and the area that is needed to discharge the freshwater is reduced, the transition zone moves closer to the freshwater source area and additional saltwater is induced to flow into the aquifer. As withdrawals continue or increase, saltwater continues to move toward the shore. When the potentiometric surface of the upper aquifer near the bay fell below sea level, freshwater discharge beneath the bay ceased, and saltwater moved into the confined terrestrial part of the aquifer beneath the shore. As withdrawals continue, the hydraulic gradient will continue to increase, and the freshwater-saltwater interface will continue to move toward the withdrawal centers.

Water Quality in and near the Saltwater Plume

Analyses of water-quality constituents from well samples within the saltwater plume in the area of Keyport and Union Beach Boroughs indicate that the aquifer water is a mixture of freshwater and saltwater; however, the chemical character of the salty ground water does not indicate a simple blend of saline and fresh ground water in all the wells. Instead, chemical reactions, principally ion exchange and mobilization of heavy metals, have occurred in response to changes in salinity (Meisler and others, 1984, p. 8). No comprehensive water-quality analyses for this area were done before 1984.

Chemical analyses of aquifer water done during 1984-86 show that the water quality within the saltwater plume is different from that in uncontaminated wells outside the plume (fig. 59, table 14). Bond (1987) indicates that the initial degradation of water quality can be observed from leakage through confining layers before lateral intrusion of seawater from offshore. However, the differences between water quality in and near the area of the saltwater plume do not seem to be caused by entry of water from confining-unit leakage; rather, the gradual changes in these water types are consistent with the dominant effect of mixing, represented by the arrows in figure 59. The trilinear diagram (fig. 59) indicates that the water types change progressively from native freshwater to bay water as the chloride concentration increases. Three distinctions in the characteristic water quality of these wells can be made: wells representative of native freshwater (wells 1, 2, 9, and 10 in fig. 59); wells in which chloride concentrations are greater than background, but which are outside the saltwater plume (wells 3, 4, 8, 13, and 14 in fig. 59); and wells within the plume (wells 5, 6, 7, and 11 in fig. 59). Although wells within the plume contain water that is similar in type to bay water, the chloride concentrations are much lower.

Conservative mixing curves show that the relation of selected ions to chloride concentrations within the plume is a function of mixing of freshwater and saltwater. Mixing curves were prepared by plotting various ion concentrations against chloride concentrations for several water samples from the area of the chloride plume. If the water chemistry resulted only from the mixing of native water with seawater, the data would define a linear plot as shown by the three solid lines in figure 60 (Meisler and others, 1984, p. 17). A linear trend in water samples is only apparent with the sulfate mixing curve (fig. 60). Although the sulfate concentrations fall below the conservative mixing curve, the quality of these water samples does not appear to be strongly affected by sulfate reduction. Calcium concentrations are higher than the mixing curve for all samples from within the plume (fig. 60), whereas magnesium concentrations are scattered about the mixing curve (fig. 60). Ion exchange of magnesium for calcium on exchange sites (base exchange) could cause calcium concentrations to plot above, and magnesium concentrations to plot below, the mixing curve (Meisler and others, 1984, p. 20).

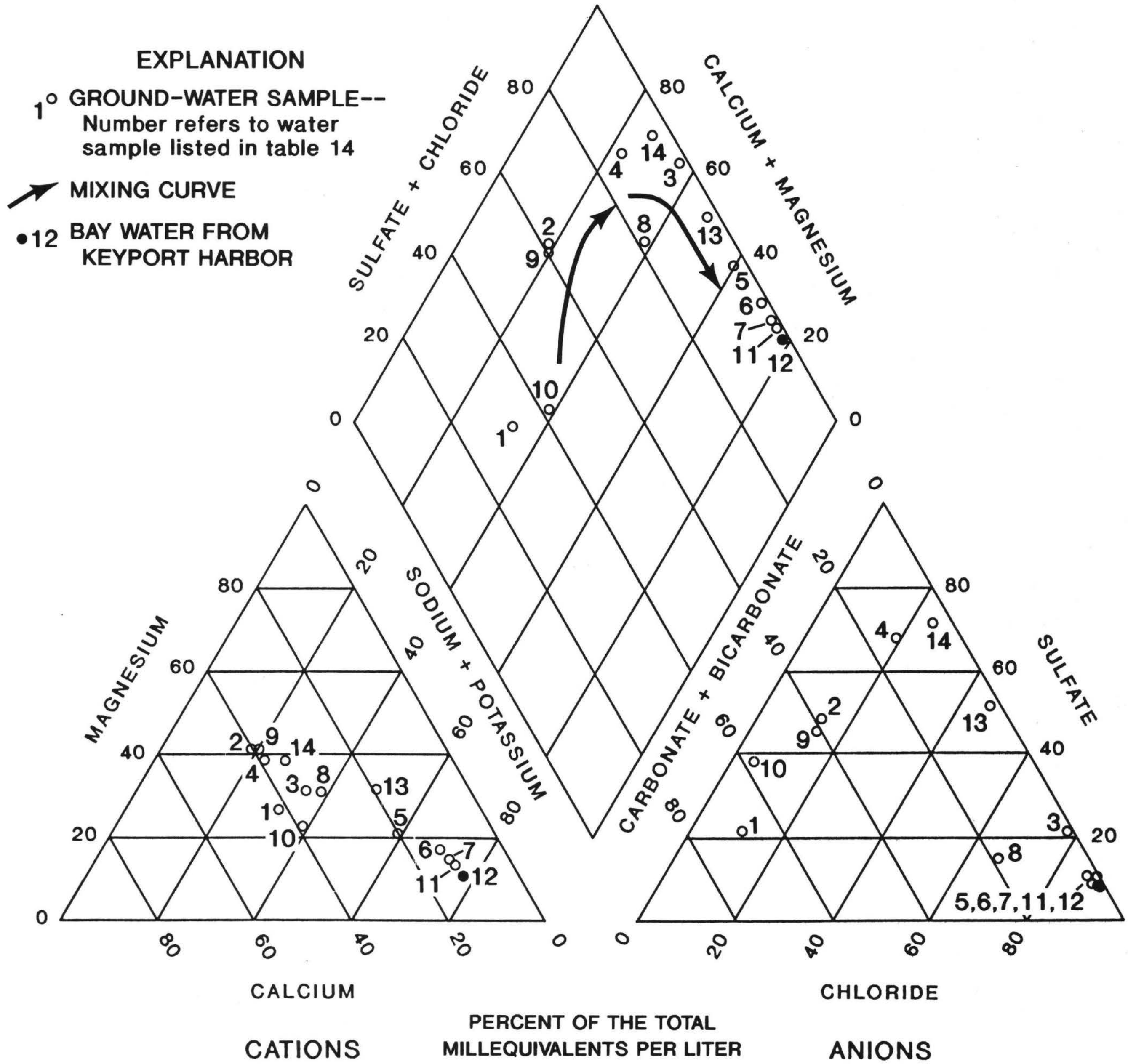


Figure 59.--Trilinear diagram showing ionic composition of water samples from the area of saltwater intrusion in and near Keyport and Union Beach Boroughs. (All ground-water samples are from the upper aquifer. Locations of sampled wells shown in fig. 55)

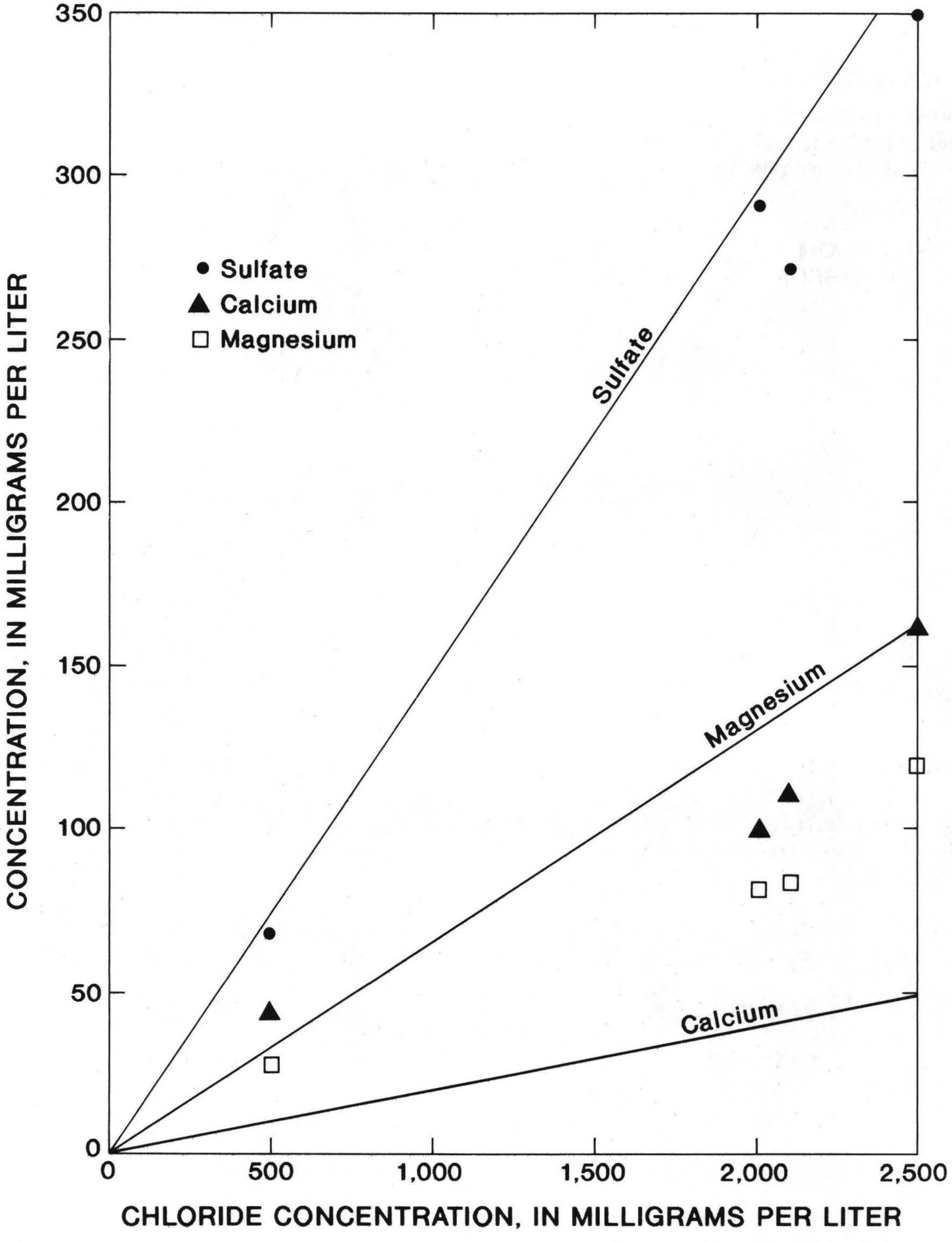


Figure 60 --Relation of sulfate, calcium, and magnesium concentrations to chloride concentrations in water samples from wells 25-207, 25-208, 25-420, and 25-568. (All wells are screened in the upper aquifer within the saltwater plume in Union Beach Borough. Well locations are shown in fig. 55; results of chemical analyses of water samples are listed in table 14)

Elevated lead and cadmium concentrations are primarily associated with wells that are within the saltwater plume (Pucci and others, 1989). Lead and cadmium are not found naturally at these concentrations in the New Jersey Coastal Plain. Maest and others (1984) and Maest and others (U.S. Geological Survey, written commun., 1989) reported concentrations of heavy metals in the benthic sediments of the estuarine Raritan River and its tributaries. The source of these metals are waste discharges from industrial plants that have been in this area since the 1800's. Some of the industrial discharges of metals could date to the early period before large ground-water withdrawals occurred and which, as discussed earlier, increased rapidly during World War I. Surface-water flow causes these sediments to be transported into Raritan Bay.

Maest and others (1984) reported that concentrations of lead and cadmium were much higher in the anoxic, ion-rich environment of the bottom sediments than in surface waters. Although concentrations of lead and cadmium in surface waters are not detected, Maest and others (U.S. Geological Survey, written commun., 1989) reported that water extracted from bottom sediments in the Raritan River estuary in this area contains lead and cadmium in concentrations of up to 2.5 μg/L (micrograms per liter) and 0.56 μg/L, respectively; the bottom sediments of the estuary are reported to contain lead and cadmium concentrations of 248 mg/kg (milligrams per kilogram) and up to 3.9 mg/kg, respectively (Maest and others, 1984). Extrapolation of lead concentrations to the source location beneath the bay (at a time when lead concentrations could have been elevated) indicates that lead concentrations could be as high as 680 μg/L (0.68 mg/L) where contaminated water enters the aquifer. This extrapolation is based on a simple dilution of bay-water chloride concentration (13,000 mg/L) to the chloride concentration in well 25-208 measured in 1984 (2,500 mg/L) with a lead concentration of 130 μg/L in the well. The association of lead and cadmium with saltwater in the area of saltwater intrusion indicates that these heavy metals are transported with the saltwater from the same source area--the area where the upper aquifer is connected hydraulically to the bottom of Raritan Bay.

The hydrodynamic processes that control the movement of chloride in the aquifer also control the movement of the dissolved lead and cadmium within the aquifer, if it is assumed that conditions promote dissolution (Pucci and others, 1989). Recirculation moves saltwater from the bay to the freshwater-saltwater interface. Because saltwater recirculated even before the effects of withdrawals caused the saltwater intrusion in this area, mobilization of lead and cadmium with recirculating saltwater to the freshwater-saltwater interface could have occurred at any time that these heavy metals were solubilized and mobilized from the bay-bottom sediments. Then the dissolved metals moved with the plume, undergoing dilution in proportion to chloride dilution. Although this mechanism cannot be tested directly by reference to historical data, it is a viable mechanism to explain the anomalous heavy-metal concentrations associated with the saltwater plume in the area.

Sayreville Borough

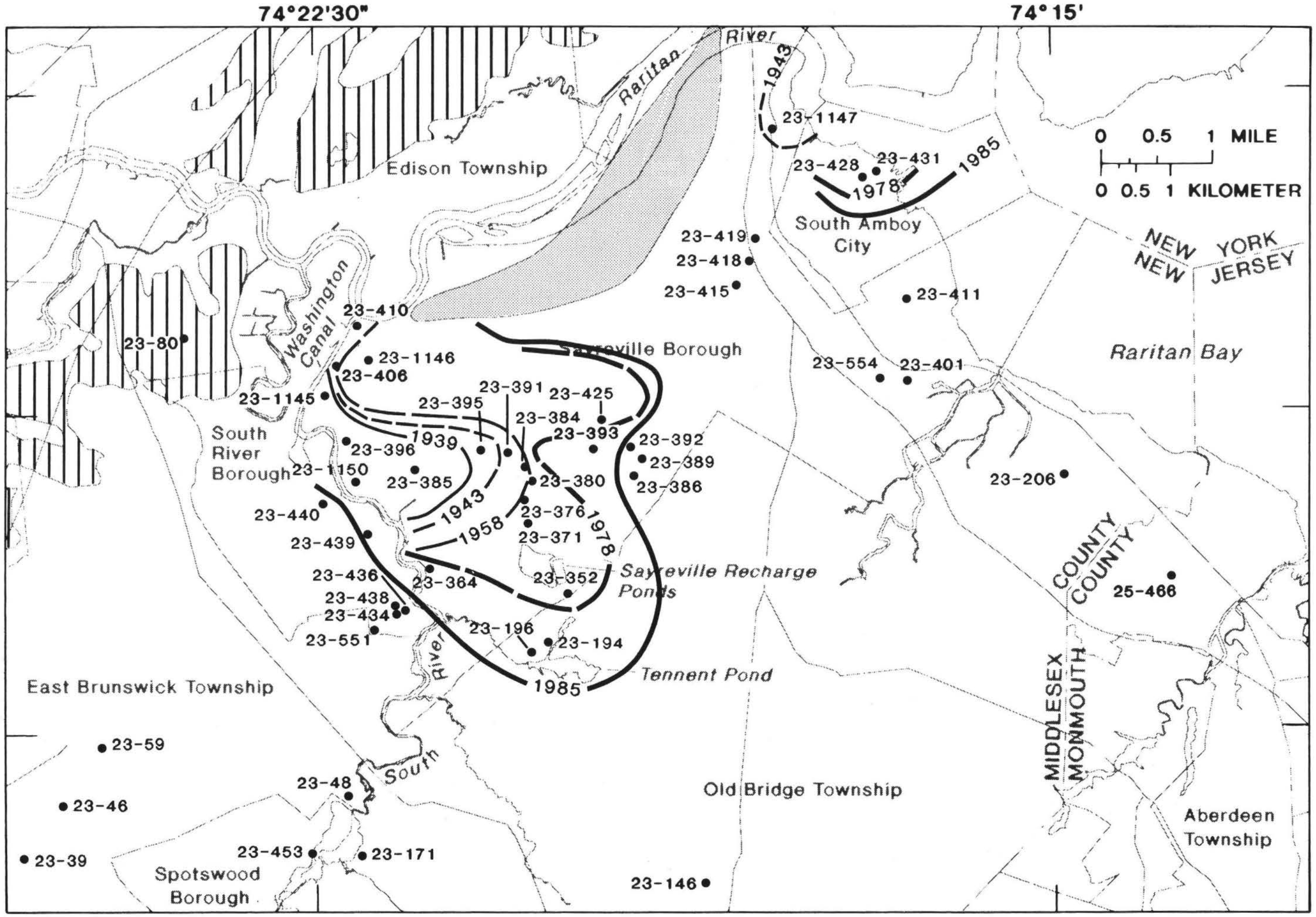
A chloride concentration of 236 mg/L in the middle aquifer in Sayreville Borough was reported in 1926 (H.G. Fairbanks, U.S. Army Corps of Engineers, written commun., 1936; appendix C). The first investigations of saltwater contamination in this area in the 1930's by Barksdale (1937) and Barksdale and others (1943) revealed the presence of saltwater in the middle aquifer southeast of the Washington Canal and north and south of Raritan River (principally in the Boroughs of Sayreville and South River) and in the City of South Amboy in Middlesex County (fig. 61). M.E. Johnson (New Jersey Geological Survey, written communs., 1925-40; appendix C) identified the main source of the saltwater as the excavation and subsequent deepening and dredging that removed the confining material overlying the middle aquifer and caused a hydraulic connection between the salty estuarine water and the underlying fresh ground water (Irwin Remson and C.A. Appel, U.S. Geological Survey, written commun., 1983). To a lesser degree, saltwater also could be moving into the middle aquifer in areas in the mouth of the Raritan River, near South Amboy City, or near the mouth of the South River, where hydrogeologic sections show that the confining unit overlying the middle aquifer is naturally thin or absent (Barksdale and others, 1943; Wehran Engineering Consulting Engineers, 1989). Schaefer (1983, p. 11) indicated that saltwater continues to move in the aquifer. In 1983, a chloride concentration of 2,200 mg/L was measured in well 23-371, approximately 2 mi southeast of the Washington Canal (Bauersfeld and others, 1983, p. 311).

In the Sayreville area, the part of the saltwater plume in which the chloride concentration is greater than or equal to 100 mg/L has varied over time (fig. 61, appendix E). The isoconcentration lines show that the plume moved eastward during 1939-45. Contours for 1958, 1978, and 1985 indicate that the plume moved southeastward. Because of the long interest in saltwater intrusion in this area, previous and concurrent reports have described migration of the plume.

Sources and Intrusion Factors

Several investigators identified the Washington Canal as the initial source of saltwater intrusion (Barksdale, 1943, p. 118; Appel, 1962, p. 11). It also has been reported (Irwin Remson and A.A. Fungaroli, U.S. Geological Survey, written commun., 1969) that fine-grained sediment deposits have covered the bottom of the Washington Canal since its construction. If the sediments that cover the bottom of the canal are moderately permeable, the net amount of saltwater flowing in the ground-water system from the canal probably continues to increase steadily because water levels in the middle aquifer are below sea level (pls. 1c and 1d). If the sediments have low permeability, intrusion into the aquifer probably has decreased as the sediment thickness increased, and the current saltwater movement represents flow of previously intruded saline water that is moving toward the withdrawal center and is undergoing dilution by ground water.

As discussed previously, the middle aquifer pinches out (is thin or absent) in northeastern Sayreville Borough. The pinchout acts as a hydraulic barrier to ground-water flow (fig. 15); therefore, withdrawal centers in the middle aquifer south and southeast of the pinchout have a limited effect on ground-water flow north of the pinchout. Ground water can flow in larger volumes through the thicker parts of the aquifer. Barksdale and others (1943) and Appel (1962) defined several small areas in or near the pinchout where the saltwater plume could flow southward for a limited distance from Raritan River. The wells used to define these small areas of



EXPLANATION

AREAS OF OUTCROP FARRINGTON SAND MEMBER OF THE RARITAN FORMATION--Dashed where approximately located. (Modified from Barksdale others, 1943, fig. 6)

AREA OF ZERO THICKNESS OF THE MIDDLE AQUIFER--Boundary is approximate

LINES OF EQUAL CHLORIDE CONCENTRATION (100 MILLIGRAMS PER LITER) FOR GIVEN YEAR--Dashed where approximately located

- 1939
- 1943 (in part from Barkesdale and others, 1943, fig. 12)
- 1958 (in part from Appel, 1962, fig.5)
- 1978
- 1985

•23-440 CHLORIDE MONITORING WELL AND WELL NUMBER--Well-construction and chloride-concentration data are listed in APPENDIX E

Figure 61.--Locations of wells and the 100-milligram-per-liter chloride-concentration contour in the middle aquifer in and near Sayreville and South River Boroughs and South Amboy City, 1939-85.

intrusion from the river, however, may have been in sandy facies within or just outside the pinchout area and may have been isolated from the main sand member of the middle aquifer. The isoconcentration lines of the historical movement of chloride shown in figure 61 are a revision of the isoconcentration lines derived from earlier data collection and incorporate the effect of the pinchout on flow lines.

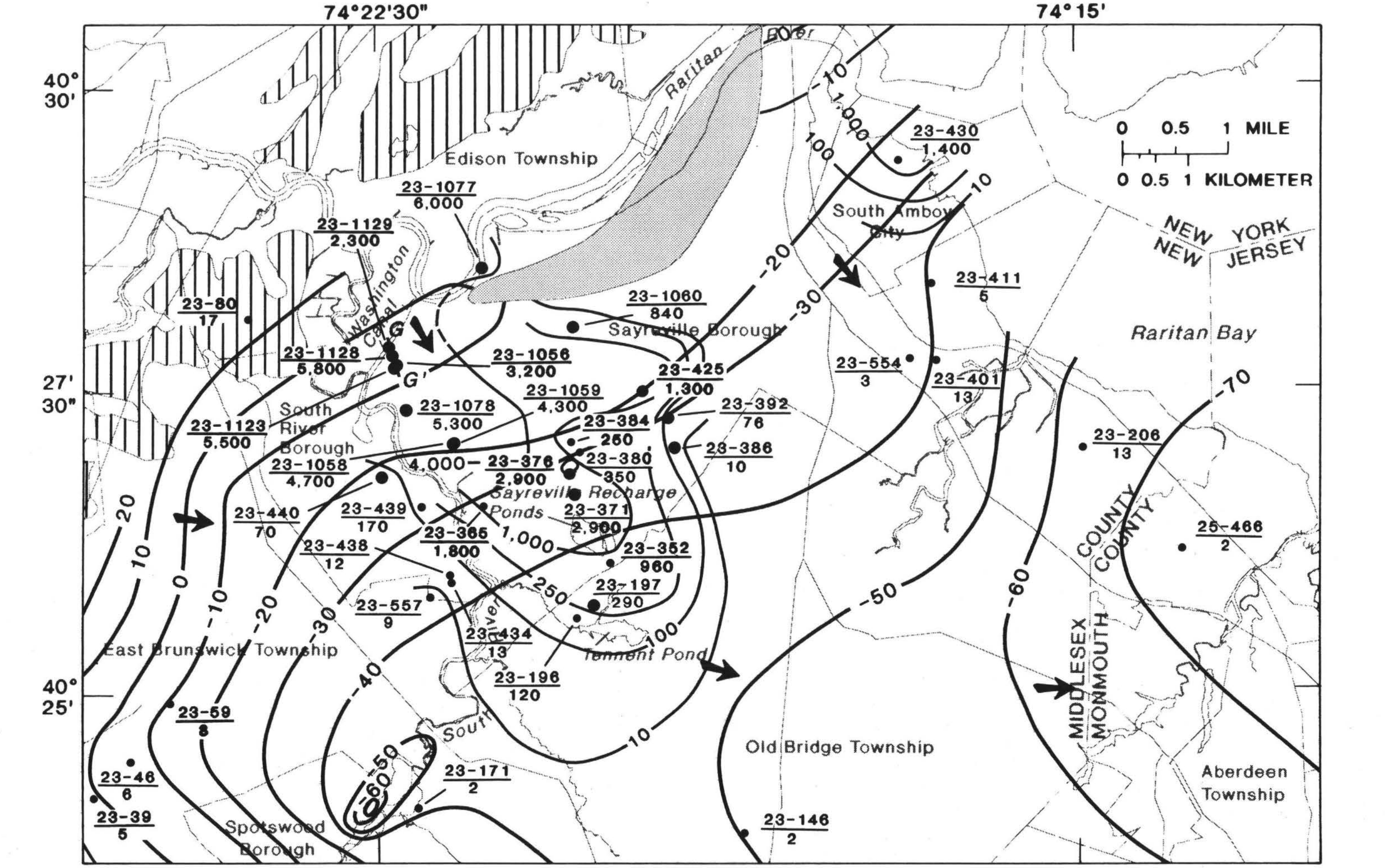
The pattern of saltwater contamination through time has been altered by the areal distribution of ground-water withdrawals. Development of the ground-water resources increased during and after World War I and, subsequently, several ground-water users in the area began to divert surface water for their supplies. Barksdale (1943, p. 113) presented the first maps that show saltwater plumes. Irwin Remson and C.A. Appel (U.S. Geological Survey, written commun., 1963) noted that the 100-mg/L isoconcentration lines for 1939 and 1943 showed that heavy withdrawals at the Duhernal Water Company well fields (in the southern part of Sayreville Borough north of Tennent Pond and southwest of South Amboy) strongly influenced the direction of saltwater intrusion. The Duhernal Water Company subsequently developed surface-water supplies, and ground-water withdrawals from the middle aquifer in this area were reduced. The sequence of 100-mg/L chloride-isoconcentration lines for 1958, 1978, and 1985 shows that the saltwater plume continued to move toward the withdrawal centers to the southeast. Comparison of the two most recent lines--those for 1978 and 1985--indicates that the chloride plume is advancing at a rate of about 470 ft/yr toward the southeast.

Data-Collection Programs and Results

Several data-collection programs were conducted during this study to evaluate whether Washington Canal remains a source of saltwater intrusion and to determine the relative importance of advection and convection in the movement of the plume. The programs included (1) a drilling program, (2) a drive-point-well-sampling program, and (3) an observation-well-sampling program.

Test drilling

A drilling program was designed to improve definition of the saltwater plume and to determine whether ground-water flow is stratified because of the effects of density on transport. Five wells (23-1058, 23-1059, 23-1060, 23-1077, and 23-1078) were drilled in Sayreville Borough in 1986 (fig. 62) in areas where supply wells had been abandoned because of saltwater contamination or where data on chloride concentrations were lacking (table 3). Chloride concentrations (table 15) in two of the wells (23-1058 and 23-1059), which were nested in the top and bottom of the aquifer about 1 mi downgradient from the canal, were 4,700 mg/L and 4,300 mg/L, respectively. This finding indicates that the chloride concentration is not stratified. Natural-gamma and electric-resistivity logs of the deeper of the two wells (23-1059) showed that the aquifer is well-defined and that no significant variations in the salinity, based on resistivity, were present within the aquifer interval (fig. 63).



EXPLANATION

AREA OF OUTCROP FARRINGTON SAND MEMBER OF THE RARITAN FORMATION--Modified from Barksdale others, 1943, fig. 6

AREA OF ZERO THICKNESS OF THE MIDDLE AQUIFER--Boundary is approximate

G —— G' LOCATION OF HYDROGEOLOGIC SECTION NEAR WASHINGTON CANAL--Section shown in fig. 64

—— -10 —— POTENTIOMETRIC CONTOUR--Altitude of spring 1986 potentiometric surface. Contour interval 10 feet. Datum is sea level

— 10 — — LINE OF EQUAL CHLORIDE CONCENTRATION FOR WELLS SAMPLED IN 1985 AND 1986--Dashed where approximately located. Interval, in milligrams per liter, is variable

GENERALIZED DIRECTION OF HORIZONTAL GROUND-WATER FLOW

23-386 / 10 OBSERVATION WELL, WELL NUMBER (ABOVE), AND 1985-86 CHLORIDE CONCENTRATIONS (BELOW)--Selected well-construction and water-quality data are listed in table 15

23-401 / 13 CHLORIDE MONITORING WELL, WELL NUMBER (ABOVE), AND 1985-86 CHLORIDE CONCENTRATION (BELOW)--Selected well-construction and water-quality data are listed in APPENDIX E

Figure 62.--Well locations, chloride concentrations in 1985-86, and potentiometric surface in spring 1986 in the middle aquifer in and near Sayreville and South River Boroughs and South Amboy City.

Table 15.--Representative analyses of ground-water samples from the middle aquifer in and near the area of saltwater intrusion in Sayreville Borough, 1984-87

[All constituents are dissolved; concentrations in milligrams per liter, (milliequivalents per liter in parentheses) unless otherwise noted; conversions to milliequivalents found in Hem (1985, table 2); double dash, --, data not available; locations of all wells shown in figure 62; uS/cm, microsiemens per centimeter; µg/L, micrograms per liter; mg/L, milligrams per liter]

Well no. (trilinear diagram no. in fig. 65)	Owner	Local identifier	Year drilled	Screened interval[1] (feet)	Sample date	Calcium	Magnesium	Sodium	Potassium
23-197 (1)	Perth Amboy WD	Perth Amboy	1944	205-260	10/17/84	47.0 (2.34)	15.0 (1.23)	85.0 (3.69)	0
23-371 (2)	Hercules Powder, Inc.	Hercules 5	1929	182-228	10/25/84	210.0 (10.48)	110.0 (9.05)	1,000.0 (43.5)	0
23-376 (3)	Hercules Powder, Inc.	Hercules 3	1928	180-220	10/25/84	170.0 (8.48)	94.0 (7.73)	960.0 (41.76)	0
23-386 (4)	E.I. Dupont, Inc.	6	1930	253-314	10/15/84	6.2 (.31)	2.3 (.19)	2.8 (.12)	0
23-393 (5)	E.I. Dupont, Inc.	1	1925	244-285	10/15/84	18.0 (.89)	6.3 (.52)	13.0 (.56)	0
23-425 (6)	E.I. Dupont, Inc.	Parlin 60F	1966	282-288	10/17/84	120.0 (5.99)	49.0 (4.03)	390.0 (16.96)	0
23-440	Hodges Bus Co.	1	1922	-- - 195	10/12/84	9.8 (.49)	3.9 (.32)	21.0 (.91)	--
23-1056	Middlesex Co. Utility Auth.	Monitoring 3	1978	43-53	08/13/87	120.0 (5.99)	350.0 (28.80)	2,900.0 (126.15)	92.0 (2.35)
23-1058	USGS	Hess Bro. 1	1986	112-122	04/21/87	--	--	--	52.0 (1.33)
23-1059	USGS	Hess Bro. 2	1986	138-148	04/21/87	--	--	--	60.0 (1.53)
23-1060 (7)	USGS	Marsh Ave.	1986	138-148	05/05/87	69.0 (3.44)	49.0 (4.03)	360.0 (15.66)	6.2 (0.16)
23-1077	USGS	JCP&L Sayreville	1987	46-56	04/27/87	--	--	--	80.0 (2.05)
23-1078	USGS	Sayre St.	1987	68-78	05/04/87	130.0 (6.49)	340.0 (27.92)	2,900.0 (126.15)	94.0 (2.40)
23-1123	USGS	Drivepoint A (bottom)	1987	35-37	11/18/87	--	--	--	58.0 (1.48)
23-1128	USGS	Drive-point B (bottom)	1987	45-47	11/23/87	130.0 (6.49)	370.0 (30.44)	2,900.0 (126.15)	100.0 (2.56)
23-1129	USGS	Drive-point C (top)	1987	10-12	11/18/87	--	--	--	55.0 (1.41)
23-1131	USGS	Drive-point C (middle)	1987	25-27	11/19/87	--	--	--	140.0 (3.58)
23-1134	USGS	Drive-point C (bottom)	1987	40-42	11/19/87	140.0 (6.99)	460.0 (37.84)	3,700.0 (160.95)	140.0 (3.58)

1 Depth below land surface

Table 15.--Representative analyses of ground-water samples from the middle aquifer in and near the area of saltwater intrusion in Sayreville Borough, 1984-87--Continued

Well number	Bicarbonate	Alkalinity (mg/L as $CaCO_3$)	Sulfate	Chloride	Solids dissolved	Specific conductance[1]	Field pH (units)	Lead (µg/L)	Cadmium (µg/L)
23-197	1.22 (.02)	1.0	33.0 (0.69)	290.0 (8.18)	--	1,080	5.4	<10	5
23-371	1.22 (.02)	1.0	350.0 (6.45)	2,500.0 (70.53)	--	8,000	5.3	130	15
23-376	1.22 (.02)	1.0	310.0 (6.45)	2,100.0 (59.24)	--	6,750	5.3	70	12
23-386	1.22 (.02)	1.0	26.0 (.54)	10.0 (.28)	--	130	5.7	60	1
23-393	1.22 (.02)	1.0	37.0 (.77)	76.0 (2.14)	--	1,070	5.5	10	5
23-425	1.22 (.02)	1.0	240.0 (5.00)	1,300.0 (36.67)	--	3,780	5.6	50	11
23-440	--	1.0	49.0 (1.02)	54.0 (1.52)	--	309	5.5	<10	2
23-1056	36.0 (.59)	31.0	760.0 (15.82)	5,400.0 (152.33)	9,700	12,400	5.5	20	1
23-1058	4.0 (.07)	3.0	690.0 (14.37)	4,700.0 (132.59)	8,210	7,500	5.7	--	--
23-1059	--	38.0	620.0 (12.91)	4,300.0 (121.30)	7,460	12,500	6.0	--	--
23-1060	24.4 (.04)	20.0	190.0 (3.96)	840.0 (23.70)	1,600	2,930	5.7	30	3
23-1077	--	460.0	490.0 (10.20)	6,000.0 (16.93)	13,200	19,000	6.9	--	--
23-1078	83.0 (1.36)	1.0	780.0 16.24	5,300.0 (149.51)	9,800	12,500	6.1	100	10
23-1123	--	67.0	430.0 (8.95)	3,200.0	5,800	10,600	5.0	--	--
23-1128	--	22.0	770.0 (16.03)	5,800.0 (163.62)	10,400	17,000	5.6	10	3
23-1129	--	63.0	220.0 (4.58)	2,300.0 (64.88)	4,200	7,200	6.8	--	--
23-1131	--	39.0	790.0 (16.45)	5,900.0 (166.44)	11,000	17,300	6.1	--	--
23-1134	--	8.0	920.0 (19.15)	7,100.0 (200.29)	13,100	20,000	5.5	20	1

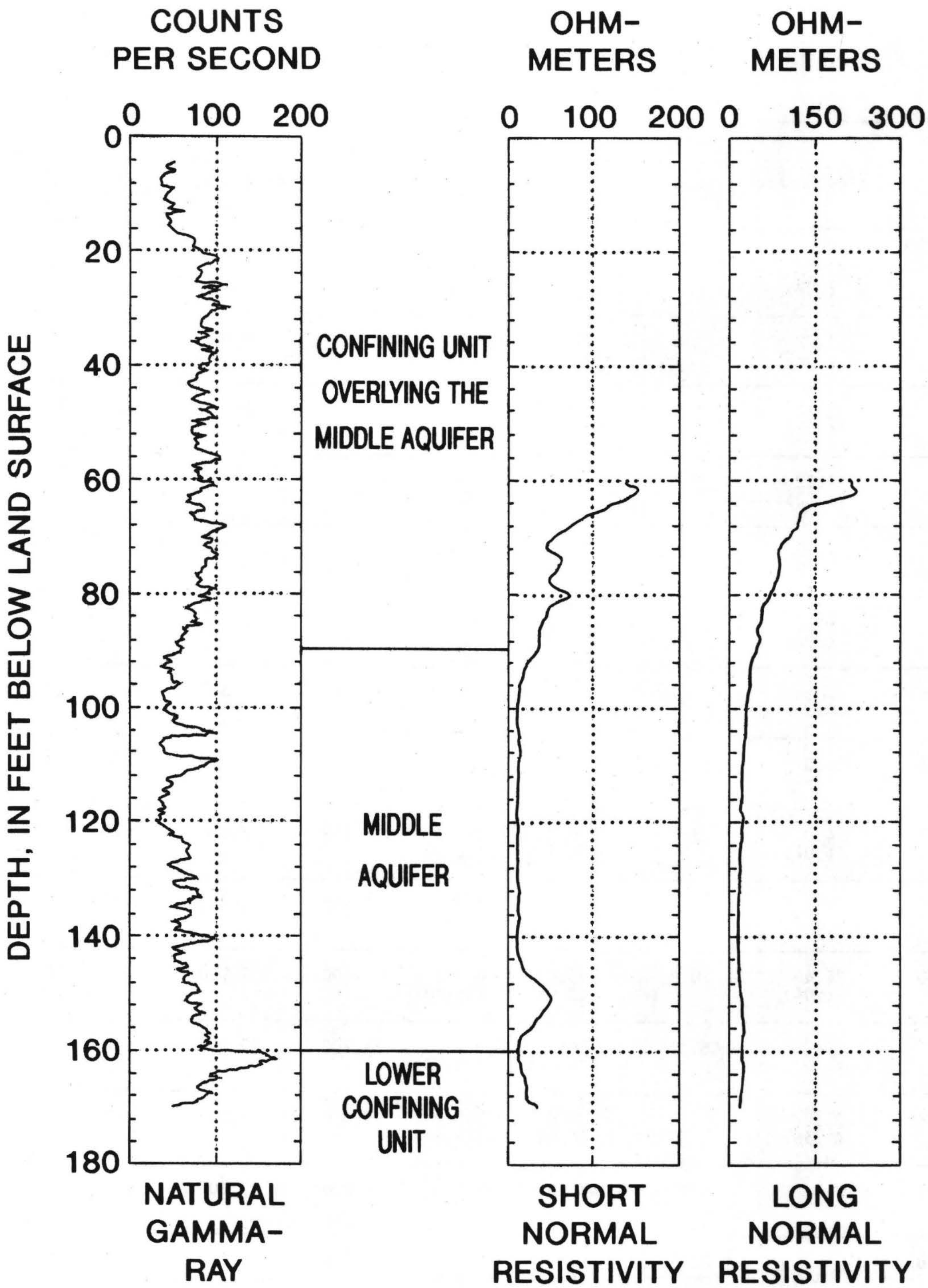


Figure 63.--Natural-gamma and electrical-resistivity logs of test well 23-1059. (Location of well shown in fig. 62)

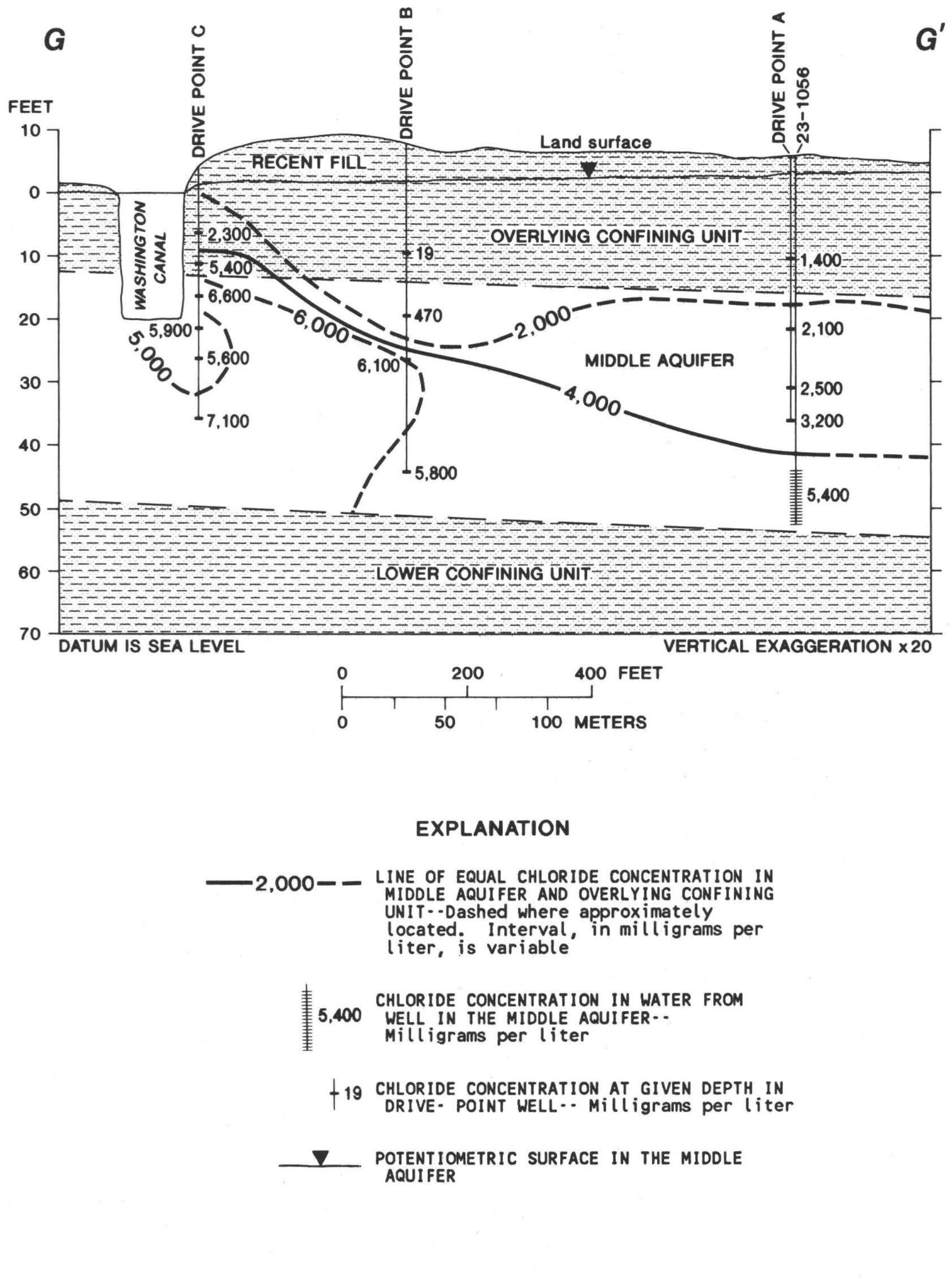


Figure 64.--Hydrogeologic section G-G′, near Washington Canal showing measured chloride concentrations and lines of equal chloride concentration in the middle aquifer, November 1987. (Location of section shown in fig. 62)

Drive-point sampling

Three drive-point wells (A, B, and C) were installed in 1987 at distances of 970, 360, and 20 ft, respectively, southeast of the canal shown along section G-G′ (fig. 64). Samples were collected from each drive-point well at discrete levels to determine whether chloride concentrations increased with depth in the wells and with distance from the canal, as they would if saltwater were entering the middle aquifer from the canal.

Local hydrogeology east of the canal (fig. 64) was generalized on the basis of logs of four nearby wells (Gronberg and others, 1989). The canal is approximately 20 ft deep, as estimated from soundings made in the field and from historical records (Irwin Remson, and C.A. Appel, U.S. Geological Survey, written commun., 1963).

Chloride concentrations in samples from drive-point wells and in a sample collected from well 23-1056, about 15 ft from drive point A, are shown in figure 64 (table 15). Samples were collected from screened intervals within the aquifer and the overlying confining unit. The chloride concentrations ranged from a minimum of 19 mg/L at drive point B, about 370 ft from the canal, to 7,100 mg/L at the deepest level of drive point C, approximately 20 ft from the edge of the canal. Recharge may have occurred from infiltration of ponded freshwater, observed near drive point B; reduced chloride concentrations at shallow depths in drive point B are consistent with this observation. The data indicate that saltwater from the canal continues to flow into the aquifer. Chloride concentrations measured in the canal near drive point C after a heavy rainfall during a tidal cycle ranged from 160 mg/L to 4,200 mg/L. Because of dilution by the rainfall, these chloride concentrations probably are lower than average.

The concentrations of chloride near the canal tend to be uniformly high, with the exception of the shallowest measurement in each drive point. Several mechanisms in addition to advection could be interacting near the canal to drive saltwater into the aquifer. The irregular concentration pattern within the vertical column could result either from the tide-driven variations in the chloride concentration of the water in the canal or from unstable convective transport that is caused when denser, saline water overlies fresh ground water (Voss and Souza, 1987, p. 1857).

At drive point A, 970 ft from the canal, chloride concentrations increased from 2,100 mg/L near the top of the aquifer to 5,800 mg/L near the bottom. Chloride was found in elevated concentrations in the confining unit, but the mechanism of transport into the confining material is uncertain. The chloride concentration in the confining unit could be the result of a local connection with the aquifer or infiltration of residual chloride from the surface after periods of seawater inundation.

Convective transport of chloride through the aquifer because of density differences does not seem to be a significant process. Vertical components of flow resulting from density differences could occur locally in the canal area because the denser surface saltwater overlies the aquifer. Vertical stratification of concentrations is likely for a short distance downgradient from the canal (fig. 64) because of the movement of the denser saltwater into the aquifer from the canal to the bottom of the aquifer; however, this stratification was not found in the nested wells 23-1058 and 23-1059 in Sayreville (tables 3 and 15), approximately 1 mi southeast of the canal (fig. 63).

Water Quality in and near the Saltwater Plume

The water chemistry in the aquifer is altered significantly by the intrusion of saltwater. Results of analyses of water sampled from wells within the plume during 1984-87 are reported in table 15; the locations of the sampled wells are shown in figure 62. The water chemistry shifts from a calcium sulfate-type water toward a sodium chloride-type water similar to seawater as chloride concentrations in the sampled wells increase (fig. 65). Relatively high sulfate concentrations are characteristic of native shallow ground water in this area and result primarily from processes typical of wetland environments (Barton and others, 1987, p. 40). As the salinity of the ground water increases with proximity to the canal, the trend of the plotted points moves toward the concentrations that are typical of seawater.

Lead and cadmium concentrations were determined for many of the samples from wells within the plume (table 15). At these wells, lead concentrations ranged from less than 10 to 130 μg/L; cadmium concentrations ranged from 1 to 15 μg/L (Pucci and others, 1989). These heavy metals are not found naturally at such concentrations in the Coastal Plain aquifers (L.L. Knobel, U.S. Geological Survey, oral commun., 1989). As in the case of Keyport and Union Beach Boroughs, the lead and cadmium concentrations probably are the result of past industrial surface-water discharges. The high concentrations indicate that these dissolved metals most likely have been transported along with the saltwater. Maest and others (1984) reported the presence of these metals in the sediments in the Raritan River. Because of tidal mixing and sediment transport, these metals probably would also be found in the Washington Canal. Variations in the concentrations of lead and cadmium in the plume could result from temporal variation in distribution of these heavy metals in the canal and from dilution caused by the mixing of saltwater with freshwater. Recent migration of lead and cadmium with the intruding saltwater is indicated by the high concentrations of lead and cadmium in well 23-1078, near the confluence of the canal and the South River (fig. 62).

Local Areas of Saltwater Intrusion

Contamination of ground water by saltwater has been found along tidal reaches of rivers bordering Raritan Bay and in several areas near unconfined parts of the upper and middle aquifers. Some mixing of freshwater and saltwater is expected where unconfined aquifers are exposed directly to the effect of tidal mixing and the alternation of gradients between surface water and ground water. This mechanism has caused saltwater contamination in the recharge area of the middle-aquifer outcrop, near Woodbridge Creek north of the Raritan River (fig. 20); in the upper aquifer, where the South River and its estuaries flow over its recharge area (fig. 20) (Schaefer, 1983); and in the upper aquifer near South Amboy, where the recharge area is submerged beneath Raritan Bay. No water-quality analyses of ground water in these areas were made before development.

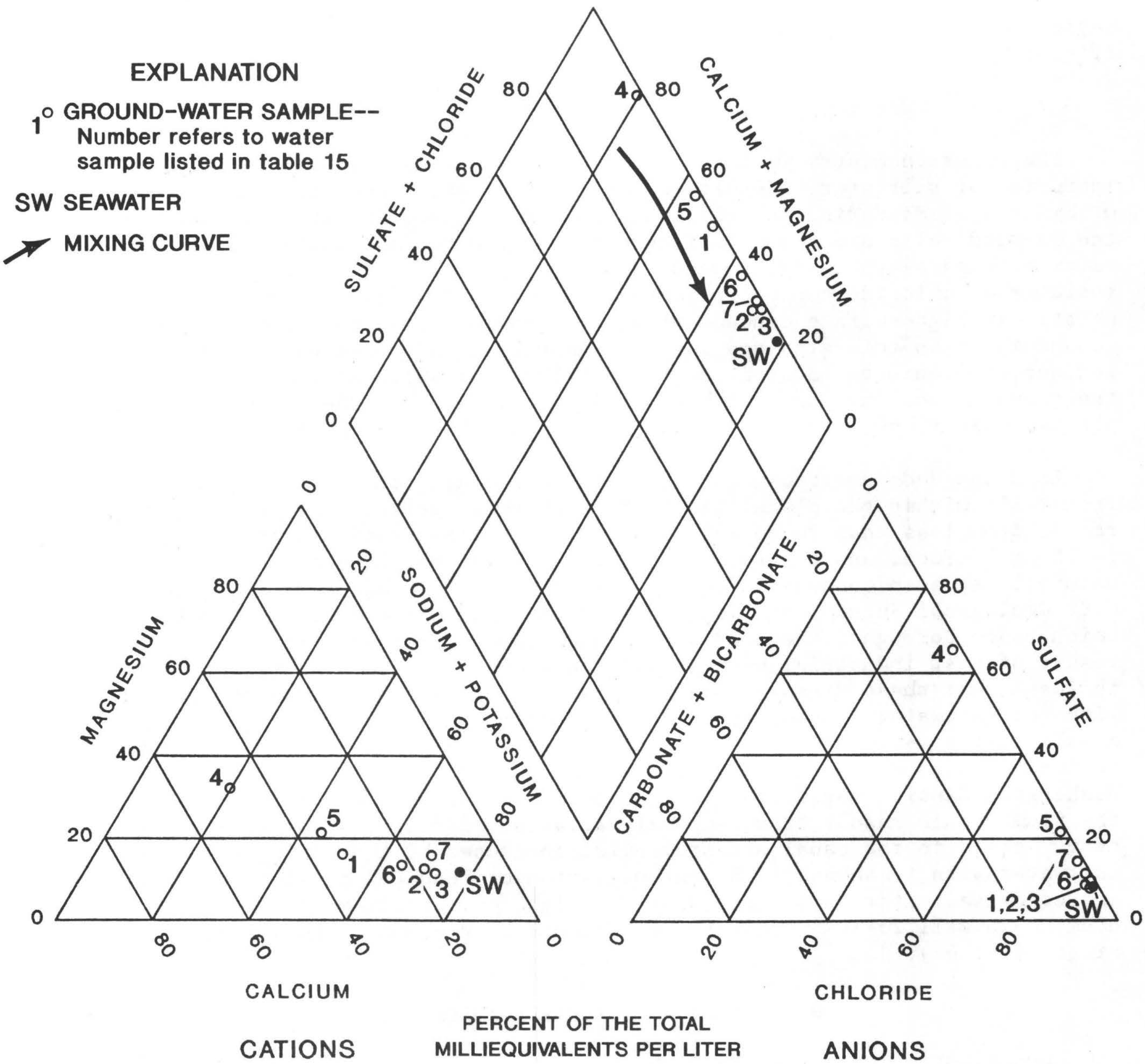


Figure 65.--Trilinear diagram showing ionic composition of water samples from the area of saltwater intrusion near Sayreville and South River Boroughs and South Amboy City. (All ground-water samples are from the middle aquifer. Locations of sampled wells shown in fig. 62)

The migration of saltwater from these unconfined areas has been limited because (1) saltwater recharge in the unconfined system is mostly away from the narrow cones of depression in the unconfined areas of the aquifers and outside the area directly affected by the regional cones of depression in the confined system, where lateral movement can be rapid; (2) the effects of fresh surface water and artificial recharge tend to isolate the effects of withdrawals, as described by Appel (1962, p. 10) for the unconfined area of the upper aquifer; and (3) ground-water withdrawals in certain areas have been reduced. For example, reduced rates of withdrawal from the middle aquifer near Woodbridge Creek have caused water levels in that area to increase to above sea level in recent years.

The effect of decreased withdrawals on the abatement of saltwater intrusion in an unconfined area is shown by the hydrograph of well 23-270 (fig. 56) in Woodbridge Township (fig. 32). In 1974, and from 1977 through 1981, ground-water levels were below sea level (fig. 56); therefore, the hydraulic gradient (and flow direction) was from the estuarine Woodbridge Creek into the middle aquifer. The reduction in ground-water withdrawals in this area since 1980 has raised the water levels and reversed the direction of ground-water flow, thereby stopping or reversing the direction of saltwater movement.

Similarly, the increased recharge of freshwater into the upper aquifer through the Sayreville Water Department recharge ponds has elevated the water table above sea level and has mitigated the intrusion of saltwater from the South River into the unconfined area of the upper aquifer in Sayreville Borough near the recharge ponds. Some slow migration of saltwater from the South River into the upper aquifer continues in other areas of Sayreville (Schaefer, 1983, p. 17).

SUMMARY AND CONCLUSIONS

The Potomac-Raritan-Magothy aquifer system in the northern Coastal Plain of New Jersey consists of the upper and middle aquifers and their confining units. The aquifer system is the most productive source of ground-water in Middlesex and Monmouth Counties. The upper aquifer provided about 57 percent of the ground-water supply for Middlesex and Monmouth Counties for the period 1981-85. About 22.8 percent of the total withdrawals from the upper aquifer was derived from the operation of three artificial-recharge facilities located in the unconfined area of the aquifer. The middle aquifer provided about 33 percent of the total ground-water supply for Middlesex and Monmouth Counties for the period 1981-85.

The upper aquifer of the Potomac-Raritan-Magothy aquifer system consists primarily of the Old Bridge Sand Member of the Cretaceous Magothy Formation and younger overlying deposits in Middlesex County. The unconfined area of the upper aquifer is a band that strikes northeast-southwest and continues (submerged) beneath Raritan Bay. The aquifer dips to the southeast and thickens from a featheredge at its outcrop to 75 to 175 ft in most of the study area. Aquifer transmissivity determined from 15 aquifer tests ranges from 1,760 to 19,400 ft^2/d. The hydraulic conductivity determined from aquifer tests and well-acceptance tests ranges from 4 to 483 ft/d, and the storage coefficient in confined-aquifer areas ranges from 1.0×10^{-5} to 1.8×10^{-3}.

The upper aquifer generally is tightly confined by the massive Merchantville-Woodbury confining unit, which consists primarily of clays and silts of the Cretaceous Woodbury Clay and Merchantville Formation. In downdip areas and locally, the confining unit includes the discontinuous Cliffwood and Morgan beds of the Magothy Formation and the Amboy Stoneware Clay Member. The confining unit generally is greater than 200 ft thick and is a maximum of 369 ft thick in Monmouth County. In updip confined areas, especially in southwestern Middlesex County, the confining unit is leaky and a hydraulic connection exists between the upper aquifer and the overlying water table.

Results of synoptic water-level measurements made during fall 1984 and spring 1986 show major cones of depression in the upper aquifer centered in areas of northern Holmdel Township, southern Marlboro and northern Freehold Townships, and Neptune Township, all in Monmouth County. In spring 1986, water levels in the centers of the two major cones were 42 ft below sea level in Marlboro Township and 36 ft below sea level in Howell Township. The change in the location of the cones of depression through time reflects the relocation of ground-water-withdrawal centers away from coastal areas because of shifts in population and saltwater intrusion.

The middle aquifer is composed primarily of the Cretaceous Farrington Sand Member of the Raritan Formation in most of the northern Coastal Plain of New Jersey. The unconfined area generally strikes northeast-southwest in a band along the Fall Line. The aquifer dips to the southeast at about 60 ft/mi and generally ranges in thickness from 75 to 150 ft, although it is thin or absent in the northern part of Sayreville Borough near Raritan River. Aquifer transmissivity determined from 11 aquifer tests ranges from 2,140 to 13,800 ft^2/d, hydraulic conductivity determined from aquifer tests and well-acceptance tests ranges from 17 to 385 ft/d, and the storage coefficient in the confined area ranges from 2.6×10^{-5} to 3.4×10^{-3}.

In most of the study area, the middle aquifer is tightly confined by clays and silts composed mainly of the Cretaceous Woodbridge Clay Member of the Raritan Formation. The confining unit generally is greater than 100 ft thick in the southwestern part of Middlesex County and is a maximum of 241 ft thick in Monmouth County. The confining unit thins and becomes sandy and causes the middle and upper aquifers to function (practically) as one aquifer in the southwestern part of the area.

The major cones of depression in the middle aquifer in fall 1984 and spring 1986 were centered in Spotswood Borough, Middlesex County, and Hazlet and Holmdel Townships, Monmouth County. Water levels in the centers of these cones of depression in spring 1986 were 77 ft below sea level in Spotswood and 93 ft below sea level at Holmdel Township. The change in location of cones of depression through time also reflects the redistribution of ground-water withdrawals away from the area of Raritan River and near the Washington Canal because of saltwater intrusion there.

A finite-difference, quasi-three-dimensional model was developed to simulate ground-water flow in the Potomac-Raritan-Magothy aquifer system and the two overlying aquifers, the Englishtown aquifer system and the Wenonah-Mount Laurel aquifer, in the northern Coastal Plain of New Jersey. The hydrologic characteristics of the upper and middle aquifers and their confining units were based on measured and interpreted values, whereas the hydrologic characteristics of overlying aquifer layers and their confining units were from the calibrated New Jersey Regional Aquifer System Analysis (RASA) flow model (much coarser grid spacing) of the entire New Jersey Coastal Plain. The New Jersey RASA model was used to calculate lateral boundary fluxes for the modeled area for this study. The model used in this study was calibrated primarily by matching computed and measured hydraulic heads for the period 1896-1985 and computed and measured potentiometric surfaces for the predevelopment period and 1984. Hydraulic parameters in the calibrated model compared favorably to measured characteristics. Horizontal hydraulic conductivity of the aquifers and vertical hydraulic conductivity of the confining units were the primary parameters used to calibrate the model.

Total simulated inflow and outflow for the upper aquifer in the modeled area is 35 Mgal/d for the predevelopment period. In the simulation, the upper aquifer receives recharge from topographic highs in South Brunswick, Cranbury, and Monroe Townships in southwestern Middlesex County, and from the unconfined areas; recharge also occurs by vertical leakage through overlying confining units in eastern Sayreville Borough. Most ground-water recharge to the upper aquifer discharges locally to low-lying regional surface-water drains that flow into the South River. Recharge to the downdip, confined areas of the upper aquifer during the predevelopment period flowed laterally to discharge areas in Raritan Bay or downward to the middle aquifer, to the confined system outside the study area.

Total simulated inflow and outflow for the middle aquifer in the modeled area for the predevelopment period is about 21 Mgal/d. Simulated recharge to the middle aquifer is derived from topographically high unconfined areas in the southwestern part of the study area and north of Raritan River and from vertical leakage from the upper aquifer. Most ground-water discharge is to low-lying wetland areas near Raritan and South Rivers.

Simulation of 1984 transient conditions in the upper aquifer results in a total inflow and outflow of 61 Mgal/d. The simulation produces regional cones of depression centered in Marlboro, Holmdel, and Freehold Townships in Monmouth County that result from ground-water withdrawals and changes in the locations of areas of recharge and discharge since the predevelopment period. Flow in the confined-aquifer areas is from the unconfined areas toward regional stream systems in the northeastern part of the study area and toward the major cones of depression downdip. For transient conditions, most recharge (39 percent of inflow) is from the unconfined areas of the upper aquifer, but significant amounts of recharge also come from leakage through the outcrop area of the Merchantville-Woodbury confining unit (24 percent of total inflow) and from induced inflow at artificial-recharge ponds (15 percent of inflow). Some simulated recharge to the upper aquifer is from surface-water bodies that contain saltwater through lateral flow from the submerged outcrop and vertical leakage through the overlying Merchantville-Woodbury confining unit. In this simulation, most discharge from the upper aquifer occurs as flow to wells (66 percent of outflow); additional discharge consists of downward flow to the middle aquifer (19 percent of outflow) and flow to streams (10 percent of outflow).

Total simulated ground-water inflow and outflow for 1984 transient conditions in the middle aquifer is 34 Mgal/d. The simulation reproduces major cones of depression centered in Spotswood Borough, Middlesex County, and Hazlet Township, Monmouth County. The regional potentiometric surface indicates flow from the unconfined areas toward Raritan and South Rivers and the withdrawal centers. Although recharge in the unconfined area is the major inflow (49 percent of total inflow), water-budget analysis shows that vertical leakage from the upper aquifer through the confining unit overlying the middle aquifer is a significant inflow of water to wells (34 percent of total inflow). For this simulation, most discharge occurs as flow to wells (67 percent of total outflow); additional discharge consists of flow to streams (22 percent of outflow).

The model was limited mainly by the simplified representation of flow interactions in the unconfined-aquifer areas and the inability of the model to account for delayed yield contributed from storage in confining units. Interpretations of the model results are subject to the limitations of the approach and simplifying assumptions. The major simplification in the representation of the water table is that the model represents the water table within the confining units as a constant-head boundary and does not account for lateral flow or ground-water discharge to streams in these areas. Because of this simplification, the model can not be used to compare ground-water discharge to stream cells with measured base flow. Development of a model that also simulates the water levels and ground-water/surface-water interactions in the unconfined parts of the aquifers and confining units throughout the modeled area would improve the accuracy of model simulations.

The confining units contribute large amounts of water through delayed yield. This source of water is potentially important because confining units are more than 200 ft thick in parts of the study area and because delayed leakage from them could take place over several hundred years. The simulation of steady flow through the confining units could misrepresent the relative distribution of flow.

Sensitivity analysis, in which selected hydraulic parameters and conditions were varied over selected ranges, revealed that the hydraulic-head distribution was highly sensitive to changes in horizontal hydraulic conductivity of the aquifers and vertical hydraulic conductivity of the confining units. The model also was relatively sensitive to the changes in ground-water withdrawals and initial hydraulic-head values in aquifer-outcrop areas. Regional head distribution in the model was not highly sensitive to changes in horizontal hydraulic conductivities in the unconfined area.

Two predictive ground-water-withdrawal scenarios--one consisting of increased withdrawals proportional to projected growth and the other consisting of reduced withdrawals based on percentages of 1983 withdrawals--were simulated through 2019. Predicted effects of ground-water withdrawals probably are more accurate in areas for which available data are more extensive and ground-water withdrawals are similar in magnitude to those in 1900-85. The accuracy of the predicted water levels also depends on the accuracy of estimated future withdrawals.

For the scenario of unrestricted increased withdrawals (scenario 1), simulated heads resulting from ground-water withdrawals from the upper aquifer (about 69 Mgal/d) were as low as 100 ft below sea level in Freehold Township and 80 ft below sea level in Hazlet Township. In the middle aquifer, simulated heads resulting from withdrawals of about 37 Mgal/d yielded heads in the middle aquifer that were as low as 170 ft below sea level in Matawan Borough and Hazlet Township, 150 ft below sea level in Old Bridge Township, and 130 ft below sea level near Duhernal Lake. Flow-budget analyses for each aquifer show that most of the supply of water to meet the additional ground-water withdrawals would come from captured surface-water discharge and induced cross-formational flow through confining units, and from overlying sediments. Increased amounts of water also would be induced from artificial-recharge. Induced flow of saltwater from Raritan Bay probably would increase.

For the scenario of reduced withdrawals (scenario 2), ground-water withdrawals from the upper aquifer would be 42.5 Mgal/d in 2019, and heads would recover to above sea level everywhere except near Hazlet Township, where they would be about 10 ft below sea level. In the middle aquifer, withdrawals of 15 Mgal/d would cause water levels in Freehold and Hazlet Townships to recover to 20 ft below sea level. Flow-budget analyses for each aquifer indicate an increase in ground-water discharge to streams and a reduction in induced flow through the confining units and from the overlying sediments. In this scenario, the discharge of water from the upper aquifer to Raritan Bay exceeds the induced flow into the upper aquifer.

The principal area of saltwater intrusion in the upper aquifer is near Raritan Bay in Keyport and Union Beach Boroughs. Chloride concentrations in upper-aquifer water at Union Beach were as high as 2,800 mg/L in 1986. Although chloride concentrations have increased since saltwater intrusion was first reported in this area in the early 1970's, the saltwater does not appear to have moved measurably in the direction of regional withdrawal centers since well fields in Keyport Borough and Union Beach Borough were abandoned in the late 1970's. Saltwater intrusion into the upper aquifer from Raritan Bay also is occurring in the Keansburg Borough area, where chloride concentrations were as high as 290 mg/L in 1986. Saltwater migration in this area is in the direction of the Keansburg well field. Additional monitoring will allow for the determination of the extent and movement of the saltwater plume.

The saltwater intrusion is the result of the landward movement of a freshwater-saltwater interface that probably existed in the upper aquifer even before development. Saltwater moves from Raritan Bay into the upper aquifer through an area where the aquifer is well connected to the bay. The area of connection probably is on the northern side of Raritan Bay at a submerged outcrop of the upper aquifer or a paleochannel, or at sand-and-gravel sediments that overlie sediments of the upper aquifer in Raritan Bay. Southward movement of the interface is most rapid toward withdrawal centers nearest the coastline of the bay.

The main area of saltwater intrusion in the middle aquifer is southeast of the Washington Canal and Raritan River in Sayreville Borough, Middlesex County. Chloride concentrations measured in well-water samples were as high as 6,000 mg/L in Sayreville in 1987 and were as high as 7,100 mg/L in samples from drive-point wells near the Washington Canal in Sayreville Borough. Chloride concentrations in well-water samples were about 4,700 mg/L in wells about 1 mi southeast of the canal and about 2,500 mg/L in wells about 2 mi southeast of the canal.

The main source of saltwater intrusion in the Sayreville area is the salty estuarine water in the Washington Canal, although the aquifer may be connected to other sources of salty water, notably in South Amboy City and possibly along the South River. Saltwater flow into the upper aquifer in these areas is controlled by the effects of the higher density of saltwater compared to that of freshwater and the induced flow caused by pumpage from the regional withdrawal centers. The movement and direction of the saltwater plume have been affected by the location of the pinchout in the middle aquifer in northern Sayreville Borough and the direction of the potential gradient toward the major regional withdrawal centers to the southeast. The rate of movement of the saltwater plume is estimated to be about 470 ft/yr toward the southeast; saltwater probably will continue to move toward the regional cones of depression, provided that the hydraulic gradient from the area of the saltwater plume in Sayreville Borough to the southeast is maintained.

Saltwater intrusion has also been observed in unconfined areas of the upper and middle aquifers. In the unconfined areas, the saltwater intrusion results from tidal mixing where the aquifers are exposed to saltwater. In these areas, however, saltwater intrusion is localized and probably is not a serious threat to regional ground-water supplies.

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GLOSSARY

ANISOTROPY: That condition in which some physical or hydraulic properties vary with direction of measurement.

AQUIFER: A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells or springs.

AQUIFER TEST: A controlled field experiment wherein the effect of withdrawal from a well is measured in the pumped well and in observation wells for the purpose of determining hydraulic properties of an aquifer.

BEDROCK: Solid rock, commonly called "ledge," that underlies gravel, soil, or other surficial material.

CONCEPTUAL MODEL: A general idea or understanding of an existing stream-aquifer system from which it is possible to mathematically simulate that system.

CONE OF DEPRESSION: A depression in the water table or other potentiometric surface produced by the withdrawal of water from an aquifer. It is shaped like an inverted cone with its apex at the area of greatest concentration of withdrawal.

CONFINED AQUIFER: An aquifer in which ground water is under pressure that is significantly greater than atmospheric pressure. The static water level in a tightly cased well in a confined aquifer will rise above the top of the aquifer.

CONFINING UNIT: A body of low-permeability material stratigraphically adjacent to one or more aquifers. The hydraulic conductivity can range from nearly zero to some value distinctly lower than that of the aquifer.

CONSTANT-FLUX BOUNDARY: A constant flux can be zero (impermeable boundary) or have a finite value.

Zero-flux boundary: A model boundary condition that is specified by assigning a value of zero transmissivity to nodes outside the boundary to simulate no flow across the boundary.

Finite-flux boundary: A model boundary condition that is specified by assigning a fixed value of volumetric flow to recharge (or discharge) wells at appropriate nodes to simulate flow across the boundary.

CONTINUOUS-RECORD STREAMFLOW-GAGING STATION: A site on a stream at which continuous measurements of stream stage are made. These records are converted to daily flow after calibration by means of flow measurements.

DIGITAL MODEL: A simplified mathematical representation of a complex aquifer system. A computer program designed to solve ground-water-flow equations.

DISCHARGE (water): The volume of water that passes a given point within a given period of time.

<u>Mean discharge</u>: The arithmetic mean of individual daily mean discharge during a specific period.

<u>Instantaneous discharge</u>: Discharge at a particular instant of time.

DISSOLVED SOLIDS: The residue from a clear sample of water after evaporation and drying for 1 hour at 180° Celsius; consists primarily of dissolved mineral constituents, but also can contain organic matter and water of crystallization.

DRAINAGE AREA: The area that drains to a stream at a specified location, measured in a horizontal plane, that is enclosed by a drainage divide.

DRAINAGE BASIN: A part of the surface of the earth that is occupied by a drainage system, which consists of a surface stream or body of impounded surface water together with all tributary surface streams and bodies of impounded surface water.

DRAINAGE DIVIDE: The rim of a drainage basin. Drainage divide, or divide, is used to denote the boundary between one drainage basin and another.

DRAWDOWN: Decline of the water level (head) in a well after withdrawal starts. It is the difference between the water level (head) in a well after withdrawal starts and the static water level (static head).

DURATION OF FLOW (of a stream): The percentage of time during which specified daily discharges have been equaled or exceeded in magnitude within a given time period.

EVAPOTRANSPIRATION: Water withdrawn from a land area by evaporation from water surfaces and moist soil and by plant transpiration.

GAGING STATION: A site on a stream, canal, lake, or reservoir where systematic observations of gage height or discharge are made.

GAINING STREAM: A stream or reach of a stream whose flow is being increased by inflow of ground water.

GROUND WATER: Water in the ground that is in the zone of saturation, from which wells, springs, and ground-water runoff are supplied.

GROUND-WATER DISCHARGE: Discharge of water from the saturated zone (1) by natural processes such as ground-water runoff and ground-water evapotranspiration and (2) discharge through wells and other manmade structures.

GROUND-WATER DIVIDE: A ridge in a water table from which the water table slopes downward on both sides. It is analogous to a divide between two drainage basins on a land surface. A ground-water divide generally is found nearly below a surface-drainage divide, but in many localities there is no relation between the two.

GROUND-WATER EVAPOTRANSPIRATION: Ground water discharged into the atmosphere in the gaseous state by direct evaporation and by transpiration by plants.

GROUND-WATER OUTFLOW: That part of the discharge from a drainage basin that occurs through the ground. The term "underflow" is used often to describe ground-water outflow that takes place in alluvium (instead of a surface channel) and thus is not measured at a streamflow-gaging station.

GROUND-WATER RECHARGE: Water that is added to the saturated zone.

GROUND-WATER RESERVOIR: Geologic units where ground water is accumulated under conditions that make it suitable for development and use.

GROUND-WATER RUNOFF: That part of runoff that has passed into the ground, has become ground water, and has been discharged into a stream channel as spring or seepage water.

HEAD, STATIC: The height above or below a standard datum of the surface of a column of water (or other liquid) that can be supported by the static pressure at a given point. In this report, static head is referred to simply as "head." Measurements of water levels in observation wells can be used to compute heads by referencing the measurements to the standard datum.

HETEROGENEITY: Synonomous with nonuniformity. A material is heterogeneous if its hydrologic properties vary with position within it.

HYDRAULIC CONDUCTIVITY: The volume of water at the existing kinematic viscosity that will move in unit time under unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

HYDRAULIC GRADIENT: The change in head per unit of distance in a given direction. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head.

INDUCED INFILTRATION: The process by which water moves into an aquifer from an adjacent surface-water body as a result of reversal of the hydraulic gradient in response to withdrawal.

INDUCED RECHARGE: The amount of water entering an aquifer from an adjacent surface-water body by the process of induced infiltration.

ISOTROPY: That condition in which significant properties are independent of direction.

LEAKANCE: The ratio of the vertical hydraulic conductivity to the thickness of a confining unit. In this report, leakance is reported in units of ft per day per foot of confining-unit thickness [(ft/day)/ft].

LEAKY BOUNDARY: A boundary condition that relates boundary flux to boundary head. It is used most commonly to represent the interaction between a water-table unconfined aquifer and a stream or river that is separated from the aquifer by a semipervious streambed layer.

LITHOLOGIC LOG: Description of the geologic material collected during the drilling of test wells.

LOSING STREAM: A stream or reach of a stream that is losing water to the ground.

MICROGRAMS PER LITER (μg/L): A unit for expressing the concentration of a chemical constituent in solution. Micrograms per liter represents the weight of solute per unit volume of water.

MILLIGRAMS PER LITER (mg/L): A unit for expressing the concentration of a chemical constituent in solution. Milligrams per liter represents the weight of solute per unit volume of water.

pH: Symbol denoting relative concentration of hydrogen ion in a solution. pH values range from 0 to 14--the lower the value, the more acidic the solution; that is, the more hydrogen ion it contains. A value of 7.0 indicates a neutral solution; values greater than 7.0 indicate an alkaline solution; values less than 7.0 indicate an acidic solution.

POTENTIAL EVAPOTRANSPIRATION: Water loss that will occur if no deficiency of water in the soil for use by vegetation exists.

POTENTIOMETRIC SURFACE: An imaginary surface representing the static head of ground water in tightly cased wells that tap a water-bearing rock unit (aquifer); or, in the case of unconfined aquifers, the water table.

PRECIPITATION: The discharge of water from the atmosphere, either in a liquid or a solid state.

RECOVERY: The rise of the water level in a well after withdrawal has stopped. It is the difference between the water level (head) in a well after withdrawal stops and the water level (head) as it would have been if withdrawal had continued at the same rate.

RUNOFF, TOTAL: That part of precipitation that appears in surface streams. It is the same as streamflow unaffected by artificial diversion, storage, or other works of man in or on stream channels. Includes surface- and ground-water runoff.

SALTWATER INTRUSION: The movement of saltwater or brackish water into a freshwater aquifer as a result of the lowering of the freshwater head below sea level by withdrawal.

SATURATED THICKNESS: The thickness of the part of an aquifer that is saturated with water. As measured for the sedimentary aquifers in this report, it is the vertical distance between the water table and the lower confining unit in the unconfined areas of the aquifers; in the confined areas, it is the vertical distance between the confining units.

SATURATED ZONE: That part of a water-bearing material in which all voids, large and small, are ideally filled with water under pressure greater than atmospheric.

SPECIFIC CAPACITY: The rate of discharge of water from a well divided by the drawdown of water level in the pumped well, expressed herein in units of gallons per minute per foot per unit of time.

SPECIFIC CONDUCTANCE: A measure of the ability of a water to conduct an electrical current, expressed in microsiemens per centimeter at 25 degrees Celsius. Specific conductance is related to the type and concentration of ions in solution and can be used to estimate the dissolved-solids concentration of the water. The concentration of dissolved solids (in milligrams per liter) commonly is from 55 to 75 percent of specific conductance (in microsiemens per centimeter at 25 degrees Celsius). This relation is not constant from stream to stream or from well to well, and it may even vary in the same source with changes in the composition of the water.

SPECIFIC DISCHARGE (of Ground Water): The rate of discharge of ground water per unit area measured at right angles to the direction of flow, expressed herein in units of ft per day.

SPECIFIC YIELD: Ratio of the volume of water that a fully saturated rock or unconsolidated material will yield by gravity drainage, given sufficient time, to the total volume of rock or unconsolidated material. Dimensionless.

STEADY FLOW: The flow that occurs when at any point in a flow system the magnitude and direction of the specific discharge are constant in time.

STEADY STATE: Equilibrium water levels or heads; aquifer storage and water levels do not vary with time.

STORAGE COEFFICIENT: Volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. In an unconfined aquifer, the storage coefficient is approximately equal to the specific yield. Dimensionless.

STREAMBED CONDUCTANCE: The property of a reach of stream (or river) that describes the ability to transmit or receive water from underlying sediments.

STREAMFLOW: Discharge that occurs in a natural channel. "Streamflow" is more general than "runoff," as streamflow may be applied to discharge whether or not it is affected by diversion or regulation.

SYNOPTIC: Displaying conditions (such as water levels in an aquifer) as they exist simultaneously over a broad area.

TRANSIENT STATE: Nonequilibrium water levels or heads; water levels and aquifer storage vary with time.

TRANSMISSIVITY: The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of aquifer under unit hydraulic gradient. It is equal to the product of hydraulic conductivity and saturated thickness of the aquifer, expressed herein in units of feet squared per day.

UNCONFINED (WATER TABLE) AQUIFER: An aquifer in which the upper surface of the saturated zone (water table) is at atmospheric pressure and is free to rise and fall.

UNSATURATED ZONE: The zone between the land surface and the water table.

WATER TABLE: The surface of a ground-water body at which the water pressure equals atmosphere pressure.

WATER YEAR: A 12-month period, October 1 through September 30. It is designated by the calendar year in which it ends.

WELL-ACCEPTANCE TEST: A controlled test in which an installed pump is used to determine the productivity of a well. Expressed as its specific capacity.

APPENDIXES

APPENDIX A

Descriptions and sources of data on the hydrogeology and water resources of the South River study area

Description	Source
Geologists' logs and geologic sections prepared for the New Jersey Department of Transportation and for various industrial projects in the Sayreville, South Amboy, and South River areas.	Professional records of Meredith Johnson on file at the New Jersey Geological Survey (New Jersey Geological Survey, written commun., 1925-40)
Geologists' logs prepared from test borings in the Raritan River, South River, and the Washington Canal for proposed bridges.	Technical reports prepared for the U.S. Army Corps of Engineers by Meredith Johnson, on file at the New Jersey Geological Survey.
Geologists' logs from eight test borings in Raritan Bay between Conaskonk Point, N.J., and Staten Island, N.Y., with a geologic section.	"Memorandum on the geologic conditions to be encountered at the proposed Raritan Bay bridge site", by C.P. Berkey, 1955. Archived material on file at Columbia University.
An assessment of the water resources and hydrogeology of the area near Parlin, N.J., and Middlesex County, N.J.	New Jersey Department of Conservation and Economic Development, Division of Water Policy and Supply, Special Reports 7 and 8 (Barksdale, 1937; Barksdale and others, 1943).
Geologists' logs prepared from test borings in the Raritan and South Rivers. Discussion of the distribution of these sediments. Hydraulic conductivities of river sediments. Assessment of saltwater intrusion in middle aquifer.	New Jersey Department of Conservation and Economic Development, Division of Water Policy and Supply, Special Report 17 (Appel, 1962).
Drillers' logs and lithologic data from foundation studies for utility projects in areas of Middlesex County, N.J.	"Miscellaneous boring series along proposed sewer pipelines," for 1955-1970, on file at Middlesex County Utility Authority offices, East Brunswick, N.J.

APPENDIX A--Continued

Descriptions and sources of data on the hydrogeology and water resources of the South River study area--Continued

Description	Source
Lithologic logs from 86 marine test borings in Raritan Bay along the shoreline of Middlesex and Monmouth Counties, N.J.	"Miscellaneous design memoranda for beach erosion and hurricane protection project," 1963, on file at U.S. Army Corps of Engineers, New York, N.Y.
Marine seismic records of submerged sediments in Raritan Bay along a track from Morgan, N.J., to Long Island, N.Y.	"Lower New York Bay Geophysical Investigation", 1965, by Edgerton, Germeshausen & Grier, Inc., on file at Transcontinental Pipeline Co., Houston, Tex.
Contour maps of the top of the Palisades Sill prepared from geologists' logs for the area of Sayreville, South River, and Perth Amboy, N.J.	Unpublished worksheets prepared by Steven Whitney, 1969, on file with New Jersey Geological Survey.
Uninterpreted logs from borings collected in the vicinity of Keyport and Union Beach Boroughs, N.J.	"Miscellaneous soil boring reports," 1972, prepared by Charles Kupper, Inc., for Bay Shore Regional Sewerage Authority, Union Beach, N.J.
Geologists' logs prepared for the New Jersey Department of Transportation from borings collected near the Raritan River.	"Paleodrainage history of the Hudson Estuary" (Lovegreen, 1974).
A report on borings collected in the shallow sediments at Conaskonk Point Marsh at Union Beach, N.J.	"Macrobiology and geology of the Conaskonk Point Marsh at Union Beach, New Jersey" (Garbisch, 1975).
A report on the geohydrology and simulation of the middle aquifer in the northern Coastal Plain of New Jersey.	U.S. Geological Survey Water-Resources Investigation Report 79-106 (Farlekas, 1979).
A map of the type and distribution of bottom sediments in Raritan Bay, prepared from various data including shallow borings and marine-seismic data.	State University of New York at Stony Brook, Marine Science Research Center (Bokuniewicz and and Fray, 1979).

APPENDIX A--Continued

Descriptions and sources of data on the hydrogeology and water resources of the South River study area--Continued

Description	Source
Uninterpreted aeromagnetic survey of central New Jersey and Delaware that indicates the location of the Palisades sill.	U.S. Geological Survey Open-File Report 79-1683 (U.S. Geological Survey, 1979)
Ground-water simulation of the Potomac-Rartian-Magothy aquifer system in the Coastal Plain of New Jersey.	U.S. Geological Survey Water-Resources Investigations Report 80-11 (Luzier, 1980).
Structure and contour maps of hydrogeologic units in the New Jersey Coastal Plain, prepared from geophysical logs.	U.S. Geological Survey Profess-ional Paper 1404-B (Zapecza, 1989).
Uninterpreted marine seismic-reflection data from Raritan Bay, collected by the U.S. Geological Survey, Woods Hole, Mass.	Unpublished data on file at U.S. Geological Survey at Woods Hole, Mass.
Ground-water-flow simulation of the New Jersey Coastal Plain.	U.S. Geological Survey Open-File Report 87-529 (Martin, 1990)
A marine geophysical survey of hydrogeologic units in the area of Raritan Bay, conducted by the U.S. Geological Survey, West Trenton, N.J., in 1984.	"Ground-water hydrology of the Raritan Bay area, New Jersey," (Declerq, 1986).
Collated geophysical logs, geologists' logs, and drillers' logs for the northern Coastal Plain of New Jersey.	U.S. Geological Survey Open-File Report 87-243 (Gronberg and others, 1989).
Structure and contour maps of hydrogeologic units of the Potomac-Raritan-Magothy aquifer system in the northern Coastal Plain of New Jersey.	U.S. Geological Survey Water Re-sources Investigations Report 90-4016 (Gronberg and others, 1991.

APPENDIX A--Continued

Descriptions and sources of data on the hydrogeology and water resources of the South River study area--Continued

Description	Source
A report on the geophysical survey of the hydrogeologic units in the areas of South Amboy, New Brunswick, and Hightstown, N.J., conducted by the New Jersey Geological Survey, 1984-87.	S.K. Sandberg and others (New Jersey Geological Survey, written commun., 1988).
A data base containing well records and lithologic, geologic, and water-quality information maintained by the U.S. Geological Survey.	U.S. Geolgoical Survey, WATSTORE Ground-water file (U.S. Geological Survey, 1975).
Miscellaneous data pertaining to permitted wells in New Jersey.	Well records at the New Jersey Department of Environmental Protection and Energy.
The interpretations of regional hydrologic properties of the Potomac-Raritan-Magothy aquifer system in the northern Coastal Plain of New Jersey.	New Jersey Geological Survey, Geological Survey Report 18 (Pucci and others, 1989).

Well-construction and synoptic water-level data for wells measured during fall 1984 and spring 1986

[Under latitude and longitude columns, the first two digits represent degrees, the second two digits represent minutes, and the final two digits represent seconds; MUA, Municipal Utilities Authority; WD, Water Department; WC, Water Company; CO, Company; --, data not available]

Well number	Latitude	Longitude	Owner	Local name	Permit number	Year drilled	Altitude of land surface[1] (feet)	Screened interval[2] (feet)	Water-level altitude[1] 1984	Date	1986	Date
				UPPER-AQUIFER WELLS								
21-4	401408	743114	PRNCTON TURF FM	S.KRISTAL 1973	28-07959	1973	145	290-330	--	--	45	05/02
21-21	401631	743246	MCGRAW HILL PUB	MCGRAW HILL 1	28-02937	1958	97	153-173*	56	11/09	54	03/29
23-15	401842	743055	CRANBURY TWP WD	CTWD 2	48-00064	1917	95	110	--	--	65	03/27
23-18	401841	742905	CARTER WALLACE	CW 2	25-02527	1957	98	161-201*	--	--	56	03/25
23-22	401857	742908	CARTER WALLACE	CW 9	48-00001	1951	120	209	57	11/07	53	03/25
23-24	401858	743015	DANSER, CLENDON	1	28-03139	1959	115	152*	61	11/08	--	--
23-32	401918	743048	BARCLAY FARMS	1 (C.DANSER)	28-01378	1954	120	152*	--	--	63	03/28
23-35	402010	742838	GENERAL FOODS	1	28-02016	1956	138	167-197	--	--	58	03/26
23-51	402432	742212	ANHEUSER-BUSCH	BUSCH 6	28-08209	1973	37	51-71	8	11/06	16	03/26
23-96	402236	742535	HELMETTA WC	6(4-R)	28-07432	1972	40	32-42	38	11/11	38	03/25
23-98	402051	742604	NJ WATER CO	JAMESBURG 6	28-01426	1954	50	99-120	--	--	46	03/24
23-100	402053	742603	NJ WATER CO	JAMESBURG 7	28-01612	1955	45	118-129*	41	11/07	45	03/24
23-109	402302	742256	DUHERNAL WC	DUHERNL OBS 26	48-00195	1942	24	101	-4	11/05	1	03/27
23-131	402334	742231	DUHERNAL WC	DUHERNAL 8	48-00215	1938	24	65-80	4	11/05	--	--
23-142	402346	741832	OLD BRIDGE MUA	BROWNTOWN 1	29-03635	1967	90	199-249	0	11/01	-9	03/26
23-145	402348	742050	OLD BRIDGE MUA	11-1972	28-07470	1972	30	80-120	6	11/01	--	--
23-150	402351	742230	DUHERNAL WC	DUHERNAL 25	28-02770	1958	10	57-67	--	--	1	03/27
23-151	402352	742224	DUHERNAL WC	DUHERNAL OBS 4	48-00320	1938	25	64-75	2	03/29	8	03/27
23-156	402353	742056	OLD BRIDGE MUA	10-1972	28-07471	1972	30	90-120	--	--	4	03/26
23-159	402353	742152	DUHERNAL WC	DUHERNAL OBS 5	48-00321	1938	20	55-63	8	11/05	--	--
23-161	402358	742211	DUHERNAL WC	DUHERNAL 2	48-00203	1938	18	62-73	-2	11/05	-28	03/27
23-172	402404	742205	DUHERNAL WC	DUHERNAL 1	48-00209	1938	13	55-75	-10	11/05	-15	03/27
23-173	402406	741620	OLD BRIDGE BD E	IRA-71	--	1971	60	173-193*	-5	11/07	-4	03/26
23-174	402407	741924	OLD BRIDGE MUA	BROWTOWN OBS	29-03635	1961	45	150	8	11/01	9	03/26
23-180	402438	742129	DUHERNAL WC	DUHERNAL OBS 1	48-00319	1938	19	57-67	5	11/05	5	03/27
23-182	402449	741819	BOWNE, CLYDE	BROWNTOWN	--	1932	31	66-71*	17	11/07	15	03/28
23-190	402526	741603	NAPPI TRUCK CO	2-1965	29-04772	1965	140	253*	5	11/02	4	03/28
23-193	402536	742012	PERTH AMBOY WD	PERTH AMBOY 4	28-01623	1955	15	52-67	4	11/05	--	--
23-195	402537	742001	PERTH AMBOY WD	PERTH AMBOY 5	28-05579	1965	15	50-80	--	--	5	03/25
23-205	402700	741454	OLD BRIDGE MUA	LAWRENCE HAR 8	29-00022	1948	60	193-213	--	--	-3	03/26
23-208	402712	741806	OLD BRIDGE MUA	1-HOPE PK	--	1956	140	167-181	25	11/02	23	03/28
23-227	402012	742833	GENERAL FOODS	3	28-06234	1967	132	168-198	65	11/05	59	03/26
23-228	402015	742757	MONROE TWP MUA	OBS 3-1961	28-04251	1961	147	128-138	64	11/05	59	03/27
23-244	402131	742245	REESE, AUGUST	1971	28-07145	1971	60	152-158	-5	11/07	-4	03/28
23-245	402202	742305	MONROE TWP MUA	RELIABLE 1	28-04638	1963	55	131-161	17	11/05	17	03/27
23-250	402252	742301	DUHERNAL WC	DUHERNL OBS 10	--	1938	22	83-93	3	11/05	5	03/27
23-292	402109	743012	MONROE TWP MUA	OBS 2-1961	49-00076	1961	107	93-104*	76	11/07	--	--
23-294	402124	742824	KORLESKI	KORLESKI 1	28-06652	--	140	104	74	11/06	68	03/28
23-299	402130	742821	BASF-WYANDOTTE	J-4	28-11549	--	120	107-129	--	--	57	03/24
23-343	402553	742033	NJ WATER POLICY	SUN BISCUIT 5	--	1968	17	36-39	8	11/01	8	03/25
23-344	402558	742013	SAYREVILLE WD	SWD 2	48-00322	1957	22	31-37	15	11/02	15	03/25
23-351	402605	741959	SAYREVILLE WD	SWD 1	--	--	35	76-82	14	11/02	18	03/25
23-359	402618	741952	SAYREVILLE WD	SWD D	28-03214	1958	29	64-75	25	11/02	21	03/25
23-369	402630	741949	SAYREVILLE WD	SWD H	28-03854	1960	45	67-83	36	11/02	35	03/25
23-403	402745	741631	SAYREVILLE WD	SWD Q-1973	29-06767	1973	40	78-136	7	11/02	0	03/25
23-433	402555	742133	NJ WATER POLICY	SO RIVER 4	--	1968	20	30-33	8	11/01	--	--
23-442	402252	742432	SPOTSWOOD WD	SWWD 3	28-07828	1973	30	63.5-78	19	11/08	20	03/26
23-444	402326	742313	DUHERNAL WC	DUHERNAL 9	--	1938	14	62-72	11	11/05	12	03/27
23-490	401925	742620	MONROE TWP MUA	8-R	28-08490	1974	167	287-325	48	11/05	45	03/27
23-494	402329	742331	SPOTSWOOD WD	SWWD 5	28-10465	1978	23	83-97	--	--	15	03/26
23-497	402109	742747	FORSGATE INC	HWH WELL	28-08737	1975	130	109-114*	--	--	54	03/26
23-507	401801	743154	DANSER, FRANK	UNUSED DOM	--	--	105	130	67	11/09	63	03/27
23-517	401923	742830	KAISER AG CHEM	MONROE TWP	28-11719	1963	120	165-196	60	11/06	56	03/25
23-557	402820	741629	SOUTH AMBOY WD	SAWD 9A	26-04812	1979	20	48-58	16	11/01	--	--
23-567	401950	742750	MONROE TWP MUA	MTMUA 16A	28-13397	1983	137	163-244	54	11/05	53	03/27
25-13	401137	740121	AVON WATER DEPT	AWD 4	29-07461	1974	29	1105-1165	-24	11/05	-17	05/01
25-33	401556	740915	NAD EARLE	NAD EARLE 1	--	1944	126	775-810	--	--	-22	04/02
25-34	401558	740908	NAD EARLE	NAD EARLE 2(B)	--	1944	135	810-836	-29	11/08	-27	04/02
25-37	401607	741209	HOMINY H GOLF C	GLF CLB 2-1963	29-04068	1963	137	686-706	-31	11/09	-23	04/02
25-45	401810	740957	FLOCK AND SONS	1	29-03972	1963	66	649-677	-35	11/07	-28	04/03

Footnotes at end of table

Well-construction and synoptic water-level data for wells measured during fall 1984 and spring 1986

Well number	Latitude	Longitude	Owner	Local name	Permit number	Year drilled	Altitude of land surface[1] (feet)	Screened interval[2] (feet)	Water-level altitude[1] 1984	Date	1986	Date
				UPPER-AQUIFER WELLS--Continued								
25-56	401744	742135	ENGLISHTWN B WD	ENGLISHTOWN 2	28-05400	1965	70	363-384	11	11/08	9	04/02
25-62	401134	741014	ROKEACH & SONS	4-DEEP	29-03492	1961	80	831-885	-27	10/25	-29	03/29
25-85	401436	741525	3M COMPANY	1	29-02370	1957	120	653-700	-38	11/09	-31	04/03
25-91	401516	741530	BROCKWAY GLASS	BROCKWAY 2	29-05708	1969	140	632-685	-33	11/13	-24	04/03
25-97	401625	741501	FREEHOLD TWP WD	6-OLD SO.GULF2	29-04708	1966	195	596-656	--	--	-27	04/01
25-99	401633	741728	FREEHOLD BOR WD	FREEHOLD 3	29-04419	1964	105	468-567	-28	11/08	-22	04/01
25-111	402532	740932	SHORELANDS WC	W KEANSBURG 1	29-02400	1958	59	326-366	-31	11/08	-22	04/03
25-112	402537	740933	SHORELANDS WC	W KEANSBURG 2	29-03096	1960	44	312-352	-36	11/08	--	--
25-116	402400	735912	HIGHLANDS W D	HWD 2 NEW	29-03509	1961	10	600-660	-21	11/07	--	--
25-118	402401	735934	HIGHLANDS W D	HWD 1	49-00004	1949	15	649-709	-30	11/07	--	--
25-119	402403	735923	HIGHLANDS W D	HWD 3	29-06480	1973	15	719-779	-26	11/07	--	--
25-121	402023	741100	PENNWALT CORP	1 (PENNWALT)	29-03033	1960	80	560-590	-30	11/07	-26	04/03
25-146	402327	741114	BELL TELE CO	CRAWFRD HILL 1	29-03673	1962	280	555-585	-33	11/09	-26	05/02
25-154	402445	741019	SHORELANDS WC	W KEANSBURG 3	29-04207	1964	73	400-430	-42	11/13	-21	04/03
25-174	401243	741520	ADELPHIA W C	2-1974	29-06947	1974	102	654-769	--	--	-36	04/02
25-177	401255	741147	SCHROTH, EMIL A	SCHROTH	29-05691	1969	95	781-801	-22	11/09	-17	04/02
25-196	402628	740744	KEANSBURG MUA	KWD 3	49-00047	1942	12	308-348	-30	11/09	-23	04/04
25-197	402535	741214	KEYPORT BORO WD	KEYPORT 7	29-08379	1976	35	304-354	-19	11/08	-15	04/04
25-199	402542	741220	KERR GLASS CO	REPLACEMENT 2	25-04275	1964	20	285-315	-25	11/08	-21	04/03
25-206	402625	741145	KEYPORT BORO WD	KEYPORT 4	49-00080	1939	14	225-249	-12	11/08	-9	04/04
25-207	402626	741144	KEYPORT BORO WD	KEYPORT 6	29-05974	1970	11	247-277	-22	11/08	-9	03/25
25-214	401429	742146	MANALAPAN TWD	LAMBS RD 1	28-07184	1971	190	585-641	--	--	-5	04/01
25-218	401557	742318	BOY SCOUTS AMER	QUAIL HILL 2	--	1967	250	510-527	17	11/06	32	05/02
25-220	401537	742012	BATTLEGROUND CC	IRRIGATION	28-06114	1967	120	539-569	-23	11/08	-18	04/03
25-244	401850	741459	GORDONS CRNR WC	GORDONS 7	29-05790	1969	172	524-594	-28	11/07	-30	04/03
25-251	401908	741510	GORDONS CRNR WC	GORDONS 9	29-06232	1971	128	478-528	--	--	-39	04/03
25-259	402035	741423	MARLBORO S HOSP	STATE HOSP 12	29-00073	1950	155	508-593	-21	11/09	-11	04/03
25-282	402507	741344	BAYSHORE SEW AU	BAYSHORE 1	29-08486	1976	10	245-260	-7	11/09	-4	04/01
25-284	402515	741450	MATAWAN BORO WD	MATAWAN BORO 3	29-01731	1956	90	231-271	-9	11/13	-2	04/01
25-288	402349	741232	ABERDEEN TWP MU	MATAWAN MUA 3	29-05351	1967	83	345-425	-31	11/09	-24	04/02
25-290	402403	741246	ABERDEEN TWP MU	MATAWAN OBS 1	--	1961	71	353*	-23	11/09	-19	04/02
25-293	402403	741245	ABERDEEN TWP MU	MATAWAN MUA 2	29-03818	1962	73	316-354	-28	11/09	-17	04/02
25-294	402428	741345	MATAWAN BORO WD	MATAWAN BORO 1	49-00042	1944	20	222-252	-18	11/13	-17	04/01
25-295	402427	741348	MATAWAN BORO WD	MATAWAN BORO 2	49-00043	1943	20	228-258	--	--	-17	04/01
25-303	402106	740810	BAMM HOLLOW C C	BHCC 1	29-05164	1966	70	527-600	--	--	-26	04/03
25-316	402536	735905	STATE OF NJ	SANDY HOOK SP1	29-04299	1965	11	371-397	-5	11/06	--	--
25-317	402612	740511	SEA COAST PROD	SMITH 1	--	1946	10	420*	-12	11/06	-10	04/03
25-321	402706	735952	NATIONAL PK SER	FT HANCOCK 4	--	1941	5	332-486	-5	11/08	--	--
25-322	401157	742418	RESTINE, P J	RESTINE 1	28-01842	1956	210	667-697	--	--	5	04/01
25-332	401930	735841	MON BCH CLD STR	MBCS 1971 DEEP	29-06173	1971	10	817-850	-17	11/08	-15	03/27
25-333	401214	740355	NJ/AMERICAN WC	JUMPING BR 5	29-01922	1956	35	999.75-10	-46	--	-22	04/01
25-334	401214	740355	NJ/AMERICAN WC	JUMPING BR 4	29-00137	1951	23	1013-1065	-41	11/05	-25	04/01
25-345	401233	740100	NJ/AMERICAN WC	LAYNE 3-1958	29-02660	1958	20	1085-1125	-22	11/05	-16	04/02
25-351	401323	740156	NJ/AMERICAN WC	WHITESVILLE	--	--	18	875*	-34	11/06	--	--
25-358	402047	740420	RED BANK W D	1B-1950	29-00079	1950	40	637-687	-32	11/01	-27	03/27
25-362	401312	742802	ROOSEVELT W D	ROOSEVELT 3	28-02219	1956	198	442-472	--	--	33	--
25-419	402632	741049	UNION BEACH W D	UBWD 1 1962	29-03786	1962	10	235-285	-17	11/07	-12	03/28
25-420	402634	741051	UNION BEACH W D	UBWD 2 1969	29-05724	1969	10	262-289	-10	11/07	-9	03/28
25-456	402640	740904	INT FLAVOR FRAG	IFF-3R	29-08092	1976	10	277-316	--	--	-18	04/01
25-457	401551	742212	KNOB HILL C C	KNOB 1-74	28-08484	1974	108	465-495	11	11/09	11	04/03
25-459	402219	740337	NAVESINK C C	1-78	29-09335	1978	80	551-612	-21	11/01	-19	03/27
25-462	402717	740816	KEANSBURG AMUSE	1-69	29-05558	1969	10	200-250	-13	11/08	--	
25-493	401231	741127	HOWELL TWP	1-1975	29-07784	--	130	860*	-18	11/09	-10	04/02
25-496	402441	740233	ATLAN HIGH W D	AHWD 4	29-10478	1980	15	510-543	-10	11/07	--	--
25-502	401411	741608	FREEHOLD TWP WD	8	29-11033	1981	125	616-671	--	--	-31	04/01
25-513	402442	740242	ATLAN HIGH W D	AHWD 5	29-11230	1981	20	506-548	-5	11/07	--	--
25-565	402704	741051	US GEOL SURVEY	CONASCONK PT.	29-15627	1985	10	201-211	--	--	-9	04/04

APPENDIX B--Continued

Well-construction and synoptic water-level data for wells measured during fall 1984 and spring 1986

Well number	Latitude	Longitude	Owner	Local name	Permit number	Year drilled	Altitude of land surface[1] (feet)	Screened interval[2] (feet)	Water-level altitude[1] 1984	Date	1986	Date
				MIDDLE-AQUIFER WELLS								
21-12	401536	742920	E WINDSOR MUA	6 TWIN RIVERS	28-07034	1971	115	520-560	--	--	31	03/27
21-22	401702	743106	E WINDSOR MUA	EWMUA 3	28-05440	1965	100	337-367	45	11/09	44	03/27
21-25	401717	743352	CARTER WALLACE	KENTILE 1	--	1954	100	205-226	65	11/08	--	--
21-27	401730	743202	E WINDSOR MUA	EWMUA 1	28-04934	1964	98	279-295	--	--	71	03/27
23-09	401800	743206	DANSER, FRANK	IRR-1950	28-00180	1950	100	250-280	69	11/09	--	--
23-11	401818	742932	CARTER WALLACE	CW 1	28-02321	1956	115	255-285	52	11/07	49	04/01
23-13	401841	743355	STULTZ, STANLEY	1-1954(CLIFRD)	28-01396	1954	100	133-163	73	11/08	72	03/28
23-17	401843	743055	CRANBURY TWP WD	CTWD 3	28-04559	1963	98	268-298	64	11/08	62	03/27
23-28	401924	742909	CARTER WALLACE	CW 5	28-05006	1964	105	298-335*	57	11/07	53	03/25
23-29	401916	742920	NJ TURNPIKE AU	7S-1	--	--	125	385	--	--	59	04/09
23-33	401923	743247	DYAL, LEROY	DYAL 1 (1951)	28-00556	1951	90	170-180	67	11/08	66	03/27
23-39	402410	742531	KONUK, JOSEPH	KONUK 1	28-02000	1956	140	225-245	--	--	0	03/26
23-50	402432	742212	ANHEUSER BUSCH	BUSCH 5	28-04657	1963	37	215-265	-51	11/06	-54	03/26
23-57	402441	742448	E BRUNSWICK TWD	COLONIAL OAKS	28-01202	1954	122	216-241	-24	11/07	-14	03/25
23-58	402448	742700	MIDDLESEX W C	TAMARACK 1-75	28-08704	1975	108	87-107	29	11/14	30	03/24
23-63	402501	742440	E BRUNSWICK TWD	EBTWD 1	28-00191	1951	110	161-181	-20	11/06	-6	03/25
23-64	402503	742812	E BRUNSWICK TWP	BEECHER OBS	--	1941	85	35-40	68	11/01	66	03/23
23-66	402516	742408	COLLINS, EDWARD	COLLINS	28-01124	1954	140	198-223	-25	11/02	-16	03/25
23-70	402555	742719	FISCHER, ROBERT	FISCHER	--	1936	73	0-21	58	11/09	57	04/01
23-72	402635	742402	SMITH, LAWRENCE	SMITH 2-1972	28-07448	1972	80	120-130	--	--	-11	03/24
23-73	402649	742524	PREMIUM PLASTIC	1 PREM PLASTIC	28-01913	1956	80	72-82*	20	11/02	--	--
23-88	403128	742049	AMERICAN CAN CO	EDISON WRKS P2	25-07915	1960	71	-29*	--	--	66	04/02
23-89	403128	742051	AMERICAN CAN CO	EDISON WRKS P1	25-09026	1959	70	-26	--	--	62	04/02
23-94	402239	742530	HELMETTA WC	5-1962 (OLD#2)	48-00242	1962	60	183-193	--	--	15	03/25
23-97	402247	742503	DUHERNAL W CO	DUHRNL OBS 49F	--	1946	39	236-301	5	11/05	--	--
23-107	402252	742246	DUHERNAL W CO	DUHRNL OBS 54F	--	1946	28	311-334	--	--	-2	03/27
23-114	402319	742246	DUHERNAL W CO	DUHRNL OBS 52F	--	1945	26	225-237	-30	11/05	-24	03/27
23-127	402330	742258	DUHERNAL W CO	DUHERNAL AF	48-00213	1945	12	236-296	-32	11/05	-25	03/27
23-132	402335	742136	DUHERNAL W CO	DUHRNL OBS 56F	--	1947	25	262-267	-38	11/05	-34	03/27
23-133	402350	742051	OLD BRIDGE MUA	OLD BRIDGE 6	28-04722	1963	30	266-350	--	--	-43	03/26
23-136	402353	742056	OLD BRIDGE MUA	OLD BRIDGE 5	28-02560	1957	30	280-312	-40	11/01	--	--
23-146	402350	741834	OLD BRIDGE MUA	BROWNTOWN 3	29-04997	1966	80	435-480	--	--	-51	03/26
23-147	402350	741840	OLD BRIDGE MUA	BROWNTOWN 4	29-04998	1966	80	425-475	-58	11/01	--	--
23-171	402404	742204	DUHERNAL W CO	DUHERNAL BF	47-00208	1946	20	240-300	-46	11/05	-41	03/27
23-176	402407	741924	OLD BRIDGE MUA	OBS 1-1972	29-06429	1972	45	321-363	-50	11/01	-47	04/28
23-179	402436	742041	OLD BRIDGE MUA	OBS 2-1972	29-06430	1972	10	250-292	-47	11/01	-44	04/28
23-194	402536	742018	PERTH AMBOY WD	RUNYON 1	--	1930	18	201-281	-43	11/05	-46	03/25
23-201	402614	741744	OLD BRIDGE MUA	MIDTOWN 1	29-02059	1956	15	266-306	-49	11/01	-42	03/28
23-202	402625	741611	NJ DEPT CONSERV	CHEESQUAKE SP1	--	1957	11	299-320	-55	11/06	-47	03/28
23-206	402700	741454	OLD BRIDGE MUA	LAWRENCE HAR 9	29-00768	1953	60	360-395	--	--	-65	03/26
23-226	402013	742834	GENERAL FOODS	2	28-06144	1967	132	330-364	59	11/05	54	03/26
23-229	402015	742757	MONROE TWP MUA	OBS 4-1961	28-04252	1961	147	319-330	57	11/05	53	03/27
23-232	402023	742858	MONROE TWP MUA	FORSGATE 11	28-04106	1961	130	272-314	--	--	62	03/21
23-238	402038	742755	FORSGATE FARMS	FARM WELL 4-R	28-05123	1964	145	337-367*	50	11/05	46	03/26
23-257	403052	741654	ALL STAR DAIRY	ALL STAR 1	--	1932	61	158	-24	11/02	--	--
23-261	403150	741603	CHEVRON OIL CO	1	46-00185	1951	30	74-83	18	11/06	--	--
23-262	403150	741603	CHEVRON OIL CO	OBS 1	46-00186	1951	30	72-82	17	11/06	17	03/27
23-263	403200	741620	CHEVRON OIL CO	2	--	1950	45	96-106	9	11/06	9	03/27
23-264	403200	741620	CHEVRON OIL CO	OBS 2	--	1950	45	96-106	9	11/06	9	03/27
23-265	403211	741612	CHEVRON OIL CO	11	26-00124	--	14	11-94	12	11/06	12	03/27
23-266	403211	741631	CHEVRON OIL CO	3	--	1951	40	87-96	17	11/06	39	03/27
23-267	403212	741635	CHEVRON OIL CO	OBS 3	--	1951	40	86-96	--	--	39	03/27
23-270	403231	741616	AMERICAN CYANAM	TEST 2	--		12	53-57*	9	11/06	9	03/27
23-284	402022	743306	SIMONSON BROS	1	28-00500	1952	90	90*	81	11/07	81	03/28
23-289	402056	742937	MONROE TWP MUA	15(KIMBRY-CLK)	49-00078	1956	134	227-257	71	11/07	76	03/28
23-291	402109	743013	MONROE TWP MUA	OBS 1-1961	28-04249	1961	107	192-203	70	11/07	--	--
23-295	402125	742920	INTERN PERMALIT	LAKES CARBON 1	28-06050	1966	120	187-233	74	11/06	70	03/24
23-298	402129	742901	STAUFFER CHEM	1	28-05434	1965	123	217-237	78	11/06	69	03/24
23-302	402138	742940	S BRUNSWICK MUA	FORSGATE 14	28-01398	1955	115	170-200	--	--	77	03/26
23-305	402143	742821	PHELPS DODGE CO	1-1957	28-02430	1957	127	205-225	70	11/06	69	03/24
23-306	402147	742847	PHELPS DODGE CO	PHELPS DODGE 3	28-06538	1968	120	201-207	75	11/06	70	03/24
23-315	402204	743024	S BRUNSWICK MUA	13	28-07187	1971	102	103-138	67	11/07	76	03/26
23-319	402220	742950	S BRUNSWICK MUA	12	28-04858	1963	93	110-135	--	--	76	03/26
23-329	402315	742652	DEY BROTHERS	2	28-09567	1955	115	215-248	36	11/01	37	03/25
23-348	402605	741957	SAYREVILLE W D	OBS WELL 101	28-06400	1968	30	269-279	-43	11/02	-41	03/25

Well-construction and synoptic water-level data for wells measured during fall 1984 and spring 1986

Well number	Latitude	Longitude	Owner	Local name	Permit number	Year drilled	Altitude of land surface[1] (feet)	Screened interval[2] (feet)	Water-level altitude[1] 1984	Date	1986	Date
				MIDDLE-AQUIFER WELLS--Continued								
23-350	402608	741955	SAYREVILLE W D	OBS WELL 102	28-06401	1968	30	267-277	-46	11/02	-45	03/25
23-353	402611	741955	SAYREVILLE W D	OBS WELL 103	28-06402	1968	35	262-273	-42	11/02	-41	03/25
23-370	402631	742053	HERCULES POWDER	HERCULES 6	--	1946	20	164-194	-35	11/06	-34	03/24
23-371	402638	742022	HERCULES POWDER	HERCULES 5	48-00324	1929	48	182-228	--	--	-35	03/24
23-376	402649	742025	HERCULES POWDER	HERCULES 3	48-00323	1928	41	180-220	-40	11/01	-41	03/24
23-380	402659	742020	HERCULES POWDER	HERCULES 2	48-00325	1927	48	181-237	-38	11/01	--	--
23-384	402705	742023	HERCULES POWDER	HERCULES 1REBT	45-00310	1939	54	170-225	-35	11/06	-20	03/24
23-386	402701	741917	E I DUPONT	6	49-00079	1930	102	253-314	-44	11/07	--	--
23-389	402710	741910	E I DUPONT	5	--	1928	107	249-304	-44	11/05	--	--
23-391	402711	742030	HERCULES POWDER	HERCULES 4	--	1928	47	163-226	-38	11/06	--	--
23-392	402716	741922	E I DUPONT	1	--	1924	102	237-291	-43	11/05	--	--
23-393	402715	741932	E I DUPONT	3	49-00077	1925	94	244-285	-43	11/05	--	--
23-401	402744	741628	SAYREVILLE W D	MORGAN P	29-05352	1967	44	254-288	-69	11/02	-44	03/25
23-404	402745	741645	SAYREVILLE W D	MORGAN OBS 1	29-05043	1966	23	238-248	--	--	-36	03/25
23-411	402822	741630	SOUTH AMBOY W D	SAWD 8	46-00144	1947	10	209-234	-61	11/01	-44	04/28
23-423	402943	741808	NL INDUSTRIES	CL TEST 1	--	1956	30	75-84	-39	11/02	--	--
23-425	402729	741937	E I DUPONT	PARLIN 60F	--	1966	147	282-288	-32	11/05	--	--
23-429	402923	741648	JERS CENTRAL PL	WERNER STA 6	--	1969	18	154-177	-35	11/01	-27	03/28
23-430	402923	741651	JERS CENTRAL PL	7-1972	26-04485	1972	12	135-165	-36	11/01	-28	03/28
23-438	402559	742142	SOUTH RIVER W D	SRWD 5	28-09722	1977	20	132-182	-33	11/01	--	--
23-439	402633	742200	SOUTH RIVER W D	SRWD 2 OBS	28-05987	1967	21	121-126	-29	11/01	-28	03/25
23-440	402648	742226	HODGES BUS CO	1	--	1922	15	195*	-22	11/01	-22	03/24
23-441	402742	742309	HERBERT SAND CO	HSC 3	28-01174	1964	6	49-52	2	11/05	2	04/01
23-445	402328	742318	SPOTSWOOD WD	TW 4F-76	28-09117	1976	10	195-264	-35	11/08	-23	03/26
23-456	402404	742235	SCHWEITZER, P J	1R	28-01955	1956	21	235-275	-67	11/05	-77	03/25
23-462	403043	741842	UNION CARBIDE	CARBIDE 1	26-03325	1965	15	47-57	--	--	12	03/27
23-482	403242	741617	AMERICAN CYANAM	TEST 1	--	--	11	44-76	10	11/02	10	03/27
23-492	402129	742823	BASF-WYANDOTTE	BASF 3	28-10192	1978	130	230-276	65	11/06	63	03/24
23-503	401938	742404	EONAITIS, PETER	EONAITIS 1	28-05725	1964	140	410-440	16	11/07	16	03/26
23-504	402047	742820	FORSGATE INC	I-IRR	28-07539	1972	141	288-340	62	11/05	58	03/26
23-506	402358	742612	SMITH, LAWRENCE	3-1958	28-03020	1958	120	213-223	11	11/02	14	03/24
23-510	402234	743114	IBM CORP	GW 20	28-10269	1978	119	30-65	85	11/09	80	04/01
23-511	402232	743114	IBM CORP	S BRUNSWICK TWP	--	--	118	65-95	82	11/09	78	04/01
23-514	402755	742258	HERBERT SAND CO	E BRUNSWICK TWP	28-09469	1976	5	25-35	3	11/05	2	04/01
23-543	403242	741526	SHELL OIL CO	5(S2)	--	--	25	42*	10	11/02	6	03/27
23-547	403250	741534	SHELL OIL CO	3	--	--	26	43*	-1	11/02	--	--
23-548	403257	741539	SHELL OIL CO	8(R7)	--	--	17	36*	-2	11/02	5	03/27
23-552	402018	743021	S BRUNSWICK MUA	15	28-10991	1979	105	116-166	--	--	64	03/26
23-566	402129	742901	STAUFFER CHEM	D-2	28-12856	1982	124	122-225	74	11/05	70	03/24
25-055	401744	742135	ENGLISHTWN B WD	ENGLISHTOWN 1	28-05189	1963	70	651-671	--	--	-9	04/03
25-153	402444	741010	SHORELANDS WC I	W KEANSBURG 4	29-05942	1970	65	635-690	-89	11/08	-93	04/03
25-230	402004	741853	GORDONS CRNR WC	GORDONS 5	29-06353	1972	125	580-670	-36	11/07	--	--
25-231	402004	741855	GORDONS CRNR WC	GORDONS 6	29-07402	1974	125	592-708	--	--	-31	04/03
25-249	401859	741809	GORDONS CRNR WC	GORDONS 4	29-05548	1968	143	741-810	--	--	-33	04/03
25-262	402102	741353	MARLBORO S HOSP	STATE HOSP 15	29-05023	1966	140	730-810	-42	11/09	-41	04/03
25-268	402117	741511	MARLBORO T MUA	2-PROD	29-06361	1972	114	632-698	-45	11/13	--	--
25-272	402208	741452	MARLBORO T MUA	MARLBORO 1 OBS	29-06527	1972	117	670-680	-50	11/07	-48	04/02
25-297	402603	741422	ABERDEEN TWP WD	MATAWAN TWP 1	29-02052	1956	80	447-487	-71	11/09	-71	04/01
25-318	402700	735958	NATIONAL PK SER	FT HANCOCK 2	--	1906	8	600-724	-7	11/06	--	--
25-320	402705	735959	NATIONAL PK SER	FT HANCOCK 5A	--	1970	14	838-878	-8	11/06	--	--
25-452	401857	741811	GORDONS CRNR WC	GORDONS 10	29-10864	1980	135	740-800	-37	11/08	-35	04/03
25-453	402632	741051	UNION BEACH W D	UBWD 3 1977	29-08985	1977	10	480-532	-85	11/07	--	--
25-466	402610	741351	ABERDEEN TWP WD	3-77	29-09580	1977	56	420-470	-74	11/13	-72	04/01
25-503	401640	741722	FREEHOLD BOR WD	FREEHOLD 6	29-11217	1981	140	835-943	--	--	-4	04/01

[1]Datum is sea level

[2]Depth below land surface

*Well depth

APPENDIX C

Chronology of events and references on saltwater intrusion of the upper and middle aquifers in Middlesex and Monmouth Counties
[ppm, parts per million]

Event or reference	Documentation
1885, Wells were drilled on the "Bank of the Raritan" by the Sayre & Fisher Brick Company of Sayreville.	H.G. Fairbanks (U.S. Army Corps of Engineers, written commun., 1936)
1926-1928, Water from Raritan Copper Company wells contained chloride in concentrations up to 236 ppm in wells in Sayreville, New Jersey. First documentation of saltwater contamination in the middle aquifer.	
1930, Sayre & Fisher Brick Company abandoned one well because of high salt-water concentrations. Three other wells at the site were not contaminated with saltwater.	
1931, Washington Canal deepened to 12 feet, which likely increased hydraulic connection between saltwater in the Raritan River estuary and ground water in the middle aquifer.	
1933, Sayre & Fisher Brick Company abandons remaining wells in the middle aquifer because of saltwater contamination.	
1936, Saltwater intrusion of the middle aquifer in the Sayreville, South Amboy, and South River area was first investigated.	New Jersey Department of Conservation and Economic Development, Division of Water Policy and Supply, Special Report 7 (Barksdale, 1937).
1940, M.E. Johnson concluded that further dredging of the Raritan River, South River, and Washington Canal would lead to further saltwater movement into the middle aquifer.	Meredith E. Johnson (New Jersey State Geologist, written commun., 1940)

Chronology of events and references on saltwater intrusion of the upper and middle aquifers in Middlesex and Monmouth Counties--Continued

Event or reference	Documentation
1943, Chloride concentrations were reported for selected wells in the middle aquifer in Sayreville Borough area. The potential for saltwater intrusion into the upper aquifer was discussed.	New Jersey Department of Conservation and Economic Development, Division of Water Policy and Supply, Special Report 8 (Barksdale and others, 1943).
1943, In an effort to contain the problem of saltwater intrusion, limitations on ground-water withdrawals from the middle aquifer in Middlesex County were proposed by H.C. Barksdale.	
1943 and 1958 chloride-concentration contours showed saltwater intrusion progressing into the middle aquifer in Sayreville Borough.	New Jersey Department of Conservation and Economic Development, Division of Water Policy and Supply, Special Report 17 (Appel, 1962).
1962, A tidal dam on the South River was proposed by the U.S. Army Corps of Engineers as a means of containing potential saltwater intrusion in the middle aquifer.	
1963, The effects of canal and river-channel dredging on saltwater intrusion into the middle aquifer were examined by use of analog-model methods.	Irwin Remson and C.A. Appel (U.S. Geological Survey, written commun., 1963).
1965, A technical and economic evaluation of the feasibility of constructing a tidal dam on the South River was done.	New Jersey Department of Conservation and Economic Development, Division of Water Policy and Supply, Special Report 21, 1965.
1969, A freshwater reservoir at Crab Island in the Raritan River was proposed by the U.S. Army Corps of Engineers to prevent saltwater intrusion into the middle aquifer.	Irwin Remson and A.A. Fungaroli (U.S. Geological Survey, written commun., 1969).

Chronology of events and references on saltwater intrusion of the upper and middle aquifers in Middlesex and Monmouth Counties--Continued

Event or reference	Documentation
1970, Saltwater intrusion into the upper aquifer was first reported in the vicinity of Keyport and Union Beach Boroughs, Monmouth County.	U.S. Geological Survey Water-Supply Paper 2184 (Schaefer and Walker, 1981).
1977, Trends in monitoring of saltwater in the Sayreville area and area of Keyport and Union Beach show continued intrusion of saltwater. Production wells for Keyport and Union Beach Boroughs abandoned.	U.S. Geological Survey Water-Resources Investigations Report 83-4061 (Schaefer, 1983).
1985, Because of the threat of saltwater intrusion, the New Jersey Department of Environmental Protection designated the middle and upper aquifers in the northern Coastal Plain of New Jersey as "Critical Area No. 1".	J.W. Gaston (New Jersey Department of Environmental Protection, written commun., 1985).

APPENDIX D

Well-construction and selected chloride-concentration data for wells in or near the area of Keyport and Union Beach Boroughs

[All wells screened in the upper aquifer; concentrations in milligrams per liter; location of wells shown in figure 55; altitude datum is sea level; screen depth in feet below surface; dates for year at top of column unless noted otherwise; --, data not available; MUA, Municipal Utilities Authority; WD, Water Department; WC, Water Company; Co, Company; Boro, Borough; Twp, Township]

Well number	Owner	Municipality	Local identifier	Date drilled	Altitude of land surface (feet)	Screen depth (feet)	Chloride measurement and date 1983 (Month/day)	(Chloride concentration)
23-205	Old Bridge MUA	Old Bridge Twp	Lawrence Harbor 8	1948	60	193-213	12/2	8
23-403	Sayreville Boro WD	Sayreville Boro	Q-1973	1973	40	78-136	9/8	13
23-414	South Amboy City WD	Sayreville Boro	10	1967	10	38-48	9/14	24
23-549	Sayreville Boro WD	Sayreville Boro	R-80	1980	25	70-111	--	--
23-569	Sayreville Boro WD	Sayreville Boro	T-82	1982	90	102-132	9/8	12
25-111	Shorelands WC	Hazlet Twp	1-58	1958	59	326-366	10/12	2
25-112	Shorelands WC	Hazlet Twp	2-60	1960	43	312-352	10/12	2
25-113	Hazlet Twp Bd. of Ed.	Hazlet Twp	1-1970	1970	87	270-302	--	--
25-190	Keansburg Boro WD	Keansburg Boro	Keansburg WD #4	1945	10	280-340	10/12	120
25-191	Keansburg Boro WD	Keansburg Boro	Keansburg WD #6	1968	10	302-362	10/12	26
25-196	Keansburg Boro WD	Keansburg Boro	Keansburg WD #5	1942	12	308-348	10/12	4
25-197	Keyport Boro WD	Keyport Boro	Keyport 7	1976	35	304-354	--	--
25-199	Kerr Glass Co	Keyport Boro	Replacement 2	1964	20	285-315	--	--
25-207	Keyport Boro WD	Keyport Boro	Keyport 6	1970	10	247-277	--	--
25-208	Infern-o-therm Co	Keyport Boro	Infero-therm	--	15	-- -300	--	--
25-282	Bayshore Sewer Aut	Matawan Boro	1-1976	1976	10	245-260	--	--
25-284	Matawan Boro WD	Matawan Boro	Matawan Boro WD	1956	90	231-271	10/13	4
25-292	Aberdeen MUA	Aberdeen Twp	Matawan 1	1962	87	341-414	--	--
25-294	Matawan Boro MUA	Aberdeen Twp	1-1944	1944	20	222-252	10/13	2
25-420	Union Beach WD	Union Beach Boro	Union Beach WD 2	1969	10	262-289	10/13	1,700
25-423	Int. Flavor & Frag., Inc	Union Beach Boro	IFF-2	1951	10	298-328	10/13	2
25-462	Keansburg Amusement Pk	Keansburg Boro	1-69	1969	10	200-250	10/13	2
25-514	Int. Flavor & Frag., Inc	Union Beach Boro	2R-1983	1983	10	266-312	10/13	2
25-565	U.S. Geological Survey	Union Beach Boro	Conaskonk Pt	1985	10	201-211	--	--
25-567	U.S. Geological Survey	Union Beach Boro	Union Beach Water Tower	1986	10	250-270	--	--
25-568	U.S. Geological Survey	Union Beach Boro	JCP&L Union Beach	1986	10	245-265	--	--

APPENDIX-D

Well construction and selected chloride-concentration data for wells in or near the area of Keyport and Union Beach Boroughs--Continued

	Chloride measurement and date					
	1984		1985		1986	
Well number	(Month/day)	Chloride concentration	(Month/day)	Chloride concentration	(Month/day)	Chloride concentration
23-205	10/24	9	9/26	12	10/2	12
23-403	10/16	13	9/20	30	9/30	27
23-414	10/12	32	--	--	10/2	38
23-549	10/18	18	4/10	24	9/30	45
23-569	10/18	8	--	--	9/30	11
25-111	10/30	2	9/19	2	10/1	2
25-112	10/30	2	9/19	2	10/1	2
25-113	--	--	--	--	11/5	2
25-190	3/14	120	9/23	190	10/8	290
25-191	10/31	44	9/23	31	10/8	59
25-196	--	--	--	--	10/8	3
25-197	10/25	3	9/20	3	10/8	3
25-199	10/25	3	9/20	2	10/1	3
25-207	--	--	--	--	10/20	560
25-208	--	--	--	--	10/9	2,800
25-282	--	--	6/12	46	10/1	12
25-284	10/23	4	--	--	10/6	--
25-292	-	--	9/19	2	9/19/85	2
25-294	10/23	2	9/19	2	10/6	2
25-420	10/24	2,300	--	--	10/9	2,300
25-423	10/31	2	9/20	2	10/9	2
25-462	10/31	2	9/20	2	8/7/85	45
25-514	10/31	2	9/20	2	10/9/88	2
25-565	--	--	--	--	4/23/87	3
25-567	--	--	--	--	7/15	2
25-568	--	--	--	--	10/3	2,300

APPENDIX E

Well-construction and selected chloride-concentration data for wells in or near the area of Sayreville and South River Boroughs and South Amboy City

[All wells screened in middle aquifer; concentrations in milligrams per liter; locations of wells shown in figures 61 and 63; altitude datum is sea level; screen depth in feet below land surface; MUA, Municipal Utilities Authority; WD, Water Department; WC, Water Company; CO., Company; BORO, Borough; TWP, Township; --, data not available]

Well number	Owner	Munici-pality	Local ident-ifier	Date drilled	Altitude of land surface (feet)	Screen depth (feet)	1939 (month/day)	1939 (Chloride concen-tration)
23-39	KONUK, JOS.	EAST BRUNSWICK TWP	KONUK	1956	140	225-245	--	--
23-46	POLYSAR CO.	EAST BRUNSWICK TWP	POLYSAR 1	1968	100	200-230	--	--
23-48	ANNHEUSER BUSH	EAST BRUNSWICK TWP	1-1931	1931	30	223-243	12/9	5
23-59	EAST BRUNSWICK TWP	EAST BRUNSWICK TWP	EB-2	1955	120	180-220	--	--
23-80	HERBERT SAND CO	EAST BRUNSWICK TWP	HERBERT SAND RANNEY WELL	--	28	-- - 18	--	--
23-146	OLD BRIDGE MUA	OLD BRIDGE TWP	BROWNTOWN 3	1966	80	435-480	--	--
23-171	DUHERNAL WC	OLD BRIDGE TWP	DUHERNAL BF	1946	20	240-300	--	--
23-196	PERTH AMBOY WD	OLD BRIDGE TWP	1A	1968	20	201-261	--	--
23-197	PERTH AMBOY WD	OLD BRIDGE TWP	2	1968	20	205-260	--	--
23-206	OLD BRIDGE MUA	OLD BRIDGE TWP	LAWRENCE HARBOR 9	1953	60	360-395	--	--
23-352	SAYREVILLE BOROUGH WD	SAYREVILLE BOROUGH	M-67	1967	34	225-280	--	--
23-364	SAYREVILLE BOROUGH WD	SAYREVILLE BOROUGH	3-37	1937	5	-- -107	--	--
23-365	DUHERNAL WC	SAYREVILLE BOROUGH	DUHSAY 4	1931	5	148-160	--	--
23-371	HERCULES INC	SAYREVILLE BOROUGH	HERCULES 5	1929	48	182-228	--	--
23-376	HERCULES INC	SAYREVILLE BOROUGH	HERCULES 3	1928	41	180-220	--	--
23-380	HERCULES INC	SAYREVILLE BOROUGH	HERCULES 2	1927	48	181-237	--	--
23-384	HERCULES INC	SAYREVILLE BOROUGH	HERCULES 1 REBT	1939	54	170-225	--	--
23-385	DUHERNAL WC	SAYREVILLE BOROUGH	DUHERNAL 32 F	1930	27	-- --	2/3	280
23-386	E.I. DUPONT	SAYREVILLE BOROUGH	6	1930	102	253-314	--	--
23-389	E.I. DUPONT	SAYREVILLE BOROUGH	5	1928	107	249-304	--	--
23-391	HERCULES INC	SAYREVILLE BOROUGH	HERCULES 4	1928	47	163-226	--	--

APPENDIX E--Continued

Well-construction and selected chloride-concentration data for wells in or near the area of Sayreville and South River Boroughs and South Amboy City--Continued

Well number	Chloride measurement and date							
	1943		1958		1978		1985[a]	
	(month/day)	(Chloride concentration)	(month/day)	(Chloride concentration)	(month/day)	(Chloride concentration)	(month/day)	(Chloride concentration)
23-39	--	--	--	--	--	--	8/26	5
23-46	--	--	--	--	--	--	7/30	6
23-48	12/2	4	9/22	5	--	--	--	--
23-59	--	--	7/24	3	--	--	7/19	8
23-80	--	--	--	--	--	--	10/28/86	17
23-146	--	--	--	--	--	--	9/26	3
23-171	--	--	--	--	--	--	8/5	2
23-196	--	--	--	--	8/21	3	9/20	120
23-197	--	--	--	--	8/21	6	10/17/84	290
23-206	--	--	--	--	8/22	2	9/26	2
23-352	--	--	--	--	8/21	140	9/20	960
23-364	--	--	7/30	4	--	--	--	--
23-365	--	--	--	--	--	--	3/10/86	1,800
23-371	--	--	--	--	7/7	1,100	9/26	2,900
23-376	--	--	--	--	7/7	910	9/26	2,900
23-380	10/4	3	--	--	7/7	300	9/26	230
23-384	--	--	--	--	7/7	170	9/26	250
23-385	9/1	170	7/30	940	--	--	--	--
23-386	10/4	2	9/16	6	--	--	--	--
23-389	10/4	2	9/16	2	--	--	--	--
23-391	--	--	9/16	13	--	--	--	--

[a]Unless otherwise noted.

APPENDIX E--Continued

Well construction and selected chloride-concentration data for wells in or near the area of Sayreville and South River Boroughs and South Amboy City--Continued

Well number	Owner	Munici- pality	Local ident- ifier	Date drilled	Altitude of land surface (feet)	Screen depth (feet)	1939 (month/day)	1939 (Chloride concen- tration)
23-392	E.I. DUPONT	SAYREVILLE BOROUGH	1	1925	102	237-291	--	--
23-393	E.I. DUPONT	SAYREVILLE BOROUGH	3	1925	94	244-285	--	--
23-395	DUHERNAL WC	SAYREVILLE BOROUGH	DUHERNAL 33 F	1938	36	-- --	8/15	21
23-396	DUHERNAL WC	SAYREVILLE BOROUGH	DUHERNAL 27 F	1946	8	-- --	8/9	2,800
23-401	SAYREVILLE BOROUGH WD	SAYREVILLE BOROUGH	MORGAN P	1967	44	254-288	--	--
23-406	DUHERNAL WC	SAYREVILLE BOROUGH	DUHERNAL 28 F	--	6	-- --	8/9	45
23-410	DUHERNAL WC	SAYREVILLE BOROUGH	DUHERNAL 29 F	--	10	-- --	8/9	7,400
23-411	SOUTH AMBOY WC	SAYREVILLE BOROUGH	SAWD 8	1947	10	209-234	--	--
23-415	NL INDUSTRIES INC	SAYREVILLE BOROUGH	NL INDUSTRIES 4	1952	108	220-251	--	--
23-418	NL INDUSTRIES INC	SAYREVILLE BOROUGH	NL INDUSTRIES 3	1934	117	240-270	--	--
23-419	NL INDUSTRIES INC	SAYREVILLE BOROUGH	NL INDUSTRIES 2	1934	104	220-253	--	--
23-425	E.I. DUPONT INC	SAYREVILLE BOROUGH	PARLIN 60 F	1966	150	282-288	--	--
23-428	JERSEY CENT P&L	SOUTH AMBOY CITY	WERNER 5	1956	10	-- -160	--	--
23-430	JERSEY CENT P&L	SOUTH AMBOY CITY	WERNER 7	1972	12	135-165	--	--
23-431	JERSEY CENT P&L	SOUTH AMBOY CITY	WERNER 4	1952	10	143-168	--	--
23-434	SOUTH RIVER BORO WD	SOUTH RIVER BOROUGH	SRWD 2-52	1952	20	173-198	--	--
23-436	SOUTH RIVER BORO WD	SOUTH RIVER BOROUGH	SRWD 1-22	1922	20	163-192	--	--
23-438	SOUTH RIVER BORO WD	SOUTH RIVER BOROUGH	SRWD 5-77	1977	20	132-182	--	--
23-439	SOUTH RIVER BORO WD	SOUTH RIVER BOROUGH	SRWD 2 OBS	1977	21	121-126	--	--
23-440	HODGES BUS CO	SOUTH RIVER BOROUGH	1	1922	15	-- -195	--	--
23-551	SOUTH RIVER BORO WD	SOUTH RIVER BOROUGH	6-80	1980	45	155-208	--	--
23-1056	MIDDLESEX CO MUA	SAYREVILLE BOROUGH	MCUA MONITORING 3	1978	5	43-53	--	--
23-1058	HESS BROS	SAYREVILLE BOROUGH	HESS BROS 1	1986	25	112-122	--	--
23-1059	HESS BROS	SAYREVILLE BOROUGH	HESS BROS 2	1986	25	138-148	--	--

APPENDIX E--Continued

Well-construction and selected chloride-concentration data for wells in or near the area of Sayreville and South River Boroughs and South Amboy City--Continued

Well number	Chloride measurement and date							
	1943		1958		1978		1985[a]	
	(month/day)	(Chloride concentration)	(month/day)	(Chloride concentration)	(month/day)	(Chloride concentration)	(month/day)	(Chloride concentration)
23-392	10/4	2	9/16	2	9/30/77	8	10/15/84	76
23-393	10/1	2	9/16	3	9/30/77	47	10/15/84	270
23-395	8/3	120	7/30	980	--	--	--	--
23-396	9/2	3,100	--	--	--	--	--	--
23-401	--	--	--	--	8/21	2	9/20	13
23-406	8/3	21	--	--	--	--	--	--
23-410	8/3	6,800	--	--	--	--	--	--
23-411	--	--	9/22	3	--	--	10/2/86	5
23-415	--	--	9/24	2	8/22	3	--	--
23-418	9/10	2	9/24	2	8/22	18	--	--
23-419	9/10	2	9/24	3	--	--	--	--
23-425	--	--	--	--	--	--	9/25	1,300
23-428	--	--	9/22	3	--	--	--	--
23-430	--	--	--	--	8/22	630	3/3/86	1,400
23-431	--	--	9/22	36	--	--	--	--
23-434	--	--	9/23	3	8/21	6	9/25	13
23-436	8/42	2	9/23	3	--	--	--	--
23-438	--	--	--	--	8/21	6	9/25	12
23-439	--	--	--	--	--	--	10/21	170
23-440	--	--	9/23	4	9/20	42	9/25	70
23-551	--	--	--	--	--	--	9/25	12
23-1056	--	--	--	--	--	--	11/6/86	5,500
23-1058	--	--	--	--	--	--	4/21/87	5,400
23-1059	--	--	--	--	--	--	4/21/87	4,700

[a]Unless otherwide noted.

APPENDIX E--Continued

Well construction and selected chloride-concentration data for wells in or near the area of Sayreville and South River Boroughs and South Amboy City--Continued

Well number	Owner	Munici-pality	Local ident-ifier	Date drilled	Altitude of land surface (feet)	Screen depth (feet)	1939	
							(month/day)	(Chloride concen-tration)
23-1060	U.S. GEOLOGICAL SURVEY	SAYREVILLE BOROUGH	MARSH AVE	1986	40	138-148	--	--
23-1077	U.S. GEOLOGICAL SURVEY	SAYREVILLE BOROUGH	JCP&L SAYREVILLE	1987	7	46-56	--	--
23-1078	U.S. GEOLOGICAL SURVEY	SAYREVILLE BOROUGH	SAYRE ST	1987	12	68-78	--	--
23-1123	U.S. GEOLOGICAL SURVEY	SAYREVILLE BOROUGH	DRIVEPOINT A (BOTTOM)	1987	1	35-37	--	--
23-1128	U.S. GEOLOGICAL SURVEY	SAYREVILLE BOROUGH	DRIVEPOINT B (BOTTOM)	1987	3.5	45-47	--	--
23-1129	U.S. GEOLOGICAL SURVEY	SAYRVEILLE BOROUGH	DRIVEPOINT C (TOP)	1987	6	10-12	--	--
23-1145	U.S. GEOLOGICAL SURVEY	SAYREVILLE BOROUGH	WELL 28-C	1937	5	-- --	--	--
23-1146	U.S. GEOLOGICAL SURVEY	SAYREVILLE BOROUGH	WELL 30, MI-58	1937	15	-- --	8/9	11
23-1147	U.S. GEOLOGICAL SURVEY	SAYREVILLE BOROUGH	WELL 34, MI-26	1941	15	-- --		
25-466	ABERDEEN TWP WD	ABERDEEN TWP	3-77	1977	56	420-470	--	--

APPENDIX E--Continued

Well-construction and selected chloride-concentration data for wells in or near the area of Sayreville and South River Boroughs and South Amboy City--Continued

	Chloride measurement and date							
	1943		1958		1978		1985[a]	
Well number	(month/day)	(Chloride concentration)	(month/day)	(Chloride concentration)	(month/day)	(Chloride concentration)	(month/day)	(Chloride concentration)
23-1060	--	--	--	--	--	--	5/5/87	4,300
23-1077	--	--	--	--	--	--	4/27/87	6,000
23-1078	--	--	--	--	--	--	5/4/87	5,300
23-1123	--	--	--	--	--	--	11/18/87	3,200
23-1128	--	--	--	--	--	--	11/23/87	5,800
23-1129	--	--	--	--	--	--	11/18/87	2,300
23-1145	8/3	200	--	--	--	--	--	--
23-1146	8/3	5	--	--	--	--	--	--
23-1147	8/2	4,600	--	--	--	--	--	--
25-466	--	--	--	--	--	--	9/19	2

[a]Unless otherwide noted.